

Wireless Seismic Data Acquisition Networks

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Abstract

Seismic data acquisition in onshore oil and gas exploration involves deploying a large-scale network of geophone sensors, typically in tens of thousands, across a predefined survey area. The recorded seismic data is transmitted to a central control unit in the field after every sweep or shot. Upon reception at the control unit, the data undergoes further processing to generate an image of the earth's subsurface structure. Geophysicists then interpret this image to locate oil and gas traps beneath the earth's surface.

Conventional seismic acquisition systems use cables to connect each sensor for oil and gas exploration. While cable-based systems are typically reliable, the enormous amount of cable required leads to logistical complications, deployment challenges, excessive weight, increased survey costs, inefficiencies and unwieldy flexibility in survey planning. This has led to a growing interest in Wireless Seismic Data Acquisition (WSDA) systems, which offer a wireless solution for seismic exploration while maintaining data acquisition reliability comparable to that of cable-based systems. Contractors, exploration companies, and researchers are increasingly focusing on this to layout the enabling wireless technology to enhance seismic exploration on land.

In this thesis, a scalable and reliable Wireless Seismic Data Acquisition (WSDA) network architecture, technology, and protocol for large-scale seismic survey is proposed. The architecture addresses the challenges and requirements associated with WSDA networks. Results show that the proposed architecture can offer a level of reliability comparable to that provided in cable based surveys. The network architecture is evaluated and validated using the following approaches employing both analytical and simulation methods.

First, a comprehensive review on the current and retrospective onshore or land seismic data acquisition systems in terms of state-of-the-art devices, acquisition methods, architectures, technologies, and protocols is presented. The necessary

requirements and potential challenges for WSDA is also outlined. In view of this, an IEEE 802.11 multi-hop ad hoc based network architecture is proposed, with IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) as the enabling routing protocol. A geophone data traffic model that is based on the concept of seismic data acquisition during geophone recording period called Recording Period Acquisition (RPA) is presented. The model addresses the real-time data transfer requirement of seismic data acquisition systems and is employed to investigate the optimal number of seismic samples or data packet size that could be transmitted in the network.

Secondly, an analytical model of the IEEE 802.11 default Distributed Coordination Function (DCF) Medium Access Control (MAC) access scheme that investigates the performance of the proposed WSDA is presented. The model mainly focus on addressing the inaccuracies in modeling the backoff procedure and packet drop probability as some of the variations in the existing literature. Based on the RPA traffic model presented, the DCF model assumes unsaturated traffic conditions and non ideal channel conditions. Expressions for MAC delay, throughput, collision probability, and average duration a geophone spends during the backoff procedure before decrementing its counter are derived. The model serves as a tool for faster performance investigation of the proposed WSDA network with regards to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) based MAC, especially at the survey planning stage for scalability analysis. The model is validated using simulation in OMNeT++ simulator.

Furthermore, a discussion and evaluation of the proposed RPL routing protocol as applied to the WSDA network architecture is presented. The selection of RPL is justified using simulations, benchmarked against two prominent ad hoc routing protocols (Ad-hoc On-demand Distance Vector (AODV) and Optimized Link State Routing (OLSR)). Furthermore, a model that estimates geophone hop count distribution based on RPL in the proposed network architecture is presented. The model serves as a tool to assess the expected network connectivity and perform other preliminary parameter tuning by estimating the hop count of geophones in the network given a certain transmit power level.

Finally, the validity and feasibility of the proposed WSDA network architecture and wireless technology is evaluated using simulations as regards to the outlined challenges and requirements. The network performance is evaluated in 2.4 and 5 GHz bands with focus on investigating the effect of interference under different scenario configurations. In addition, energy consumption analysis and modeling, as well as discussions on the results obtained and what it generally implies as regards to WSDA is presented. Results show that the proposed architecture, technologies, and protocols can scale to large number of geophones in the network and effectively address the outlined challenges for WSDA.

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1 Introduction

This chapter gives an overview of the fundamental concepts and principles of seismic data acquisition or in other words seismic survey, mainly in the field of oil and gas exploration. This includes the concept of seismic waves fundamentals, equipment and devices used, survey planning, and data acquisition methods. Furthermore, the chapter outlines some background information and justification on the need for Wireless Seismic Data Acquisition (WSDA), the main requirements and challenges, motivation for the research, as well as the contributions presented in the thesis.

1.1 Seismic Survey

The desire to unravel the catastrophic nature of earthquakes by seismologists led to the discovery that seismic waves generated by earthquakes contain important information about the earth's subsurface structure. It was later discovered that artificial seismic waves can be employed to examine the subterranean structure of the earth to locate water, hydrocarbon, and mineral resources. Thus, Seismic survey or Seismic Data Acquisition (SDA) came into existence. SDA is a method of obtaining information about underlying geological structures beneath the earth's subsurface in a particular location by means of analysis of seismic waves. An image of the earth's subsurface structure is then produced from analyzing the information carried in the acquired reflected waves. Some area of application includes earthquake early warning systems [1], observation and monitoring of volcanic activities [2], glaciers and ice sheets [3], landslides [4], mineral resources, as well as oil and gas explorations [5].

In oil and gas exploration, hydrocarbon resources can be located either beneath land or sea. As such, SDA can be classified into onshore and offshore. Although

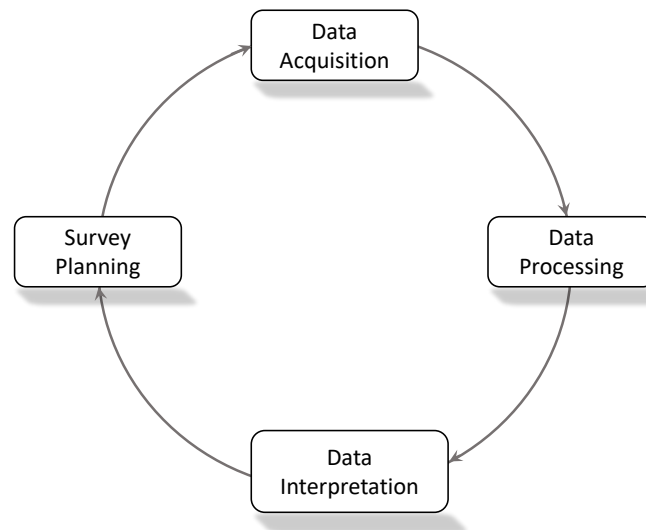


Figure 1.1: Stages involved in seismic survey process

both have the same goal of imaging the earth’s subterranean structure, the environmental difference make them both to have unique differences in the survey methods and technologies used. In this thesis however, the focus is on onshore (or land) seismic survey.

Several important stages are involved in onshore seismic survey. These includes the survey planning and design, data acquisition, data processing, and data interpretation stage as illustrated in Figure 1.1. Each of these stages is critical in the survey process and has to be properly executed the first time as re-surveying can be greatly expensive. Considering the fact that the success or failure of the survey is determined at the data interpretation stage (last sage of the survey), careful planning and acquisition of seismic data are of paramount importance [6]. In this thesis, the focus is mainly on the data acquisition stage with some part of survey planning stage.

Onshore SDA is often achieved using a technique called “seismic reflection”, which is quite analogous to the ultra-sound scanning procedure done in hospitals. This method is employed by oil and gas industries to locate optimal places to drill for oil and gas. In this technique, an energy source generates variable frequency waves (acoustic wave) for a period of time called the “shot or sweep period”, that propagate down the earth surface. Upon hitting various geological boundaries, these waves are reflected back to the earth surface. Devices placed at the surface called geophones record, amplify, filter, and digitize these reflected signals for a duration of time called the *recording period*.

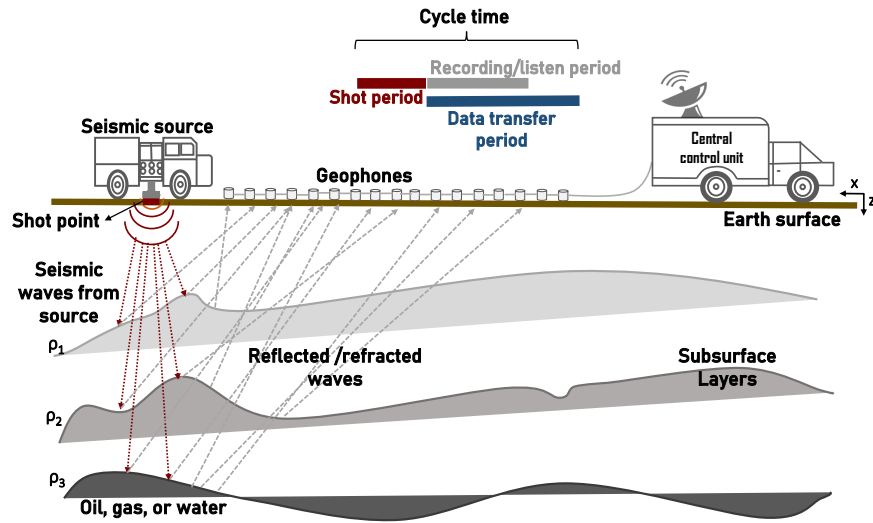


Figure 1.2: Overview of onshore seismic data acquisition process depicting the shooting and data delivery stages [8]

These signals are then forwarded down to the Central Control Unit (CCU) for further signal processing to come up with the subsurface image of the area being surveyed [7]. The time it takes for the wave to return back to the surface depicts how far down the geological boundary is located. The shot period plus the recording period and the time it takes to transfer the data from the geophones to the CCU is referred to as the *cycle time* or *sweep cycle*. The energy source is then moved to the next shot point and the process is repeated over again throughout the survey area. Figure 1.2 gives an illustration of the SDA process.

1.1.1 Seismic Wave Fundamentals

SDA basically employs propagation of elastic waves through the earth surface. Two types of waves are considered, *surface* and *body* waves. Surface waves are low frequency waves that propagate along the earth's surface [9]. Body waves propagate through all distance level of the earth's subsurface geological boundaries. SDA is primarily stationed around the analysis of body waves except for some specific application cases. Compressional and shear waves also known as primary (P-wave) and secondary wave (S-wave) respectively are the two types of body waves used in SDA. The motion of a particle under the influence of a P and S wave is parallel and orthogonal to the direction

of the wave propagation respectively. The P-wave can propagate in solids or fluids (water, oil, and gas) and has the fastest velocity (V_p) in the range of 200-800 m s⁻¹ for dry sediments like clay, sand or gravel and 1500-2500 m s⁻¹ for water logged materials. This makes them an appropriate tool for subsurface explorations. S-wave velocities (V_s) are much slower in the range of 100-500 m s⁻¹ and can only propagate in solids. The depth of different geological layers could be derived using the wave travel velocity (which carries information on the type of rock or sediment in the subsurface) and the time required for the wave to return to the earth surface. The P and S wave velocities can be expressed in terms of the share modulus μ , compressional modulus k , and the density of the subsurface layer ρ as expressed in Eq. (1.1) and (1.2) respectively [10].

$$V_p = \sqrt{\frac{k + (4\mu/3)}{\rho}} \quad (1.1)$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (1.2)$$

Similar to sound waves, these waves are reflected and refracted as they hit boundaries between different subsurface layers. The magnitude of the difference between boundary densities and seismic velocities define the intensity of the reflected wave. The seismic wave energy is proportional to the square of its amplitude, and the propagation velocity is the product of its wavelength (λ) and frequency (f).

1.1.2 Survey Equipment

SDA requires an energy source to generate seismic waves, and sensors to detect and convert these waves into electrical signals. Thus, equipment used in SDA can be generally classified into energy source, and recording equipment also referred to seismic receivers.

Seismic Energy Source

Seismic energy sources equipment can be either impulsive or vibratory.

Impulsive: This type of energy sources often employ the use of explosives such as ammonium nitrate or dynamite, stuffed at the bottom of drilled holes on the survey field prior to the commencement of the data acquisition. The explosives are then triggered by an operator causing it to detonate. A considerable part of the energy generated is transmitted as seismic waves which radiates outward in all direction. The reflected waves reaches a geophone sensor placed at the surface through a minimum time path, providing a straightforward estimate of time from the explosive to the earth surface (an important information employed in data processing stage). In addition, this technique minimizes surface waves generated and reduces signal attenuation. However, high amplitude horizontal noise produced by explosives as well as high energy lost are some drawbacks of using explosive [7]. Near surface conditions and accessibility of other seismic sources especially with regards to terrain conditions are the main factors influencing the choice of explosives as the energy source in a survey [11].

Vibratory: Vibroseis technology employs the use of vibrators as an energy source in a survey. Vibrators are the most popular sources used for generating seismic energy in an onshore exploration [12]. A vibrator is a vehicle-mounted energy source often referred to as *vibroseis truck* that generates low frequency vibrations into the earths subsurface also known as sweep signals. The vibration is controlled by converting an electrical signal (reference sweep signal encoded in the vibrator electronics) into high pressure hydraulic flow to administer the vibration of a heavy base plate kept in contact with the ground for a given sweep or shot duration, and isolated from the vehicle by an air-bag suspension [13]. The vibroseis technique is based on the concept that signal containing a known set of frequencies is transmitted into the earth subsurface. The reflections received at the surface will produce a signal which is a projection of the earth's subsurface [6]. Higher frequencies produce more detailed seismic information, while lower frequencies propagate deeper and enhance the reflection or response accuracy. In oil and gas exploration, most of the sweep start with a frequency range of 1-2 Hz and ends in 80-90 Hz, with a sweep duration ranging from 8-20 s [14].



Figure 1.3: Vehicle mounted vibrator [11]

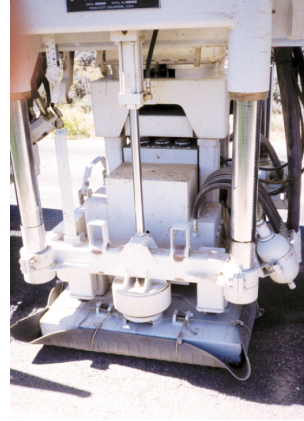


Figure 1.4: Vibrator base plate [11]

A survey with one group of vibrators serving as the seismic energy source is often referred to as single-fleet operation. As a form of increasing survey productivity and noise cancellation, multiple fleet operations (array of vibrators) are normally employed in most oil and gas exploration. The number of vibrators in a fleet often varies between 3 to 5, and most survey crew run two fleets per acquisition [11]. Some advantages of vibrators over impulsive sources includes; signal spectral control, low-power source, longer energy emission time, less safety concerns as well as better control of sweep repetition. Some drawbacks of using vibrators include, high surface-wave noise generation, distortion resulting from signal traveling through the earth's near surface [13], and difficulty to use in complex terrains such as mountainous or marshy areas, or in jungles. Figure 1.3 and 1.4 show an image of a vehicle mounted vibrator and a vibrator base plate respectively.

Seismic Receivers

Seismic receivers are devices that detect seismic waves in the form of ground motion (in land operations) or pressure wave (in marine operations) and converts them into electrical energy. Motion sensitive receivers employed in land surveys can either be a geophone or accelerometer. The output of a geophone, measured in millivolt per inch per second (mV/in/s), is proportional to the ground velocity while the output of an accelerometer is proportional to the ground acceleration and is measured in millivolt per inch per second squared (mV/in/s²). However, in land seismic exploration, geophones are the most commonly used seismic receivers [15]. A geophone consists of a permanent

magnet, a conductor or coil suspended by means of a spring, which basically operates based on Faraday's Law of electromagnetic induction. Vibration of the ground causes movement of the conductor through the magnetic field space, thus generating voltage that is proportional to the ground vibration or velocity of the conductor [6]. Resonant frequency refers to the particular frequency with which the coil vibrates, that depends on the mass and the stiffness of the spring used. If no outside forces are driving the coil motion, the output frequency of the geophone can be expressed as in Eq. (1.3), where f_r is the resonant frequency, K is the spring constant, and M is the mass of the geophone. In oil and gas exploration, geophones with resonant frequency ranging from 4 - 15 Hz are commonly used [6].

$$f_r = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \quad (1.3)$$

Equation (1.4) shows the geophone output voltage where E represents the EMF of the output voltage, L is the number of turns in the coil, V is the relative velocity of the coil in relation to the magnet, B is the magnetic field strength, and C is a component geometry factor set by the manufacturer.

$$E = BLVC \quad (1.4)$$

Seismic reflections or vibrations arriving at the earth surface causes the geophone case to move up and down, consequently resulting in the movement of the coil mass later in time. The time lag between the case and mass movement is referred to as the geophone's phase response. The relationship between the ground velocity and the coil velocity is given in Eq. (1.5).

$$V = \frac{G \cos \phi}{R} \quad (1.5)$$

G is the vertical ground velocity, ϕ is the phase between the case and mass motion, and R is the damping constant usually ranging from 0.5 to 0.7 [6]. Geophone sensitivity refers to the voltage produced per unit ground velocity, measured in mV/in/s.

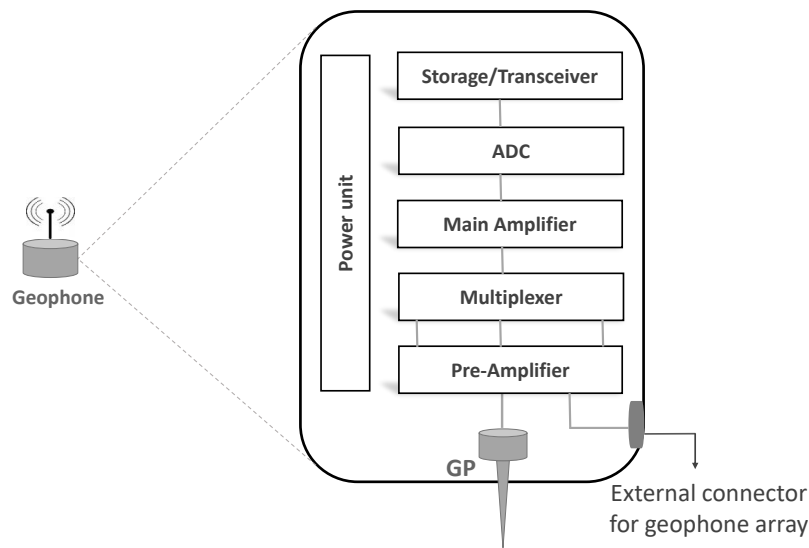


Figure 1.5: Components of a node or recording unit [6].

To reduce coherent noise level as well as enhance the reflected signal in former land surveys, an array of geophones are connected together in geometrical pattern via cable to form a single unit usually referred to as recording (or acquisition) unit [6]. However, recent development in modern electronics has led to a full cable-free stand-alone recording unit commonly referred to as ‘node’. A node is a self-contained unit that consists of a battery, filter, amplifier, multiplexer, analogue to digital converter (ADC), clock for timing precision, processor, memory, transceivers, internal geophones as well as external connectors for attaching array of geophones [16]. Figure 1.5 illustrates the components of a geophone node.

1.1.3 Seismic Signal Recording

Reflections from the generated seismic signal are recorded at the surface by geophones or recording instruments. The reflected signals have a wide dynamic range comprising of reflections, refraction, ground roll, and environmental noise, all with different amplitudes varying in a range from micro-volts to volts. Consequently, filtering, amplification, and digitization are some important stages the signal has to go through in order to correctly capture the information contained in the signals. Received seismic signal must undergo frequency filtering prior to the recording process. Noise outside the expected seismic signal spectrum is removed by analog or digital filtering. Noise with frequencies

corresponding to that of the seismic signal are removed using special data processing techniques at the central control unit. A fixed form of amplification with only a relatively small number of data bits (such as 14 bit) cannot handle the reflected signal dynamic range without some form of clipping at the most significant bit end of the converter. Instead, an automatic gain control (AGC) level is determined for application by the main amplifier in the feedback loop with an Analog-to-Digital Converter (ADC) to reduce or amplify incoming signal to keep levels within the desired converter range [6]. A 24 bit ADC expands the signal dynamic range to a theoretical value of 138 dB. However, because of internal system noise or ambient background noise which is converted into a value in bits, the absolute converter range is slightly reduced to a practical value of 114 dB. The higher the ADC resolution the better the subsurface image quality, which most oil and gas industries are more interested in, as it provides clearer image insight on optimal locations to drill for oil and gas. A stream of digitized samples drawn from a single geophone is called a *seismic channel* [17].

The ADC resolution (R) and sampling interval (T_{samp}) of the reflected signal defines the rate at which data (D) is generated from geophones or recording units. Modern recording devices or geophones employed in seismic surveys employ 24-bit ADC resolution. Depending on the instrument used, T_{samp} ranges from 0.25 ms to 8 ms [6]. Equation (1.6) gives an expression for the data generation rate.

$$D = \frac{R}{T_{samp}} \quad (1.6)$$

For a sampling interval of 0.5 ms, a geophone with 24 bit ADC resolution will generate data at a rate of 48 kbit s⁻¹.

1.1.4 Survey Planning

For a successful seismic data acquisition, thorough and mindful planning is imperative. Several steps are involved in the survey process which include [18]:

- i). Identifying target location: The surveyors should define and describe the targeted area with regards to location, geological nature, depth, terrain or areal extent and geological dips.
- ii). Budgeting: Costs for data acquisition, processing, interpretation, drilling, and other associated costs should be budgeted prior to the survey. In general, acquisition predominantly takes higher percentage of the budget (up to 80%).
- iii). Prospective production and profits estimate: Ideally, expected profit should exceed the budget costs otherwise it will be meaningless to proceed with the survey.
- iv). Defining survey objectives, priorities, as well as data quality standards that can yield the desired objectives and consistent with the budget.
- v). Survey time planning: Reasonable deadlines and schedules should be defined from prior to the survey in terms of production requirements.
- vi). Obtaining permissions: Since every inch of the earth's surface is owned by an entity or person, it is imperative to obtain permissions before the survey operations begin.
- vii). Locating and establishing desired survey lines: The surveyor should determine the feasibility of these lines in the targeted locations in terms of elevation and position with regards to each receiver and source point in the survey with desired degree of accuracy.
- viii). Selecting specific survey equipment and methods depending on the environment and data acquisition parameters defined to comply with the survey goals.

1.2 Wireless Seismic Data Acquisition (WSDA)

The continuous interest in WSDA systems by oil industries and researchers arose as a result of various rationale. Impediments introduced by cables in conventional SDA systems such as complications in survey logistics (transportation, deployment, and maintenance) are some of the fundamental reasons

in moving towards cable-free acquisition. In addition, cables account for up to 50% of operational costs and 75% of the total equipment weight in land seismic surveys [17]. Cables are also vulnerable to damages by natural and cultural causes, resulting in survey down-time as considerable field time is expended troubleshooting faulty cables [16]. Another reason is the growing interest in large-scale SDA for better subsurface image quality, flexibility, and automation in survey [19]. In comparison with cable-based acquisition systems, WSDA provides increased productivity, greater seismic trace density, ease of deployment, and better subsurface imaging quality [20]. In WSDA systems, the acquired seismic data is conveyed to the CCU using wireless telemetry. Such system often employ a network of geophones, equipped with wireless transceivers to form what is termed as WSDA networks, or in other words wireless geophone network (Wireless Geophone Network (WGN)). Throughout the rest of this thesis, the term *geophone* will be used to denote a “node” as discussed in Section 1.1.2.

1.2.1 Historical perspective

The notion of WSDA systems has been in existence since few decades ago. The first cable-less systems were introduced during the second world war in early 1970s [20]. These systems were developed for shallow offshore acquisition with the node placed on a float and can also be used for land acquisition systems. The “Acquatronics Telseis” series acquired by Fairfield in 1796 is an example of such system. These node units are relatively heavy, had limited battery life, and take some significant amount of time to transmit acquired data. For example, the OpSeis 5500 system weighed 17 kg, has a battery life of 72 h, and took 5 min to receive data from 95 seismic channels [21]. During acquisition, data is first stored locally within the node before it is sequentially transmitted to the CCU over radio.

The idea of “blind recording” was first introduced by GUS manufacturing in 1979 and applied in the “Seismic Group Recorded (SGR)” system. Data is stored locally in the node during acquisition and then later downloaded after completion of the survey or acquisition process. The node units are synchronized via radio messages. Subsequently, the weight of the geophone

unit was reduced to around 9 kg [20]. However, recorded data integrity was a major cause of concern as no form of Quality Control (QC) monitoring or real time status update. As such, many clients find it difficult to accept such systems at that time. Example of such systems include Sercel Eagle/SU6-R, Fairfield BOX etc.

The first QC enabled seismic recorder system was introduced in 1995 by Inova. The system was a 6- channel remote seismic recorder (RSR) that stores data using a flash memory. In addition, weight of nodes was significantly reduced as a result of advancement in electronics technology. The “G5” system (a relatively smaller radio controlled recording unit) was introduced by Ascend Geo in 2005. The system continuously record seismic data using a timing or control signal sent over radio from the CCU. GPS was the backbone technology that lead to a true blind continuously recording systems as previous systems rely on radio signals for synchronization [20]. A considerably lighter and smaller unit was later developed in 2009 by Wireless Seismic. The system offers a real-time radio data transmission and runs on battery with approximately 100 hrs of life time before recharging is required. Wireless seismic further advance their product into a full real-time radio systems with the development of RT system 2 and RT system 3 in 2012 and 2017 respectively [22]. In these systems, each node sends its recorded seismic data to a relay unit it associates itself to via Wireless Local Area Network (WLAN), which then sends it down to the CCU for further processing.

1.2.2 Network Coverage and Deployment

Depending on the coverage area of the target location, a typical onshore SDA can cover several square kilometers, comprising of about 10,000 to 30,000 geophones [23], with an average density of up to 2000 devices per km². The orthogonal geometry is often employed in seismic surveys [24] where source and receiver lines are placed perpendicular to each other according to predefined survey parameters as depicted in Figure 1.6.

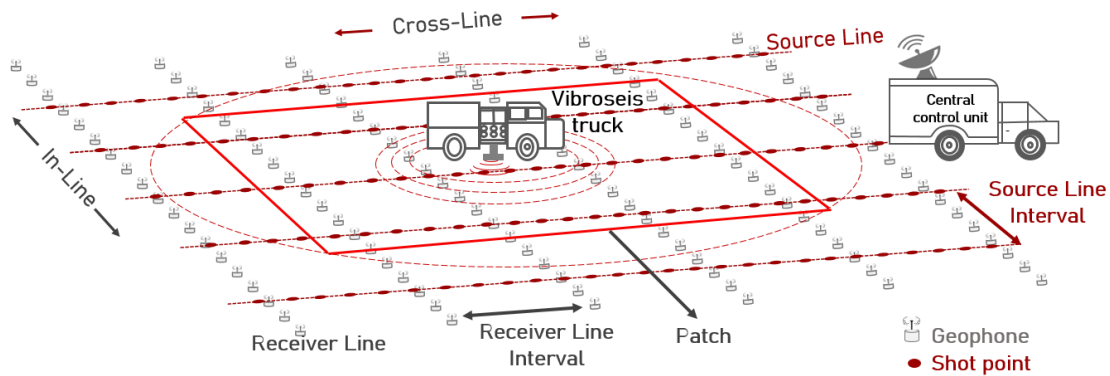


Figure 1.6: Typical SDA orthogonal geometry network layout

Some common terminologies related to orthogonal geometry network layout include:

Receiver line: a line comprising of geophones deployed at regular intervals usually between 10 - 30 m [25]. The straight receiver lines are employed to counter aliasing noise effect with low apparent velocities (a problem that causes different signals to be identical during sampling) [24].

Receiver line interval: is the distance between two successive receiver lines usually up to 300 m [25].

Cross-line direction: direction orthogonal to the receiver lines.

In-line direction: direction parallel to the receiver lines.

Source line: consists of shot points marked at uniform intervals along the line.

Source line interval: is the distance between two successive shot points usually 50 m.

Shot points: are locations on the earth surface where the seismic waves are generated by an energy source which propagate down the earth surface [26].

Patch: refers to all the active geophone nodes that record data during a shot or sweep at a particular source point, forming a rectangle comprising of several receiver lines as shown in Figure 1.6. A typical value of the distance from the edge of a patch to a shot point is 800 m [11].

Geophones deployment is a one-time activity done prior to commencement of the acquisition. Thus, WSDA networks are static in the sense that mobility of geophones is not expected after initial deployment. This implies that geophones can stay connected wirelessly long enough to support hierarchical networks with autonomous entities [17].

1.2.3 Data Generation and Transmission

As mentioned in Section 1.1.3, the rate at which data is generated depends on the sampling interval and the resolution of the geophones ADC. For a survey with a minimum sample interval (T_{samp}) of 0.5 ms, and a 24 bit ADC resolution, each geophone in the network will generate data at rate of 48 kbit s^{-1} . Although the data generated by a geophone is quite small, the aggregate data from geophones required to be transmitted to the CCU for each record or shot could be quite large. This can be quantified by an example that entails 30,000 seismic channels or geophones, with seismic signal sampled at 0.5 ms interval, 5 s geophone recording period and a time lapse between records of 60 s. For each record, 240 kbit of data is generated per geophone and an overall data of 7.2 Gbit (900 MB) is generated in the network. To keep up with the data throughput, at least 120 Mbit s^{-1} bandwidth is required, as well as multiple radio links to share the bandwidth load [27]. A typical survey with up to 30,000 geophones transmitting data in real time will require a sum throughput of 1.44 Gbit s^{-1} per shot, which will scale down to 720 Mbit s^{-1} if a sampling interval of 1 ms is used. Support for such throughput is quite uncommon for traditional Wireless Sensor Network (WSN). In addition, majority of seismic contractors regard QC data monitoring as an important part of SDA operations [28]. The QC data contain information on things like geophone status, tilt, battery state and has a data rate usually ranging from 1 to 10 B min⁻¹ or (0.133 - 1.33 bit s^{-1}) [17].

1.2.4 Energy Consumption

As SDA is often carried out in remote and harsh terrains with hindered or limited mobility, energy consumption in geophones is a crucial factor to address.

Considering the fact that SDA can last for several days or weeks, WSDA network lifetime should be maximized for as long as possible. Thus, protocols and technologies employed should be able to minimize energy consumption so as to maximize time between recharging geophone batteries [29], and by extension the network lifetime.

1.3 Problem Statement

Traditional approach of deploying SDA networks is to connect each sensor node via cable. Cable-based survey is known to have a lot of downside, such as excess weight, reliability issues, complexities in deployment and maintenance over large survey area, human resource costs [30], as well as high operational costs. An example is the case history of a real-time wireless seismic survey carried out in the Kurdistan region of Iraq by Asian oilfield Services Limited (an Indian based exploration company) [31]. The survey covers an area of over 270 km² across different terrains ranging from rocky cliffs and steep hills to flat landscape across the villages. Due to the rugged nature of the environment and high temperatures of up to 52 °C, deploying cables was very challenging from logistics point of view under very harsh and unpleasant working conditions. The survey was reported to have successfully utilize the RT system 2 developed by Wireless Seismic for a cable-free data acquisition. The system employs more than 6000 live channels out of an array of 8000.

According to [32], since 1970 seismic channel count has doubled every 3.5 years and in few years to come, a survey with 100,000 seismic channel will be common. Dave Monk refers to this exponential increase as **Moore's law** of seismic channel count as shown in Figure 1.7 [33].

The projection in Figure 1.7 shows that future seismic survey might require recording channels ranging from hundreds of thousands to million [27], following the need to enhance the quality of the earth's subsurface image obtained. This will result to even more complex, cumbersome and expensive logistics around cable-based exploration. Resorting to wireless telemetry is a viable way to address the problems associated with cable based survey. This involves utilizing a network of wireless geophones that incorporates components like batteries,

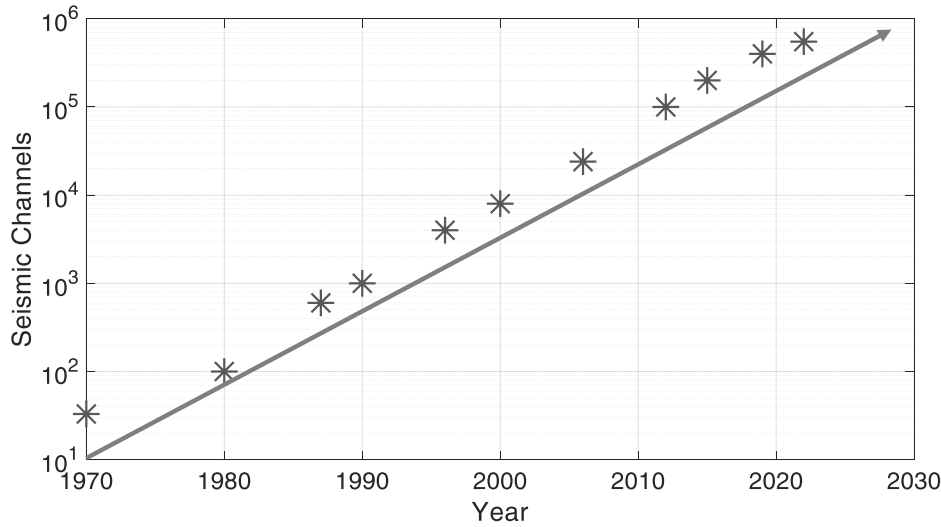


Figure 1.7: “Moore’s law” for seismic channel count (modified from [33])

processing unit, Analogue to Digital Converters (ADC), filters, memory, clock for timing precision, transceivers as well as sensor [16], to wirelessly convey seismic data to the CCU. Unlike traditional WSN, WSDA networks employ high density network of geophones. According to [17], the traffic volume in such networks is comparable to what a telecommunication operator handles in a medium sized or less populated city. As such, WSDA network presents a number of challenges, which are outlined in Section 1.3. As such, it is imperative to have a bench mark or simulation platform for testing WSDA networks prior to commencement of the survey, to have some insight on SDA deployment strategies and expected performance based on predefined survey requirements and parameters.

Challenges and Requirements

Despite the advancement in the modern day standards and products in the field of wireless communications, some features of real-time WSDA are uncommon to conventional WSN. One major challenge in WSDA is the large volume of seismic data collected. Although the data generated by a single geophone is small, the aggregate amount of data collected in the network could be significantly huge, considering the large scale deployment of geophones in the network. According to [28], as at the year 2016, 70 Tbit of data is generated per day in a typical survey. Therefore, the issue of how this data should be transmitted reliably and effectively to the CCU in real-time (or with reasonable

latency) should be addressed especially when selecting wireless technology and protocols to be used.

Another challenge is the WSDA network architecture or design. With future surveys targeting hundreds of thousands of seismic channels, the issue of scalability should be well considered when designing the network. In some parts of the world, seismic survey is conducted in unconventional areas with rough terrains (mountainous, marshy, rain forest e.t.c), and nodes can be left unattended for several days or weeks. As such, the network should be designed in such a way that it can self-organize and configure, providing the ability to remotely control the geophones after deployment, as well as provide the required quality and reliability of the acquired data.

Furthermore, the network needs to be designed for continuous operation up to several days, depending on the survey type or size. Information on geophone positioning and elevation are of vital importance for the surveyor to easily keep track of all geophones in the survey in case of failure or damage to ensure robustness of the system. Most geophones use the Global Positioning System (GPS) for localization and timing. To avoid degradation of the subsurface image quality, accurate positioning with error below 1 meter is necessary after deployment. Seismic reflections from the earth subsurface are simultaneously detected and sampled by geophones in the vicinity of seismic sweep within the survey area. Data acquisition needs to be synchronized with time-reference distributed over the survey area and a maximum acceptable timing skew/jitter of 10-20 μs [25].

The key challenges accompanying WSDA networks are summarized in the following text:

Scalability: Considering the large scale-deployment of geophones in WSDA networks, scalability is an important factor that needs to be addressed. A scalable WSDA network should be able to maintain performance characteristics irrespective of network size. Therefore, the network architecture, technologies, and protocols should be scalable to large number of geophones and bound by communication and survey costs with regard to network size.

Self-Organization and Maintenance: Geophones should be able to set up and maintain a network among themselves, especially considering the large

scale geophone deployment. Moreover, new geophones may join the network and some may fail due to physical or electronic damage. Thus support for self-organization as well as autonomous network management should also be addressed.

Data Reliability: To correctly interpret the subsurface structure in WSDA, receiving seismic data successfully from each and every geophone is very crucial, especially at the processing stage. This is contrary to traditional WSNs in which most of the data collected from neighboring sensors is redundant as a result of high correlation between nodes [34]. Thus, reliability of acquired seismic data is of crucial importance. In addition, as WSDA is aimed at replacing cable-based telemetry survey systems, its reliability should at least match or be very close to that provided by cable-based systems. This involves offering guarantee in terms of quality of service parameters like delay, bandwidth, packet error rate/packet loss etc.

Latency: To increase the overall survey productivity, SDA systems require real or near real-time transmission of both seismic and equipment Quality control (QC) data to the CCU with minimal latency during operations [35]. This enables contractors to monitor the quality of data acquired for a particular shooting phase before moving to the next, and avoids the risk of repeating the shooting phase all over again in case of faulty records.

Wireless Technologies and Protocols: Due to the high data rate requirement in WSDA networks, technologies used in conventional WSNs such as, IEEE 802.15.4 or LoRa are not suitable. In view of the huge survey field layout and the large scale geophone deployment, technologies employed in WSDA networks should be able to offer long communication range, high data rate, cost effectiveness, availability, as well as low power consumption. However, procuring a single technology that address all this can be quite challenging. Utilizing off-the-shelf IEEE 802.11 random access technologies in multi-hop ad hoc form of communication could be a way to extend coverage while providing required data rate to relay large volume of aggregated seismic data to the CCU. Employing ad hoc communication will address the issue of self-organization, which is the main goal in ad hoc networks, allowing nodes to dynamically configure and manage themselves without the need of a central control entity [36]. Furthermore, this will eliminate the need for deploying

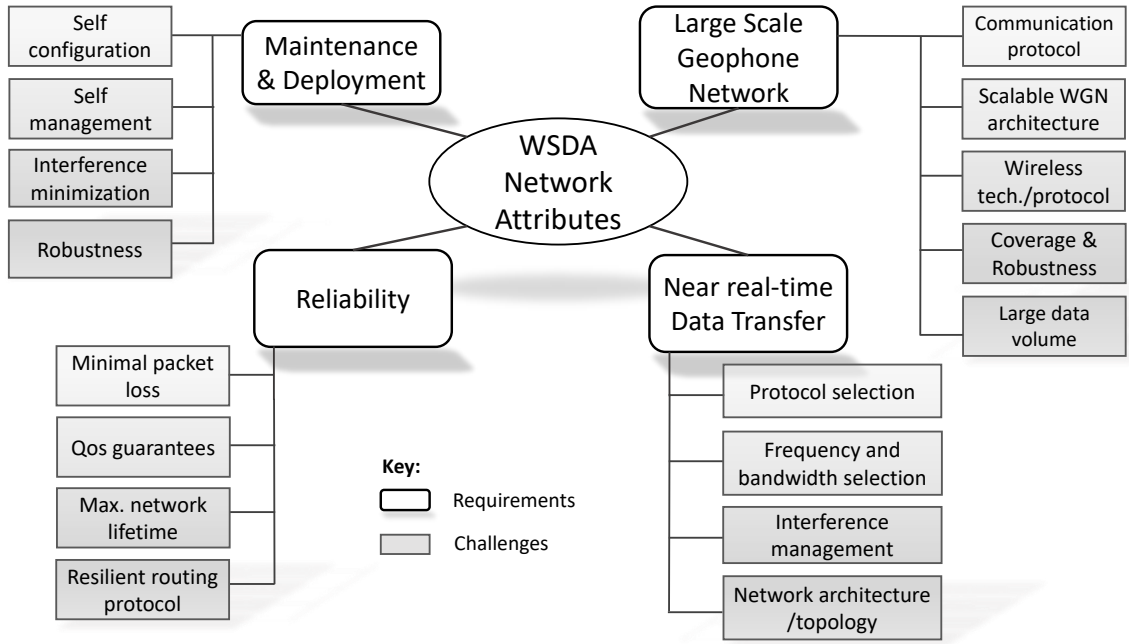


Figure 1.8: Attributes and challenges in WSDA networks

infrastructures or access points in most present day WSDA systems, which will consequently lead to reduced overall survey costs. Nonetheless, appropriate routing protocols need to be defined to enable multi-hop connectivity. WSDA networks are static in nature, i.e., no movement of nodes is required after the initial deployment. Hence, employing protocols supporting hierarchical networks with auto-configuring entities can be justified. This is because two or more geophones can stay within communication range for an extended period of time.

Energy Consumption: Although WSDA offers a good alternative to cable-based acquisition, it comes with the trade-off of increased energy consumption demands as each geophone node will require power for sensing, processing, and radio communication. As such, energy consumption issues should be addressed at all layers of the communication system so that geophones can stay operational for as long as possible without the need for battery replacement. Figure 1.8 gives a summary of the requirements and challenges that need to be addressed in WSDA.

1.4 Contributions

In this thesis, a comprehensive model that describes a Wireless Seismic Data Acquisition (WSDA) system for onshore data acquisition applications in oil and gas explorations is presented. The model addresses challenges and issues attributed to WSDA networks as outline in Section 1.3. The model serves as a tool and benchmark to analyze and predict the performance of WSDA systems prior to commencement of the survey or data acquisition process. The main contributions in this work can be summarized as follows:

- i). A comprehensive review on the state-of-the-art in the field of WSDA ranging from devices employed, data acquisition methods, network architectures, technologies, and protocols is presented.
- ii). Based on the above, a scalable and reliable architecture for WSDA networks in which the entire survey area is divided in subnetworks is presented. Each subnetwork comprises of a gateway running IEEE 802.11 WLAN technology in ad hoc mode and deployed based on the frequency reuse concept.
- iii). An analytical model which serves as a general tool for investigating the performance of IEEE 802.11 based WSDA networks for single-hop ad hoc communication is presented. The model is an extension of the classical bi-dimensional Markov model that describes the behavior of the IEEE 802.11 DCF under non-ideal channel conditions and unsaturated traffic based on the proposed geophone Recording Period Acquisition (RPA) traffic model presented in this thesis. The model could be very beneficial at the survey planning stage for scalability investigation and other network related performance investigation for any wireless technology of the IEEE 802.11 family.
- iv). An evaluation and validation of the WSDA network performance is presented based on the proposed architecture, technology, and routing protocol using OMNeT++ simulation framework. KPIs such as throughput, delay, overhead e.t.c., are analyzed and compared to the network requirements in WSDA.

- v). An analytical model that estimates geophone hop count distribution based on the proposed WSDA architecture is presented. The model serves as a tool for quick determination of some predefined parameters like geophone transmit power settings at the planning stage, prior to commencement of data acquisition.
- vi). An evaluation of the energy consumed in geophones during the data acquisition process to estimate the network lifetime i.e., the number of sweep cycles to be carried out before the first geophone runs out of battery is presented.
- vii). A model that estimates or predicts energy consumed in geophones per sweep cycle based on the IEEE 802.11 medium access control (MAC) transmit, receive, and idle operation modes is presented. The model is an extension of our IEEE 802.11 DCF model mentioned in III above. The model serves as a tool to determine which hardware to buy or use based on the predefined survey specifications especially at the survey planning stage.

1.5 Thesis Organization

This manuscript is organized in 7 chapters. Chapter 1 gives a comprehensive introduction to the fundamentals of onshore seismic data acquisition as applied mainly in oil and gas exploration. Furthermore, the chapter describes some background information necessary to understand the main problems and challenges the thesis focuses on. Chapter 2 presents a general review on state-of-the-art information relative to the field of WSDA with regards to devices employed, network architectures, technologies, protocols, and channel access methods employed. Chapter 3 discusses the proposed WSDA network architecture, data traffic model, wireless technology, bottlenecks, research questions, as well as the methodology and scenarios considered. Chapter 4 presents an analytical model for the IEEE 802.11 DCF channel access mechanism based on the proposed network architecture in Chapter 3, as well as an evaluation of the proposed geophone data traffic model. Chapter 5 presents a discussion, evaluation, and validation on the proposed RPL routing protocol as applied to

the proposed WSDA architecture. In addition, the chapter presents a model based on geophone hop count distribution as regards to the proposed RPL routing protocol. Chapter 6 investigates the feasibility and validity of the network architecture, wireless technology, and protocol proposed in this thesis with respect to addressing challenges and requirements outlined in Chapter 1. The evaluation is carried out using simulations for a real world seismic data acquisition setting. Finally, conclusions, recommendations, future work, and other areas of application of the proposed architecture and model is presented in Chapter 7.

2 Related Work

This chapter presents a comprehensive review on the state-of-the-art and related work in the field of WSDA. This includes information on recently developed wireless geophone devices, WSDA methods, network architectures, technologies, and protocols used. On this basis, a discussion on the selection criteria for the choice of wireless technology and routing protocol employed in this thesis is presented, with a view to addressing WSDA requirements and challenges outlined in Chapter 1.

2.1 Recent Advancement in WSDA Devices and Systems

The increasing interest for high quality subsurface imaging as well as impediments associated with cables is one of the fundamental motives for moving from cable-based to wireless seismic acquisition systems by oil and gas industries. Such systems comprise of advantages which include increased survey productivity, greater trace density, and improved earths subsurface tomography [20]. Advancement in modern electronics have given rise to a complete stand-alone battery powered cable-free seismic acquisition system referred to as ***nodal systems*** or ***node*** as described in Section 1.1.2. Based on the acquired data collection strategy and type, nodal systems can be categorized into Blind, QC capable, and real-time or full radio nodes [37].

2.1.1 Blind Nodes

A blind node, often referred to as autonomous node or recording system has no means of transmitting acquired seismic or QC data to the CCU during

operations. Data for each shot or series of shots are stored on an internal memory unit and collected by field crew members moving around during the survey, or downloaded weeks after commencement or at the end of the survey. Timing synchronization for nodes is provided via GPS.

2.1.2 QC Capable Nodes

Such nodes enable the collection of QC data for monitoring the integrity of seismic records at the CCU either via downloading the data directly by survey crews or transmitting it remotely via low speed radio links. Typically, the seismic data are collected by survey crews moving across the survey field. Some of these systems have capability for initiating data acquisition via radio messages from the CCU, while the acquired data is still stored internally [20]. As mentioned in Section 1.2.3, QC data contains information such as geophone status, available memory unit capacity, geophone tilt, ambient field noise etc.

2.1.3 Real or Near Real-Time Systems

In these systems, both seismic and QC data are transmitted directly to the CCU in real-time or within a significantly short period of time (usually before the energy source moves to the next shot point) during operation using dedicated radio links or infrastructures. Continuous monitoring of noise level, QC data, damaged or destroyed units, are some obvious benefits of using such systems. In addition, with such systems, high survey cost and delay in data retrieval as compared to when blind nodes are used is eliminated. Table 2.1 gives a summary of some recently developed seismic acquisition nodes and their specifications.

2.2 WSDA Methods

Data recording in WSDA is generally event-driven, attributed to shots or sweeps from an energy source. Geophones sensing and transmitting functional-

Table 2.1: Recent nodal seismic units and their specifications

Device	Operating mode	Battery life time	Storage/ Technology employed	Sampling rate/ADC resolution	Vendors/ Website
Innoseis Tremornet	Blind	50 days continuous	Low energy bluetooth	1,2,4 ms/ 24 bit	Innoseis/ www.innoseis.com
GCL recorder	Blind	60 days @24hrs/day	16 or 32 GB storage	0.25,0.5, 1,2,4, ms/ 24 bit	Geospace Technologies / www.geospace.com
Hawk	Blind	90 days @24hrs/day	16 or 32 GB storage	0.25,0.5, 1,2,4, ms/ 24 bit	INOVA / www.inovageo.com
DTCC smart solo	Blind	25 days @24hrs/day	8 GB memory	1,2,4, ms/ 24 bit	SmartSolo / www.smartsolo.com
GTI NRU 1C	Blind	23 days @24hrs/day	8 GB memory	0.5,1,2,4, ms/ 24 bit	Geophysical Technology / www.geophysicaltechnology.com
Sercel WTU 508	Real-time QC	30 days @24hrs/day	WLAN (a,b,g,n), XT-Pathfinder	0.5,1,2,4, ms/ 24 bit	Sercel / www.sercel.com
Sercel WiNG	Real-time QC data	40-50 days @24hrs/7day	WLAN 2.4 GHz, Pathfinder	0.5,1,2,4, ms/ 24 bit	Sercel / www.sercel.com
Sigma	Blind, QC, &Real-time	-	8 GB, WiFi, Cellular	0.25,0.5, 1,2,4, ms/ 32 bit	iSeis / www.iseis.com
RT2 system	Real-time	25 days @12hrs/day	WiFi 2.4 GHz ISM band	0.5,1,2,4, ms/ 24 bit	Wireless Seismic / www.wirelessseismic.com
RT3 system	Real-time	27 days /battery charge	WiFi 2.4 GHz ISM band	0.5,1, 2,4ms/ 24 bit	Wireless Seismic / www.wirelessseismic.com

ity becomes active only after sensing the reflected seismic signal generated from these shots. Depending on the type of node employed in a survey, seismic data can be acquired using either the *blind* or *real-time* acquisition method.

2.2.1 Blind Acquisition Method

This method employs autonomous nodes in the survey to store seismic data internally in the memory unit of nodes, and later retrieved by survey personnel during or after the survey. However, concerns about the integrity of data collected were raised by contractors in such systems, as it might take weeks to analyze collected seismic data. As such, later systems developed by vendors offered some form of capability to monitor QC data, which contain information

such as the node condition, battery status, background noise etc. The QC information can be retrieved in either of the following ways [20];

- i). Survey personnel drive past the units, or use drones to retrieve the data from nodes across the survey field.
- ii). Transmitting through low speed radio from the geophones nodes to the CCU in form of dynamic autonomous mesh network. Continuous monitoring and transmission of QC data is possible in such systems.

2.2.2 Real-time Acquisition Method

A real-time system supports instant transmission of data from equipment in the field to the CCU during acquisition with reasonable latency. This enables contractors to monitor the quality of data acquired for a particular shooting phase before moving to the next. In such system, it is important that seismic data collected by geophones for a given sweep or shot, should be delivered to the CCU without slowing down the next sweep [29]. Assuming the vibroseis truck moves at a speed of 10 m s^{-1} to the next shot point, which is typically 50 m away, a latency of at most 5 s is required. A predefined network architecture is employed in real-time acquisition, to coordinate and relay huge amount of acquired data to the CCU. QC data can be transmitted by each node either on-demand or periodically. Throughout the rest of this thesis, the focus will be on real-time wireless acquisition systems and methods.

2.2.3 Multi-vibroseis Acquisition Technique

The frequency of seismic trace acquisition is the major factor affecting the productivity of a seismic survey. A way to address this is to increase the shot or sweep frequency in a swift manner during the survey [38]. State-of-the-art acquisition techniques employ multi-vibroseis acquisition to significantly increase overall survey productivity by limiting the amount of time lost between shots. This technique involves the use of multiple vibroseis or vibrator trucks arranged in groups called “fleets” as depicted in Figure 2.1.

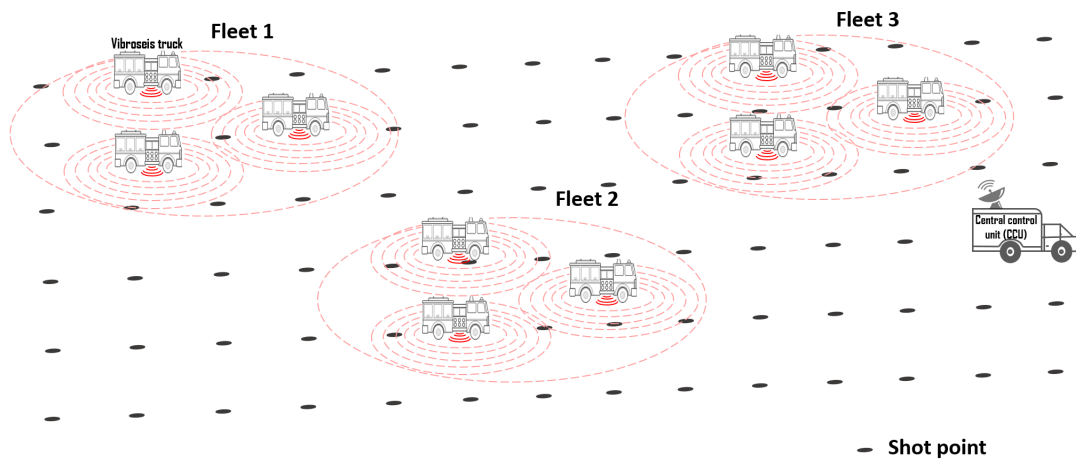


Figure 2.1: Multiple fleet acquisition technique

According to a survey carried out in the middle east as reported in [38] for a single sweep of about 12s duration per shot point, a sweep frequency of 95 sweeps/h was achieved with a single fleet of vibrators. The two major methods used in the multi-vibroseis acquisition are “flip-flop” and “slip sweep” acquisition techniques.

Flip-flop Acquisition

Flip-flop is the most commonly used technique in SDA. In this technique, while a particular fleet start its sweep, the other fleet moves to the next shot point and begin its sweep immediately after the first fleet finish its sweep, thereby reducing the dead time between records. A sweep frequency of up to 145 sweeps/h can be achieved using this method with a dual fleet of vibrators [38].

Slip Sweep Acquisition

In slip sweep technique, a fleet start its sweep without waiting for the other fleet to finish, thereby resulting in better survey productivity than flip-flop technique. Nevertheless, this comes with a drawback of increased negative impact of vibrator distortion on seismic records. However, advanced signal processing techniques are used to remove the distorted signals at the CCU. A sweep frequency of up to 215 sweeps/h can be achieved using this methods

with four fleets of vibroseis trucks [38]. In this thesis, the most widely used acquisition technique i.e., flip-flop is considered.

2.3 Network Architectures for WSDA

As mention in Section 1.2.2, orthogonal geometry is the most commonly used topology in seismic survey networks. Several geophones are placed along multiple receiver lines throughout the survey area. Source lines are then placed perpendicular to the receiver line as depicted in Figure 1.6. Various WSDA network architectures have been proposed and discussed in literature.

A hybrid architecture which employs a core network , and extended network layer was proposed in [39]. The core layer uses Wi-Fi link in star topology for communication between the control unit and root nodes. The extended network layer employs ZigBee technology for communication between sub-nodes (geophones) and root nodes with multi-hop form of communication enabled. However, this might not be so feasible for real-time data transfer mainly in terms of delay and throughput especially when multi-hop communication is enabled as ZigBee has low data rate. Also, the architecture will less likely be scalable to high number of nodes.

A hierarchical two-tier network architecture was proposed in [29]. At the first stage, geophones transmit acquired seismic data to a gateway they are associated with over short range radio links such as UWB technology. The aggregated data at the gateway is then forwarded to the CCU over multiple hops using long range technologies like WiFi or WiMax signals in the second stage. The gateways should also be able to propagate control commands to geophones for positioning and synchronization. However, no evaluation of the proposed architecture was carried out to measure its performance.

An architecture based on the IEEE 802.11af standard that involves dividing the survey area into tessellating hexagonal cells was proposed in [40]. It employs frequency reuse concept in which the number of available TV white-space channels would determine the cluster sizes. Each cell is managed by a Wireless Gateway (WG) that aggregates data from all geophones within the cell. The geophones communicate with the WG using a star topology in infrastructure

mode as a means of avoiding additional energy consumption by relaying data via multi-hop network. The aggregated data by the WG is then relayed to the CCU using longer communication technology. Conversely, co-channel interference, geophone power consumption, as well as regional regulations for accessing TV white space spectrum are some subject area of concern.

A cluster-mesh WSDA network comprising of multiple sub-networks was proposed in [17]. Each sub-network is controlled and coordinated by a WG that utilizes short and long range wireless technologies. The sub-network is further divided into clusters with geophones connecting to their associated cluster heads. Geophone members periodically transmit their acquired seismic data to cluster heads down to the WG using Ultra-wide Band (UWB) technology and from the gateway to the CCU using long range Wi-Fi technology. However, concern for energy consumption and coordination may arise particularly in cluster heads close to the WG as majority of the traffic will be relayed through them. Moreover, no performance evaluation of the proposed architecture was carried out.

A dual layer (lower and upper layer) network design for a real-time remote seismic data acquisition was proposed in [41]. The sensor array is divided into subnetworks, each comprising of gateway and collecting nodes (geophones). In the lower layer, geophones employ star topology to communicate with the gateway using WLAN technology to achieve short range high data rate transmission. Long-term evolution (4G LTE) is used at the upper layer for long range communication from gateway nodes to the CCU. However, as most seismic survey applications are conducted in remote areas with limited or no availability of cellular network, cost of establishing base stations can be quite expensive. Furthermore, a significant amount of gateways will be required with such network architecture.

An architecture based on a multi-level radio network for real-time SDA was proposed in [42]. Geophones are combined into domains at the first level and transmit their data to a domain coordinator over a low-speed radio channel in the sub-gigahertz band. At the second level, domain coordinators are combined into cluster using an IEEE 802.11b/g based radio and forward their data to base station. The base station transmits its data to a CCU at the third level if the number of channels is more than 1000. However, considering

the multi-level architecture, realizing real-time data transfer could be quite challenging as seismic data has to go through multiple hops before reaching the CCU. In addition, no performance evaluation was carried out to investigate the applicability of such architecture.

Authors in [43] proposed a WGN architecture to address the high-data rate wireless requirement for communication between gateways and the CCU. They employed Schemes based on Unmanned Ariel Vehicles (UAVs), Free Space Optical (FSO) communications, and standards like IEEE 802.11ad. The network architecture is divided into three layers (L1, L2, and L3). L1 comprises of communication links between gateways and geophones stationed in a hexagonal repeating pattern. L2 addresses data transfer from gateways to a nearby relay nodes down to the data collection center. L3 represents the uppermost layer of the architecture responsible for communication between relay nodes to the data collection center. UAVs travel across the spread and hover over adjacent relay nodes to collect all the buffered data using IEEE 802.11ad and FSO schemes. However, deploying relay nodes at L2 will mean additional delay and power consumption as seismic data will have to travel over several hops before reaching the data collection center. Moreover, for large seismic surveys with high productivity acquisition requirements, a significant amount of UAVs will be required which will consequently result in increased survey cost.

RT3 system developed by wireless seismic Inc [22] comprises of two layer network architecture that operates in the 2.4 GHz ISM band. The first layer consists of group of motes (or geophone units) communicating with their associated relay unit (or gateway) to transmit acquired seismic data. The aggregated data at the relay unit is then forwarded down to the CCU.

Majority of the proposed architectures are infrastructure-based, with star topology and single hop communication between geophones and gateways. However, this means that the network coverage is restricted to the communication range of the technology employed. This drawback can be addressed by employing multi-hop form of communication between geophones and gateways.

With multi-hop ad hoc network structures enabled, advantages such as *enhanced capacity, robustness, extended coverage, self configuration and organization, as well as less spatial interference at low power levels* [44] can be

explored. The ability of nodes to act as routers or forwarding nodes will not only help extend the communication coverage, but also minimize interference with low transmit power configured in nodes, consequently resulting in proper bandwidth utilization on frequency channels. With routing enabled, the network becomes more robust as alternate paths to the destination can be quickly computed in case of node failure, thereby enabling self-organization and configuration in the network [44]. This raises the question on which routing strategy or algorithm should be employed in WSDA. A review of different routing protocols proposed in literature for both WSNs and ad hoc networks is presented in Section 2.6. In the following section, a discussion on various technologies proposed for WSDA networks in literature is presented.

2.4 Technologies for WSDA

Many literature have proposed technologies for WSDA taking into account factors like network coverage, data volume, energy consumption, real-time data transfer, acquisition type (seismic or QC capable data acquisition) etc. In view of these factors, technologies for WSDA can be generally classified in terms of data rate (high or low) and communication range (long or short).

Authors in [29] proposed employing a mixture of long and short range wireless technologies for WGN. Short range technologies such as Bluetooth, ZigBee, IEEE 802.15.3 WPAN, and Ultra-Wideband (UWB) for transferring seismic data collected from geophones to wireless gateways. Long range technologies like UMTS 3G, HSPA 3.5G, WLAN, WiMax for transmitting aggregated data from gateways to the CCU for processing. However, most of the proposed technologies will not be suitable for future large scale SDA especially in terms of large data volume, high data rate requirements, imposed cost, network coverage, and power consumption. Moreover, due to the UWB short communication range¹, most geophones will be operating close to their transmission range limit.

Long Range (LoRa) technology was proposed by authors in [45] in the design of a wireless distributed three-component QC data acquisition system to observe

¹5–10 m for up to 480 Mbit s⁻¹, and 30 m expected for outdoor line-of-sight environment with 53.3 Mbit s⁻¹ data rate [17]

seismic waveform in real-time for high-precision exploration. Seismic data acquired by nodes are stored locally on an SD card and then forwarded using LoRa technology to a computer monitoring unit. However, with future surveys targeting hundreds of thousands of geophones, LoRa might not be a suitable technology to employ in WSDA considering the high data rate and latency requirements.

WSDA based on Internet-of-Things (IoT) Low-Power Wide-Area networks (LPWANs) was proposed for seismic QC data acquisition in [46]. Authors aim at exploring the long range low power properties of the technology to propose a network architecture, data aggregation and transmission technique for delay-tolerant WSDA. However, the applicability of this technology could be quite challenging due to the large seismic data volume and the real-time or near real-time seismic data transfer requirement.

A Wireless Geophone Network (WGN) based on the IEEE 802.11af standard that enables WLAN operation in TV White Spaces (TVWS) was proposed in [40]. TVWS refers to the unutilized TV channels assigned to a broadcasting station in a particular geographic location. The standard operates in the very-high frequency (VHF) and ultrahigh frequency (UHF) spectrum bands ranging from 54 MHz to 698 MHz in the United States, thereby achieving longer transmission range. However, challenges such as interference with primary users (i.e., TV stations), coexistence with other standards and applications, dynamic nature due to temporal and spatial variations, e.t.c needs to be addressed properly [47]. In addition, operations in TVWS might be limited depending on the regional access regulations [48].

Authors in [49] developed an integrated energy-efficient wireless sensor node for micro-tremor exploration. 4G technology was proposed for communication between recording unit and control center to address issues of low data accuracy, blind acquisition, and long measurement time. Data sampling display and real-time status configuration is carried out at the control center using the 4G wireless monitoring system. In addition, authors in [41] proposed an exploration system based on 4G LTE technology for long range communication between CCU and gateway nodes to convey aggregated seismic data. However, cost of deploying 4G could be a cause for concern as majority of surveys are carried out in remote areas where there is significantly little or no deployment of

Table 2.2: Proposed technologies for WSDA

Technology	Freq. (GHz) Europe	Data rate (Mbit s ⁻¹)	Comm. Range (m)	Comm./ Data Type	Reference
UWB	6 - 8.5	0.1 - 5	70-1000 SR	Gp to WG/ SD	[29]
WiMax	3.5/5.8	70	2000-10000 LR	GW to CCU/ QC	[29]
Bluetooth	2.4	1 - 2	100 SR	Gp to Gp/ SD	[29]
ZigBee	0.868/2.4	0.25	50 SR	Gp to Gp/ SD	[29], [46]
LoRa	0.863 - 0.870	0.01	11000 LR	Gp to CCU/ QC	[45]
GSM (EDGE)	0.9/1.8	0.384	1000-2000 LR	GW to CCU/ QC	[29]
3G (UMTS)	2.1	2	1000-2000 LR	GW to CCU/ QC	[8]
4G (LTE)	1.8/2.1/2.6	100 - 1000	>1000 LR	GW to CCU/ QC	[8]
5G	3.3 - 3.8	>1000	250 SR	GW to CCU/ QC	[8]
IEEE 802.11g	2.4	6 54	160 (SR) 70 (SR)	Gp to WG/ SD	[8], [42]
IEEE 802.11n	2.4/5	125	750 (LR)	Gp to WG & WG to CCU / SD	[8]
IEEE 802.11af	0.47 - 0.79	26.7	1000-2000 LR	GW to CCU/ SD	[8], [40]
IEEE 802.11ah	0.8630 - 0.8686	40	1000 LR	Gp to WG/ SD	[8]
IEEE 802.11ac	5	up to 6900	-	Gp to WG/ SD	[50]

Gp: Geophone, WG: Wireless gateway, QC: Quality control data, SD: Seismic data.

such technologies. Similarly, complexity and spectrum usage in 5G technology makes it unattractive in WSDA networks. As such, it is better to go for license-free technology options like IEEE 802.11-based technologies.

Authors in [43] proposed an architecture that employs IEEE.802.11ac standard for communication between WG and the closest data collection center relay as described in Section 2.3. However, in their performance analysis, they found out that the standard is unable to hold the minimum layer 1 latency for data transfer between geophones and gateways for cell radius of greater than 550 m.

Table 2.2 gives a summary of the technologies proposed in literature likely to serve as enabling wireless technologies for short and long range communications in WSDA [29].

Choice of Wireless Technology in WSDA Networks

Following the requirements for WSDA outlined in Chapter 1 and the review of technologies proposed in the literature as summarized in Table 2.2, the following criteria determines the choice of wireless technology in WSDA.

- i). **Data rate and throughput:** due to the high sampling rates, large volume of aggregated seismic data from geophones, and the frequency at which the data ought to be transmitted, high data rate technologies are necessary for high resolution WSDA.
- ii). **Coverage:** seismic data acquisition often employs large-scale deployment of geophones over several squared kilometers of area. Thus, the wireless technology employed should provide a good communication coverage or range. However, a mixture of long and short range high data rate technologies might be needed in WSDA to ensure proper and efficient coverage.
- iii). **Latency:** to maximize survey productivity, seismic data is required to be transmitted as quickly as possible to minimize dead time between seismic sweeps or records. Thus, it is essential that the wireless technology employed addresses the near-real time WSDA requirements with some acceptable latency.
- iv). **Scalability:** for better subsurface imaging quality, future surveys are targeting more dense geophone deployment in the range of hundreds of thousands. As such, the chosen technology should be able to handle additional number of geophones in the case of future network expansion without affecting the network performance.
- v). **Energy consumption:** SDA process can last for several days or weeks depending on the survey type and area. Thus, it is essential that the wireless technology employed is energy efficient to be able to maintain extended network lifetime.
- vi). **Frequency band:** the wireless technology should be able to operate in a frequency band that minimizes interference due to the large scale deployment of geophones.

- vii). **Operational cost:** increased survey cost is one of the motives of moving away from cable-based to wireless acquisition systems. Thus, the wireless technology should be cost effective with regards to the available survey budget in the context of the hardware, frequency spectrum, installation, deployment, and operations.
- viii). **Compatibility:** due to the cost and complexity of seismic survey equipment as well as data processing and software tools, it is vital to ensure that the chosen wireless technology can smoothly integrate with all existing tools and equipment.
- ix). **Regulatory Compliance:** the wireless technology should comply with the operational rules and regulations governing the locality in which the seismic survey is to be carried out.

Considering the above listed criteria, it is difficult to find a single wireless technology or standard that addresses all the requirements. Low data rate technologies such as ZigBee, LoRa, Bluetooth, GSM etc., are not suitable for WSDA applications. Moreover, as SDA is normally carried out in remote areas where no existing infrastructures are available, cellular network based technologies such as 3G, 4G, 5G etc., are also not suitable. This is in view of the fact that the incurred cost of licensing and establishing base stations for these technologies could be significantly high, which is a factor of prime concern in seismic industries.

Thus, utilizing off-the-shelf license-free *IEEE 802.11 based technologies* is proposed as the suitable wireless technology for WSDA networks in this thesis. In the following section, a review of IEEE 802.11-based technologies is presented.

2.5 IEEE 802.11-Based Technology Solutions

In-line with the WSDA requirements and challenges outlined in Chapter 1, and comparison on different proposed technologies in Section 2.4, a combination of long and short range high data rate WLAN technologies are best suited for WSDA networks. This is because, in addition to their license free and

off-the-shelf nature, they also address the large data volume aggregated from geophones and extended coverage requirements. WLAN can be configured in two main modes of operation, **infrastructure-based** or **ad hoc-based** mode.

In infrastructure-mode, a centralized coordinator, often referred to access point (AP) is employed, which acts as a bridge between a wired and wireless network. All communication between nodes go through the access point. Such a WLAN topology is referred to as Basic Service Set (BSS). However, some downsides of employing infrastructure-mode of operation in relation to WSDA includes scalability and incurred cost issues as multiple access points needs to be deployed to ensure proper coverage. Furthermore, the requirement of self-configuration and management of geophones is another concern in this mode of operation as communications between geophones is controlled and managed by APs.

In ad-hoc mode, stations within the range of each other dynamically configure themselves to establish peer-to-peer mode of communication without the need for central coordination. According to the WLAN standard [51], this topology is referred to as Independent Basic Service Set (IBSS). This will be the main focus in this thesis as the goal is to enable communication between geophones in the absence of established infrastructure as discussed in Section 1.3.

The first version of the IEEE 802.11 standard [52] was approved in 1997 for WLAN operation. The main target was to allow wireless connectivity for portable devices or stations that require swift deployment, providing a data rate of 1 and 2 Mbit s⁻¹. The standard defines MAC and physical layer for data transmissions in the Industrial, Scientific and Medical (ISM) frequency band. Since then, various amendments and improved versions have been presented till date. The evolution of these various standards was mainly to address the need for higher nominal data rates and extended coverage by employing technologies such as Multiple Input Multiple Output (MIMO), complex and faster Modulation and Coding Schemes (MCS), and wider channel width [53].

Succeeding the legacy 802.11 standard was the IEEE 802.11b and IEEE 802.11a standards introduced in 1999 with a data rate of 11 Mbit s⁻¹ in the 2.4 GHz band and 54 Mbit s⁻¹ in the 5 GHz band respectively. Succeeding

these standards was the IEEE 802.11g [51] approved in 2003, which provides an increase in the nominal data rate to 54 Mbit s^{-1} in the 2.4 GHz band. In 2005, IEEE 802.11e [54] was introduced with modifications to the MAC layer to support Quality of Service (QoS) requirements in WLAN multimedia applications (transmission of voice, audio, and video). IEEE 802.11n [55] amendment approved in 2009 was aimed at enabling WLAN operations that are capable of much higher throughput (up to 600 Mbit s^{-1}) in both 2.4 and 5 GHz band. Following the growing demand for an improved user experience by providing higher throughput (7 Gbit s^{-1}) using advanced technology like multi-user MIMO, the IEEE 802.11ac [50] standard was approved in 2013 for operations in the 5 GHz band. In 2021, the IEEE 802.11ax [56] was approved with modification to the physical layer and MAC sub-layer with the goal of improving throughput per area (up to 9.6 Gbit s^{-1}) in high density scenarios, enabling operations in the 2.4 and 5 GHz frequency band.

In addition to the 802.11 standards that mainly focus on the conventional 2.4 and 5 GHz ISM band, there are few other standards that were proposed for operation in the sub-giga Hertz as well as Ultra High Frequency (UHF) and Very High Frequency (VHF) bands. The IEEE 802.11af standard [57] approved in 2013 provides enhancement to the 802.11 PHY and MAC sublayer to allow WLAN operations in TVWS band. The TVWS refers to the unutilized TV channels allocated to TV broadcasting stations in the VHF and UHF, ranging from 54 and 790 MHz. In 2016, the IEEE 802.11ah was approved to enable operation in the sub-giga Hertz frequency band (excluding TVWS band) with a data rate of at least 100 kbit s^{-1} and up to 1 km transmission range. Table 2.3 summarizes the main features of the 802.11 based standards mentioned above.

2.5.1 PHY and MAC Sub-layer

The Physical Layer (PHY) is the interface responsible for providing coordination between the wireless medium and the MAC sublayer. The main functionalities of the PHY include [58]:

- i). Allows frame exchange between the PHY and MAC using the Physical Layer Convergence Procedure (PLCP) sublayer.

Table 2.3: Comparison of some of the most prominent standards in the IEEE 802.11 WLAN family

<i>Standard</i>	Frequency (GHz)	Channel width (MHz)	Max. data rate (Mbit s⁻¹)	Modulation scheme	PHY Modulation Type	Spatial streams	Coding rate
802.11 (1997)	2.4	22	2	DSSS, FHSS	-	-	-
802.11b	2.4	22	11	DSSS	CCK	-	-
802.11a	5	20	54	OFDM	BPSK, QPSK, 16-QAM, 64-QAM	-	1/2, 2/3, 3/4
802.11g	2.4	20	54	OFDM	BPSK, QPSK, 16-QAM, 64-QAM	-	1/2, 2/3, 3/4
802.11n	2.4 & 5	20/40	600	HT MIMO-OFDM	BPSK, QPSK, 16-QAM, 64-QAM	4	1/2, 2/3, 3/4, 5/6
802.11ac	5	20, 40, 80, 160	6900	VHT Multi-user MIMO-OFDM	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	8	1/2, 2/3, 3/4, 5/6
802.11ax	2.4, 5, & 6	20, 40, 80, 80+80	9600	HE Multi-user MIMO-OFDMA	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM	8	1/2, 2/3, 3/4, 5/6
802.11af	VHF & UHF (0.47 - 0.79 EU) [40]	6, 7, 8	up to 568.9 with (4 SS, 4, 8 MHz chs) [57]	MIMO-OFDM	MIMO-OFDM	4	1/2, 2/3, 3/4, 5/6
802.11ah	Sub-GHz (0.863 to 0.8686 EU) [8]	1,2,4,8,16	up to 347 with (4 SS, 16 MHz channel) [53]	MIMO-OFDM	MIMO-OFDM	4	1/2, 2/3, 3/4, 5/6

- ii). Utilizes the Physical Medium Dependent (PMD) sublayer to transmit data frames over the wireless medium using spread spectrum or signal carrier modulation.
- iii). Verifies activity on the wireless medium by providing a carrier sense indication to the MAC sublayer.

Signals over the wireless medium are affected by fast fading as a result of multipath propagation, a phenomenon caused by signal reflection, refraction, scattering, or diffraction from the transmitter to the receiver, leading to Inter-symbol Interference (ISI). Orthogonal Frequency Division Multiplexing (OFDM) and spread spectrum (Direct sequence Spread Spectrum (DSSS) or Frequency Hopping Spread Spectrum (FHSS)) are the techniques commonly used to address the issue of fading. In spread spectrum, the signal is spread to significantly occupy larger bandwidth thereby reducing the effect of frequency selective fading. In OFDM however, frequency selective fading is addressed by dividing the data signal stream into a particular number of sub-streams or sub-carriers, each having a bandwidth smaller than the channel bandwidth [58]. OFDM is the commonly used modulation scheme used in the 802.11 family for high data rate wireless communication because of its high resilience to multi-path fading and frequency selective fading, as well as high spectrum efficiency. Digital modulation types such as Binary Phase-Shift Keying (BPSK), Quadrature Phase-Shift Keying (QPSK), and Quadrature Amplitude Modulation (QAM) are used to represent each signal sub-carrier. Recent technological advancements have made it possible to achieve even higher data rates in the 802.11 family using technologies like MIMO in IEEE 802.11n [55] and Multi-User MIMO (MU-MIMO) in IEEE 802.11ac [50] by employing multiple transmitting and receiving antennas to increase the capacity of the wireless medium.

The 802.11 defines a medium access control (MAC) sublayer which controls how nodes access the radio frequency (RF) channel via logical functions which includes the Distributed Coordination Function (DCF), the optional Point Coordination Function (PCF), and the Hybrid Coordination Function (HCF) access mechanisms as illustrated in Figure 2.2 depicting the IEEE 802.11 MAC architecture. In this thesis however, we only consider DCF which is the fundamental channel access mechanism in the IEEE 802.11 standard.

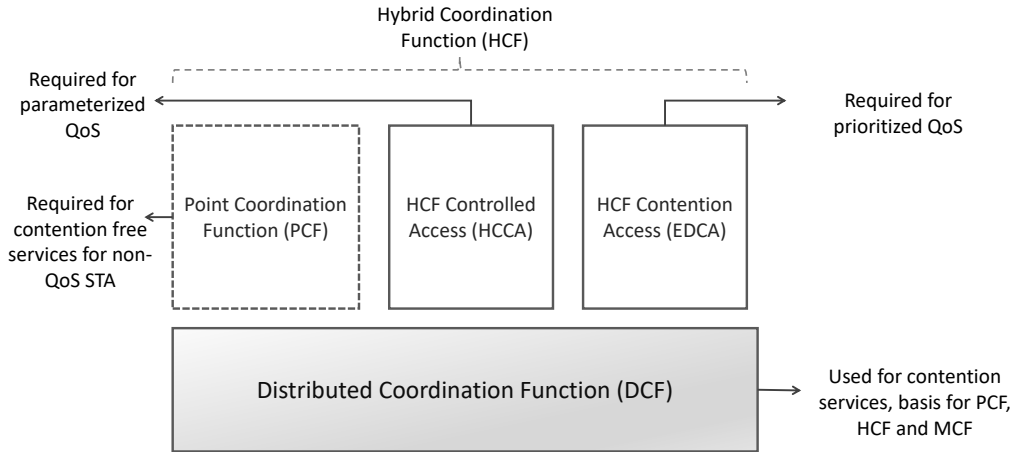


Figure 2.2: IEEE 802.11 MAC Architecture

Distributed Coordination Function (DCF)

DCF is the fundamental channel access mechanism in IEEE 802.11 networks that provides contention based service. It is a random access protocol which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm where collisions are managed according to the exponential back-off algorithm. There are two access mechanisms employed in DCF, the Request-To-Send/Clear-To-Send (RTS/CTS) and the basic access method. An error can occur as a result of collision due to concurrent packet transmission by nodes or wireless channel errors.

In the basic access mechanism, a station senses the channel to determine whether or not the channel is idle before initiating a transmission. If the medium is sensed idle for a time duration equals to the distributed inter-frame space (DIFS), the station then transmits. However, if the medium is sensed busy, the node defers its transmission and randomly selects a back-off counter value uniformly between $[0, CW]$, where CW is the contention window, which can be calculated using Equation 2.1.

$$CW = 2^n - 1 \quad (2.1)$$

The starting value of n for the initial transmission attempt in OFDM based WLANs with best effort traffic is 4. This value increments with each successive

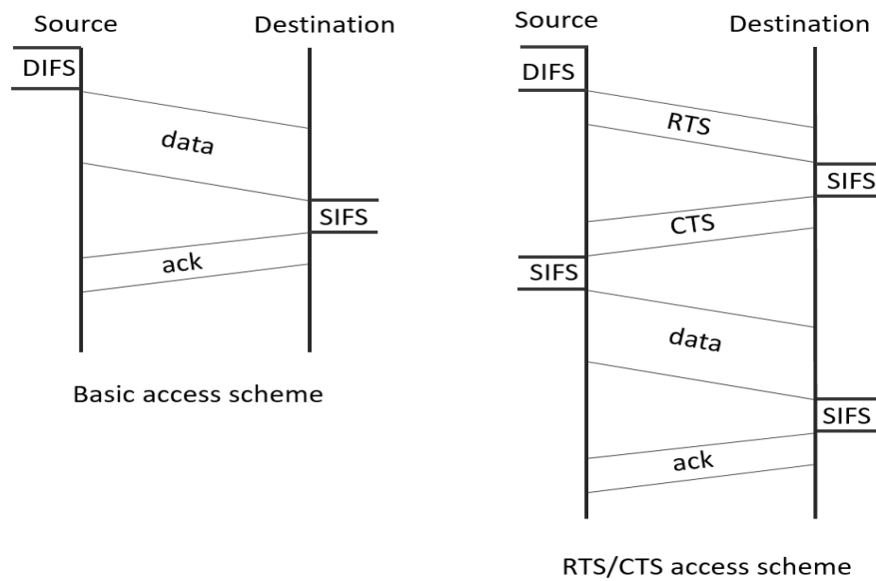


Figure 2.3: Illustration of the IEEE 802.11 DCF basic access and RTS/CTS access mechanisms

collision until a successful transmission occurs after which it resets to 4. An 802.11 station will typically attempt to transmit a packet up to 7 times (which corresponds to an N value of 10), beyond which the packet is dropped.

In RTS/CTS access scheme however, if the channel is sensed idle for a DCF Inter-frame Space (DIFS), the node first sends a RTS packet before transmitting the data packet. The destination node then replies with a CTS packet if there is no ongoing activity at the destination node that is hidden from the source node, otherwise it defers its transmission after a Short Interframe Space (SIFS) duration according to the binary exponential backoff algorithm. Figure 2.3 illustrates this mechanism for both the basic access and RTS/CTS schemes. However, in this thesis only the basic access mechanism was considered.

The backoff timer is decremented in terms of slots provided that the channel is sensed idle for a duration more than DIFS, and freezes when the channel is sensed busy. As soon as the back-off timer reaches zero, the station will transmit at the beginning of the next slot. An acknowledgment(ACK) packet is received by a transmitting node following a successful transmission after a period of time called the short inter-frame space (SIFS). A packet is assumed to be lost if an ACK packet is not received after successful transmission. Following a duration equals extended inter-frame space (EIFS), a retransmission is scheduled and a new back-off interval is uniformly chosen from $[0, CW_i]$, where

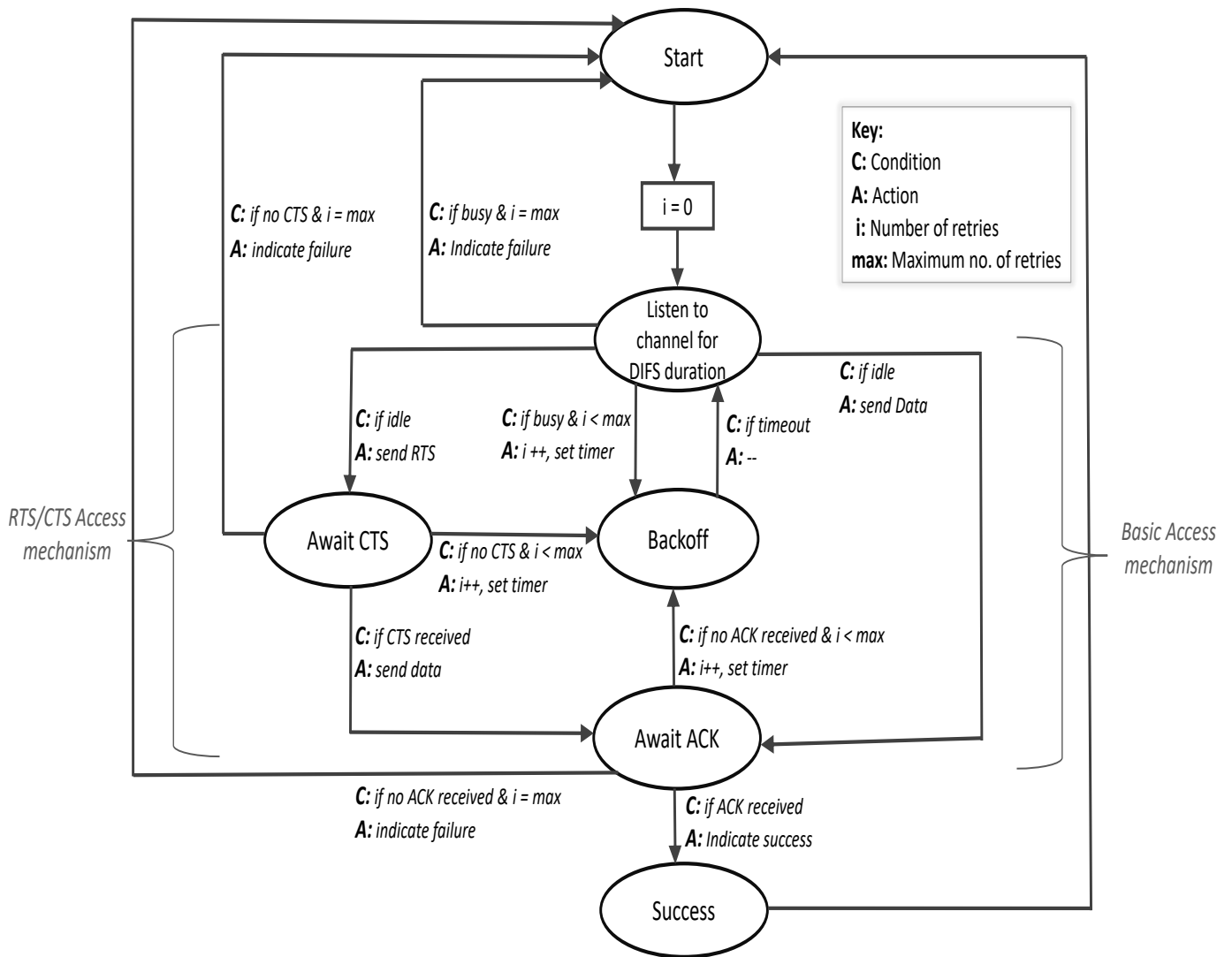


Figure 2.4: Schematic of the CSMA/CA protocol for both basic access and RTS/CTS access mechanisms modified from [59]

$i \in (0, 1, \dots, m)$ denotes the number of transmission attempts, ranging from a minimum value 0, to a maximum value m (retry limit). Figure 2.4 shows a schematic depicting the CSMA/CA algorithm operation.

Channel Access

As mentioned earlier, CSMA/CA is a random access protocol that operates in a distributive manner and is the fundamental channel access method in the IEEE 802.11 family. Unlike fixed assignment or demand assignment MAC protocols, there is no central entity that coordinates how nodes access the shared wireless medium, making it a more suitable channel access method

Table 2.4: Channel access methods comparison in relation to WSDA.

	<i>Random Access Protocols</i>	<i>Fixed Assignment Protocols</i>	<i>Demand Assignment Protocols</i>	<i>Polling Protocols</i>
<i>Scalability</i>	High (+)	Medium	Medium	Small (-)
<i>Delay (Low loads) (High load)</i>	Good (+) Medium	Medium Medium	Medium Good (+)	Medium Medium
<i>Complexity</i>	Low	High (-)	High (-)	Low
<i>Power saving</i>	Yes	Yes	Yes	Possible
<i>Link state Information</i>	Yes	No	No	Yes
<i>Message size</i>	Variable	Fixed	Fixed	Variable

in scenarios with large number of nodes. Nodes asynchronously contend for channel access whenever there is a packet to be sent. Probability of collision increases as the number of nodes or offered traffic increases. Although random access or contention-based approach provide good scalability, some of its major drawbacks includes collision, idle listening, overhearing and control packet overhead [60]. Table 2.4 outlines some comparison between the random access MAC protocol and other prominent MAC in relation to WSDA [61].

Throughout the rest of this thesis, the focus is centered around the IEEE 802.11 default random access CSMA/CA protocol. This is because in addition to the advantages outlined in Table 2.4, there is no need for modifications to accommodate other channels access methods due to its ubiquitous nature in almost all existing modern day WSDA and WLAN devices.

2.5.2 802.11 Ad Hoc Networking

As stated in Section 2.5, an ad hoc network is a peer-to-peer network in which nodes configure themselves temporarily to communicate with each other in a decentralized manner without the need for central coordinator or infrastructure. The network control is distributed among nodes to self configure and manage themselves in the network for data transfer. Each node can act as a host or a router [44]. According to [62], one of the main technologies for wireless ad hoc networks is the IEEE 802.11 standard. The

term used to refer to ad hoc networks in these standards is Independent Basic Service Set (IBSS). Due to its simplicity and ubiquitous nature in modern day electronics, IEEE 802.11 standard is a well fitting platform to exploit and implement single-hop as well as multi-hop wireless ad hoc networks. In single hop networks, nodes can only communicate with each other if they are within the same transmission range. This impediment can be overcome by employing multi-hop ad hoc communication, which as a result will significantly extend the network communication coverage [62]. This is more so for WSDA networks considering the large scale geophone deployment and the need for self configuration. The network topology in ad hoc networks is generally considered to be dynamic as nodes can join, depart, or fail in the network. Thus, an efficient routing protocol² is needed to allow nodes to communicate with each other and forward packets towards the destination node over multiple hops and properly have an insight on the overall topology of the network. In WSDA however, topology is mainly considered to be static as geophones are not expected to move after initial deployment.

Node synchronization in an IBSS is required for proper transmission and reception of data. The two functions used for synchronization in an IBSS are acquisition and maintenance [62]. In synchronization acquisition, a node's receiver is tuned on different radios to scan the wireless medium for control frames which are used to detect an IBSS. A node can only join an existing IBSS if the scan procedure is successful, otherwise initiates a new IBSS. In synchronization maintenance, all members of the IBSS perform synchronization function via distributed algorithm that is based on the transmission of beacon frames at a given rate. The beacon interval is decided by the initializing node in the IBSS [62].

2.5.3 Energy Consumption

Energy consumption in IEEE 802.11 ad hoc networks has been widely evaluated in literature [63], [64], [65], [66] etc. Others investigate energy consumption in Wireless Sensor Network (WSN)s [67], [68], [69], [70], [71] etc. In the area of WSDA networks, very few investigation on energy consumption exist

²Refer to section 2.6 for review on routing protocols for ad hoc networks

in literature. To the best of the literature review carried out in this thesis, only [34].

A modeling and evaluation of energy consumed in wireless geophone networks is presented by authors in [34]. The evaluation is based on their proposed Adaptive Clustering of Wireless Geophones (ACWG) architecture that utilizes a distributive cluster formation technique. In addition, ACWG combines data compression, energy efficient routing of data and medium access protocol to provide better performance in terms of latency and geophone energy consumption. With an initial battery capacity of 5184 joules, their findings show that geophones can last up to 60 sweeps with ACWG architecture as compared to the case where ACWG is not applied in which the first geophone dies after the second or third sweep. However, the network lifetime of 60 sweeps is impractical in a typical seismic survey as several thousands sweeps might be required to cover the entire survey area.

Energy consumption is one of the fundamental considerations when implementing wireless ad hoc networks. Operations such as transmitting, receiving, sleeping e.t.c., should be properly taken into consideration when implementing such networks [44]. The transmit power assigned to a node normally defines the transmission range of that node. Two nodes within the range of each other can communicate directly, or otherwise have to relay data via neighboring node in multi-hop form of communication when routing is enabled. Thus, the larger the transmission power of a node the more its communication coverage. Nevertheless, this comes at a cost of increased energy consumption [62], especially for nodes with low battery capacities. However, this might not be the case in WSDA as nodes are equipped with large enough batteries that can run for days³.

The energy consumed in a geophone can be either due to sensing, processing, or communication. Energy consumed due to sensing and processing is significantly lower as compared to energy consumed due to communication. According to [44], at least 15% of the total energy consumed in a wireless node equipped with IEEE 802.11 wireless card comes from the communication part. The ability of a wireless node to actively adjust its transmission power is the basis in majority of the algorithms and protocols employed in power assignment

³Refer to Table 2.1 for battery lifetime in some of the recently developed seismic acquisition devices

and topology control for ad hoc networks. This functionality is available in most IEEE 802.11 wireless cards, making it even more suitable to adopt in WSDA networks. Some major factors that influence energy consumption in the MAC layer includes collision, idle listening, protocol overhead, and overhearing [72].

Generally, it is very important to have a comprehensive energy consumption evaluation and modeling based on the network architecture, wireless technology, and protocol employed in Wireless Seismic Data Acquisition (WSDA) networks.

2.5.4 IEEE 802.11 Challenges

In dense networks, such as WSDA networks, the most obvious and fundamental source of performance degradation is high interference [73]. Several literature have experimentally studied the causes of packet loss in IEEE 802.11-based networks.

Authors in [74] carried out a measurement study to analyze packet loss caused by the wireless channel over long distance WLAN network deployment as well as losses due to the 802.11 MAC protocol. The network is based on a real-world network deployment consisting of 6 links over a range of 2-20 km. In addition, authors used a wireless channel emulator to carry out repeated controlled experiments. Three common causes of packet loss which includes multi-path interference, interference from external WLANs, and interference from non-WLAN devices were investigated across rural and urban settings.

Their findings was that vast majority of the packet loss occurs due to interference from external WLAN devices on same and also adjacent channels, which depends on channel separation between the primary and external traffic as well as the power level between them. In addition, they reported that the interference is much more significant in long distance deployment than in local mesh network.

In [75], authors carried out an experiment to study the performance of IEEE 802.11g over long distance links in a flat desert terrain, 170 km from the city with no obstacles and non or minimal interference. Metrics such as path loss,

signal strength, noise, jitter and round-trip time were employed in the network performance study. They used a test bed consisting of two access points each with directional antennas operating in the 2.4 GHz band mounted on two pillars each of height 3 m. A file was transmitted for each experiment with a transmit power level kept at 255 mW. For a file size of less than 10 MB, the signal was able to successfully reach 9 km. For file size greater than 10 MB, the signal is lost after 7 km. Furthermore, authors found that path loss, jitter and round-trip time increases with distance.

Authors in [76] carried out an outdoor WLAN experimental measurement using a test-bed implementation that is based on the IEEE 802.11b and 802.11g wireless interfaces. Eight point-to-point outdoor links were set-up at a university campus, and measurements were independently carried out for both links direction with distances ranging from 100-250 m. Omnidirectional antennas were used and the transmit power was set to 20 dBm. Their finding was that, due to errors from the physical layer (mainly short PLCP preamble and limited tolerance of the cyclic prefix), 802.11g shows poor performance compared to 802.11b.

In [77] authors carried out an experiment to study the performance of long distance 802.11b links ranging from 1-37 km at different layers of the network stack. Two WLAN radios communicating with each other, and directional antennas placed on top of tall buildings were used to attain the required transmit or receive gains to setup the links. They found out that packet error rate is independent of the link length, but rather on the received Signal-to-Noise Ratio (SNR) and modulation scheme or data rate used. Furthermore, they observed that the packet size has insignificant effect on the error rate. In terms of effect of weather conditions (periods of rains and fog for two days) on the link, very small effect was observed.

In summary, careful planning of long and short range WLAN links, especially in terms of MCS, data rate, and SNR can prove beneficial in minimizing packet loss. Furthermore, as WSDA networks are usually deployed in remote areas, minimal or no external interference from other devices is expected. Considering the large-scale deployment of geophones in WSDA, a direct approach to addressing interference caused from nodes on same or adjacent channels is

to adopt frequency re-use concept while utilizing only the non-overlapping channels in either 2.4 or 5 GHz band.

2.5.5 Proposed IEEE 802.11 Standards

It is important to choose an IEEE 802.11 standard that meets the criteria outlined for WSDA networks in Section 2.4 to ensure reliable and efficient seismic data transfer. As mentioned earlier, providing proper coverage in such large-scale geophone networks will entail a mixture of short and long range technologies. The most important factors to look into before proposing an IEEE 802.11 standard for WSDA requirements includes data rate or speed, power consumption, compatibility with existing devices, regulatory compliance and range (long or short range). With all these factors taken into consideration, the following IEEE 802.11 standards are put forward in this thesis:

IEEE 802.11n/ac/ax

As introduced in Section 2.5, the IEEE 802.11n, 802.11ac and 802.11ax share similar fundamental functionalities of the legacy IEEE 802.11 standards in terms of the PHY and MAC sub-layer. However, each of these standards were developed with the aim of addressing the specific needs and challenges at the time of its development. All these standards are suitable for short range communication between geophones and gateways, data rate support in addition to other criteria outlined above.

The **IEEE 802.11n** [55] was developed to enhance the data rate as well as overall network throughput offered by its predecessors (IEEE 802.11a and IEEE 802.11g) in the 2.4 and 5 GHz band using a channel width of either 20 or 40 MHz. It introduces the use of MIMO technology, enabling multiple antennas to simultaneously transmit and receive data, thereby resulting in improved signal strength, reliability, better coverage and range. Additionally, the standard ensures backward compatibility with its predecessors, enabling devices operating on the older standards to connect to 802.11n networks.

The **IEEE 802.11ac** [50] was developed to provide higher throughput and data rates than 802.11n (in Gbit s^{-1}) by introducing additional channel width

(80 or 160 MHz) as compared to 802.11n and enhanced signal modulation scheme (256 QAM) in the 5 GHz band. It introduces support for MU-MIMO with 8 spatial streams thereby increasing the overall data rate. The band is less congested compared to the 2.4 GHz band thereby reducing interference and subsequently providing better performance.

The **IEEE 802.11ax** [56] was developed with modification to the PHY and MAC sub-layer with the goal of improving throughput per area (up to 9.6 Gbit s^{-1}) in high density scenarios, enabling operations in the 2.4 and 5 GHz frequency band. It employs a new PHY protocol with higher MCS and can operate using either 20, 40, 80, and 160 MHz channel width. An important feature of the IEEE 802.11ax is the integration of Orthogonal Frequency Division Multiple Access (OFDMA) technique which is commonly used in cellular networks. Compared to 4G LTE, OFDMA operates on top of the DCF, which is coordinated by an access point. The idea is to group adjacent subcarriers together into a resource units (RUs), and a transmitting station can select the best RU for each specific receiver. This consequently leads to higher MCS, Signal-to-Interference Plus Noise Ratio (SINR), and throughput [73].

IEEE 802.11af

The IEEE 802.11af [57] defines modification to the legacy IEEE 802.11 PHY and MAC sub layer to enable WLAN operation in the unused TV White Spaces (TVWS) VHF and UHF frequencies ranging from 470 to 790 MHz in Europe. Unlike the IEEE 802.11n/ac/ax, 802.11af has better signal propagation characteristics due to the lower operating frequency. This makes it suitable for long range (up to 1 km) WSDA applications especially for communication between gateways and CCU. Furthermore, its support for channel bonding via enabling multiple adjacent channels to be combined allow for increased data rate, thereby enabling large volume of data to be transmitted with minimal latency. It employs MIMO-OFDM technique alongside various modulation scheme which include BPSK, QPSK, 16-QAM, 64-QAM etc., which allows for different data rates to be used.

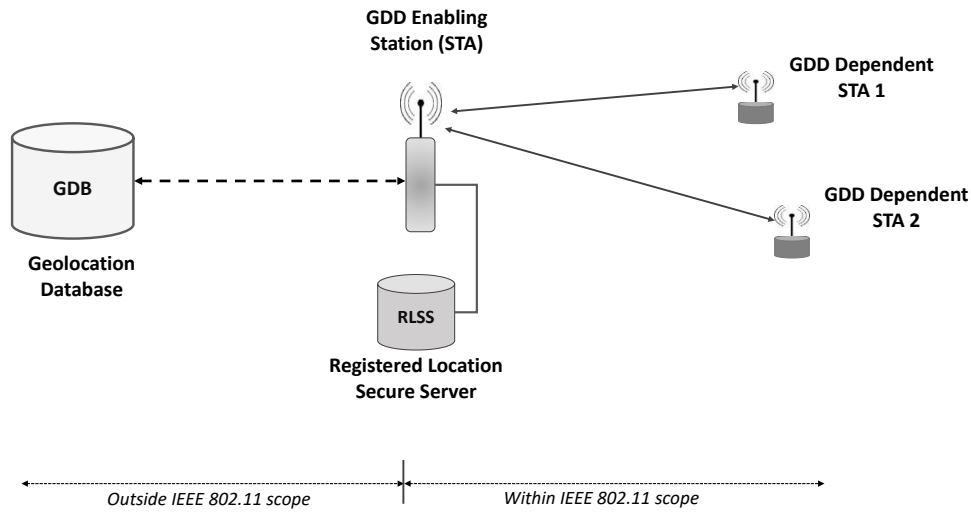


Figure 2.5: IEEE 802.11af network architecture of devices operating under geolocation database control modified from [57].

Devices utilizing the IEEE 802.11af standard are configured or designed with measures to identify and avoid interference with incumbent users. This is mainly achieved by devices searching a Geolocation Database (GDB) entity in order to determine which TVWS frequencies are currently been utilized and which are not in a given area or location. Figure 2.5 shows the IEEE 802.11af network architecture.

GDB represents the database authorized by a regional regulatory body that maintain, organize, and store information by geographic location on the current channel usage, also referred to as White Space Maps (WSM). Geolocation Database Dependent (GDD) describes an entity or station whose operation is dependent on received information from a GDB. A GDD can either be an access point or that initiate and maintain a network connection based on information received from a GDB or a non access point STA which operates under the control of a GDD enabling STA. A GDD enabling STA denotes a station that has the ability of obtaining the available spectrum or unused channels in its location as well as control the operation of GDD dependent STA. A GDD dependent STA is a station under the control of a GDD enabling STA. Registered Location Secure Server (RLSS) is an entity that stores WSM information of its geographic location and securely holds some operating parameters and location of basic service sets (BSSs) [57].

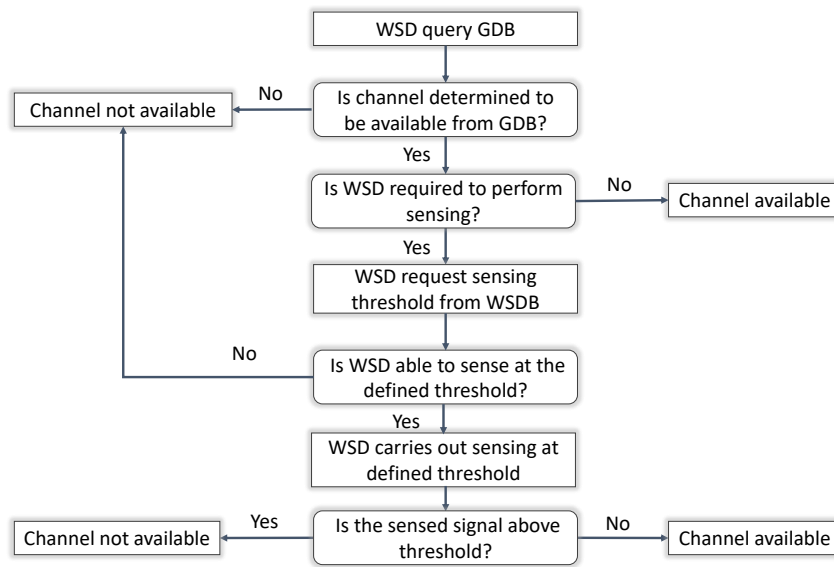


Figure 2.6: Decision making flow chart of determining available TVWS by WSDs through combining GDB and spectrum sensing as defined by ECC.

The Electronic Communications Committee (ECC) under the European Conference of Postal and Telecommunications Administrations (CEPT) provides a documentation [78] to improve the implementation of GDB. The report provides the fundamental principles of location accuracy, database management, master-slave device operation, GDB interpretation process, and combining GDB with spectrum sensing to ensure proper protection of co-channel Digital Terrestrial Television (DTT) receivers as well as Program Making And Special Events (PSME) [79]. The ECC also provides another document [80] that further defines the operational and technical requirements for the operation of White Space Devices (WSD) in the 470-790 MHz frequency band. The report mainly focuses on areas like technical classification and characterization of WSDs, using collaborative sensing for autonomous operation of WSDs, assessment of potential available spectrum for WSDs, protection of PSME equipment, DTT services, and aeronautical radio navigation in the 645-790 MHz, fixing maximum permitted power levels for WSDs etc. Figure 2.6 shows a flow chart of how WSD decides on accessing or utilizing the TVWS channels by combining sensing and GDB [79].

The IEEE 802.11af defines a Television Very High-Throughput (TVHT) physical layer specification with basic channel units (BCUs) of 6, 7, and 8 MHz, depending on the regional regulatory authority. The very high-throughput OFDM scheme for 40 MHz channel defined in IEEE 802.11ac is the basis for

the TVHT physical layer specification of a BCU. Its MAC sublayer architecture includes the Distributed Coordination Function (DCF), Point Coordination Function (PCF), the Hybrid Coordination Function (HCF), and the Mesh Coordination Function (MCF) access mechanisms as defined in IEEE 802.11-2012 [81]. Refer to [79] for more detailed information on the PHY and MAC sublayer specifications of the IEEE 802.11af.

One major drawback in utilizing TVWS spectrum is the regulatory considerations and approval. Majority of regional governments and regulatory bodies require that frequencies used by devices operating 802.11af should not interfere with licensed users or other television broadcast channels operating on the same spectrum.

2.6 Routing Protocols for WSDA

Generally, the choice of routing strategy largely depends on the requirements and characteristics outlined for WSDA networks. Similar to most WSNs, WSDA networks are homogeneous and static in nature, i.e., less topology changes and no movement of geophones is expected after the initial deployment, thereby enabling a link between two or more geophones to exist for an extended period of time. Thus, in this section, potential routing strategies for WSDA networks commonly employed for both WSNs and wireless ad hoc networks are discussed. Due to the nature of WSDA networks, especially with respect to large scale deployment of geophones and how seismic data is collected, the routing protocols are reviewed mainly based on two approaches, namely; *network structure* and *path discovery process*.

2.6.1 Routing Based on Network Structure

Depending on the network structure or node functionality, routing can be categorized into *location-based*, *flat*, and *hierarchical protocols* [82], [44], [83]. Figure 2.7 shows the routing protocols classification considered based on network structure in relation to WSDA.

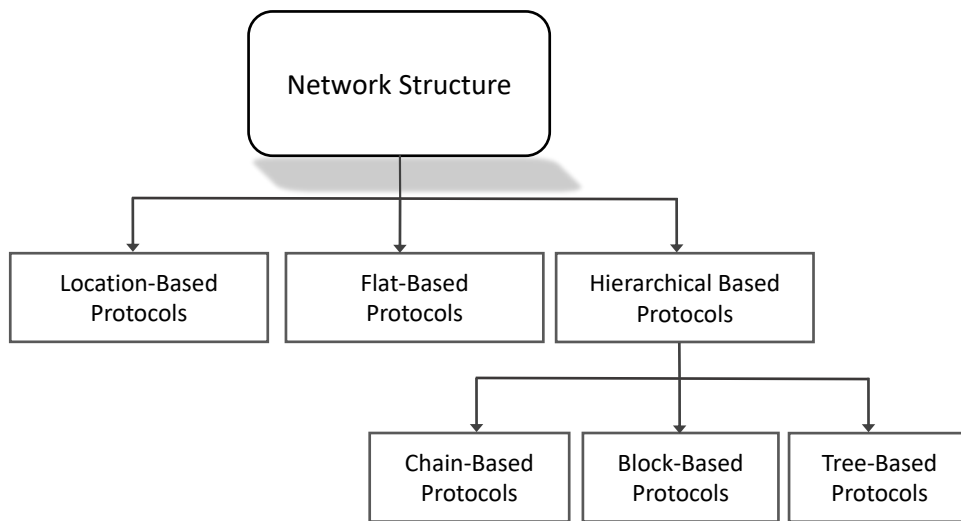


Figure 2.7: Routing protocols classification considered for WSDA

Location-Based Routing Approach

In geographic or location-based routing, the decision of a node to forward its data to a given destination is based on the geographical location of the destination node. Greedy routing is normally employed whereby a node forwards a packet via a neighbor that is located closer to the destination than itself. Each forwarding or intermediate node needs to know its position and that of its one-hop neighbors before deciding on which node will forward the packet. In this way, information on the network topology is not needed before a packet can be routed to the destination. The presence of small low-power GPS receivers in devices and methods for using signal strength to obtain relative coordinates have made this possible [44]. A comprehensive survey on location-based routing have been presented in literature [84], [85], [86], [87] and discussed based on some features such as guaranteed delivery, scalability, robustness, loop-free behavior, decentralized operation (global, zonal, or localized), path strategy (flooding, multipath, or single path), and metrics used (hop count, power e.t.c).

However, location-based routing does not scale well in dense networks as maintaining explicit routes is not necessary. For large-scale networks, location information maintenance and routing table update in nodes can become very prominent, thereby leading to increased message overhead and delay in the network. In addition, for scenarios with physical barriers where direct line-

of-sight communication is prevented, the greedy routing might fail, leading to the local minimum problem. In geographic routing, nodes are required to frequently update their location information. This will be a problem in battery powered devices, which is the case in geophones, as significant amount of energy will be required for each transmission. Examples of some location-based routing protocols includes Distance Routing Effect Algorithm for Mobility (DREAM) [88], Greedy Perimeter Stateless Routing (GPSR) [89], Geographic and Energy Aware Routing (GEAR) [90], Implicit Geographic Forwarding (IGF) [91], Graph Embedding for Routing (GEM) [92], Scalable Energy-efficient Location Aided Routing (SELAR) [93], Greedy Distributed Spanning Tree Routing (GDSTR) [94], Minimum Energy Relay Routing (MERR) [95], On-demand Geographic Forwarding (OGF) [96] e.t.c. Table 2.5 gives a comparison of some of the reviewed location-based protocols based on various criteria such as scalability, path establishment type, algorithm used, protocol objectives, advantages and disadvantages [83].

Flat Routing

Several literature have discussed flat-based and hierarchical routing [82], [97], [98], [99], [100], [101] for WSNs. In flat routing, each node or router has the same functionality and is connected to every other router in the network. Packets are routed through available paths without regard for the network hierarchical order or distribution. Each router periodically receives and broadcasts routing information to all other nodes in the network, which can result in large number of control messages. Route discovery and maintenance in such protocols may result in significant number of unreliable links [102]. Example of such protocols include Topology-Based Reverse Path Forwarding (TBRPF) [103], Temporarily Ordered Routing Algorithm (TORA) [104], Energy-Aware Routing Protocol Based on TORA (E-TORA) [105], AODV [106], OLSR [107], Gossip [108], Rumor Routing (RR) [109], Wireless Routing Protocol (WRP) [110] etc.

However, such protocols are associated with scalability issues as number of routing updates or entries each node needs to maintain increases with increase in network size, subsequently leading to significant message overhead and high memory requirements. In the case of link failures whereby alternate routes

Table 2.5: Comparison of location-based routing protocols as modified from [83]

Protocol	Scalability	Algorithm	Message Type	Path Formation	Protocol Objectives	Pros	Cons
DREAM [88]	Limited	Power Consumption Minimization	Control	Proactive	-Optimize the frequency at which routing updates are sent - Optimize bandwidth and energy usage	- Efficiency in data transmission	- Bandwidth under-utilization
GPSR [89]	Good	Greedy	Beacons	Proactive	- Improved network scalability - Increasing mobility rate	- Scalability - Uses greedy forwarding for packet transmission	- Ineffective without GPS device - Performance depreciates with high mobility
GEAR [90]	Limited	Best route	Hello Messages	Proactive	- Energy aware forwarding node selection	- Improved energy consumption and network lifetime	- Periodic exchange of routing information
IGF [91]	Limited	Best route	-	-	- Delay and packet loss improvement	- Robust performance - Improved end-to-end delay	- Depends on updated local neighbor table information
GEM [92]	Good	Shortest path	-	-	- Efficient packet routing	- Increased packet routing efficiency - Does not completely rely on node geographic information	- Poor load balancing especially for nodes at low level of the tree
SELAR [93]	Limited	Nodes with highest power route	Control Messages	-	- Location and energy-aware routing	- Avoids data implosion problem - Improved energy efficiency	- Performance degraded in networks where nodes frequently change location
GDSTR [94]	Limited	Shortest path	Hello Messages	-	- To address local dead ends where greedy forwarding fails	- Generates low route maintenance traffic	- Increased overhead
MERR [95]	Limited	Paths with minimal power consumption	-	-	- Minimizing total power consumption	- Energy consumption distributed uniformly among nodes	- Higher energy consumption in the case where nodes are close to each other
OGF [96]	Good	Best route	-	Reactive	- Efficient data delivery in large scale and resource constrained networks	- Improved scalability, energy consumption, and void handling	- Depends on local neighbor update table

are not readily available, flat based routing will encounter difficulties in link recovery, which can result in increased packet loss and subsequently decreased reliability. Table 2.6 gives a comparison of some of the reviewed flat-based protocols based on various criteria such as scalability, path establishment type, algorithm used, protocol objectives, advantages and disadvantages [83].

Hierarchical Routing

In hierarchical or cluster-based routing, nodes are logically structured into multiple levels, domains, or clusters, with various nodes connected with one another at each level. This decreases the overall number of routing information that has to be processed in the network, consequently resulting to quicker network convergence time [112]. Contrary to flat routing, nodes can have different functionalities in hierarchical protocols. For example, nodes with low energy can be assigned to perform sensing functionalities while those with higher energy can be utilized for aggregation, processing and transmission of the sensed data [82]. In these protocols, the number of messages transmitted to the sink or base station can be reduced through data aggregation within a given cluster. Furthermore, energy efficiency is improved by enabling multi-hop communication among nodes in a given cluster [97], thereby reducing the need for long distance data transmission by nodes in the network.

Most techniques used in hierarchical routing protocols focus on either optimizing cluster head selection, which node aggregate the data and when, channel allocation, as well as routing the data. Example of hierarchical protocols include Low-energy Adaptive Clustering Hierarchy (LEACH) [113], LEACH-Mobile-Enhanced (LEACH-ME) [114], Mobile Sink-Based Routing Protocol (MSRP) [115], Mobility-Based Clustering (MBC) [116], Enhanced Cluster-Based Routing Protocol for Mobile Wireless Sensor Networks (ECBR-MWSN) [117], Mobile Sink Improved Energy-Efficient PEGASIS-Based (MIEEPB) [118], Ring protocol [119] e.t.c. Hierarchical routing can be further categorized based on the network structure into *chain*, *block*, and *tree-based routing* [101].

Chain-based routing: Nodes are connected in a chain-like structure in such a way that data from the furthest away node from the destination is

Table 2.6: Comparison of flat-based routing protocols

Protocol	Scalability	Algorithm	Message Type	Path Formation	Protocol Objectives	Pros	Cons
TORA [104]	Good	Shortest path	Hello Messages	Reactive	- Achieving high degree of scalability	- reduces overhead and energy consumption - Multiple routes available	- Multicast not considered in its basic operation [111]
E-TORA [105]	Good	Best route	IMEP control	Reactive	- Energy consumption Minimization	- Network lifetime extension	- Multicast not considered in its operation
Gossip [108]	Good	Random	-	Reactive	- Dissemination of common data to all nodes in a network	- Addresses implosion problem	- Higher propagation delay
AODV [106]	Limited	Shortest path	Hello message	Reactive	-Fast adaptation to dynamic link conditions	- Low overhead -Higher energy efficiency and bandwidth utilization - Does not require non-active nodes to maintain routes to destination	- Suitable for low traffic load - Low scalability -Takes longer time when building route table
RR [109]	Good	Shortest path	Hello Messages	Reactive	- For queries to be delivered to specific events in the network	- Robust in terms of node failure	- Duplicate message transmission leading to overhead
TBRPF [103]	Limited	Shortest path	Hello messages	Proactive	- Provide hop-by-hop routing along shortest paths to destination	- Full topology information available and maintained at each node	- Not suitable for static or low mobility networks
OLSR [107]	Limited	Link state	Hello messages	Proactive	- Optimization of classical link state algorithm	- Lower end-to end delay - Suitable for high traffic load	- Maintains all possible route in routing table - High overhead
WRP [110]	Limited	Shortest path	Table exchange	Proactive	- To ensure reliable message transmission by addressing routing loops	- Faster route convergence in case of failure	- Complexity in routing table maintenance - High processing power and large memory needed

transmitted along the chain towards the sink. Each chain comprises of a head node that aggregates data from member nodes in the chain. However, packet delay is a major concern in such routing approach as packets have to traverse several hops before reaching the destination. Furthermore, failure of one node along the chain may affect the whole chain making it less robust.

Block-based routing: The entire network is partitioned into groups called clusters, with each cluster having a dedicated node called cluster head. The cluster head is in charge of receiving and aggregating data from its member nodes before transmitting the data down to the sink or destination node. Optimizing cluster head node selection is one of the major problems in these routing protocols. In addition, such routing approaches are known to have limited scalability with increase in network size as managing block or cluster information can introduce additional overhead.

Tree-based routing: In these type of hierarchical protocols, nodes are organized in a tree like structure with the sink node being the tree root. The hierarchical tree structure provides increased scalability by decreasing the number of direct path or connection each node has to maintain. The sensing node is the leaf or child node and the forwarding node is the parent node. Child nodes send data to their respected parent nodes, which then forwards the aggregated data to the top level parent node towards the sink node. Table 2.7 summarizes some hierarchical-based and hierarchical routing protocols in the literature, outlining some advantages and disadvantages of each [101].

Considering the large scale deployment of geophones in WSDA, **hierarchical tree-based routing protocols** are best suited for WSDA networks as they ensure scalability by logically organizing nodes into multiple levels, thereby requiring less resources and resulting in better performance.

Table 2.7: Comparison of Hierarchical-based routing protocols modified from [101]

Protocol	Scalability	Algorithm	Path Establishment	Network structure	Protocol Objectives	Pros	Cons
LEACH [113]	Limited	Shortest path	Proactive	Block-based	- Maximizing network lifetime and mobility support	- Low energy consumption - High scalability	- Additional overhead due to clustering - Inefficient data delivery and energy consumption - High delay
LEACH-ME [114]	Limited	Shortest path	Proactive	Block-based	- Improving packet delivery ratio (PDR)	- Improved QoS interms of PDR	- High energy consumption - Extra slots required for computing mobility factor
MSRP [115]	Good	Shortest path	Proactive	Tree-based	- Maximizing network lifetime	- Controls sink mobility based on cluster heads (CH) residual energy - Addresses the hotspot problem	- High overheads - No guaranteed CH to sink communication - High delay
RPL [120]	Good	Shortest path	Proactive	Tree-based	- To provide support for MP2P traffic flow in low-power networks	- High scalability - Employs trickle timer algorithm to minimize overhead - Supports MP2P traffic	- No mobility support
MBC [116]	Good	Shortest path	Proactive	Tree-based	- PDR, energy consumption, and control overhead improvement	- Utilizes residual energy and mobility in CH selection - Connection time taken into account in CH selection - Lower delay	- Medium energy efficiency - Node occurrence problem not addressed leading to reduced network utilization, link breakage, and packet drop - Transmission delays not considered
ECBR-MWSN [117]	Limited	-	Reactive	Tree-based	- Load balancing and maximizing network lifetime	- Balances energy consumption among nodes	- Limited scalability - high overhead and delay
MIEEPB [118]	Limited	-	Proactive	Chain-based	- Energy utilization and delay improvement	- Chain head selection based on residual energy and distance from sink - Avoids long link formation	- Hotspot problem - High delay
Ring protocol [119]	Limited	-	Reactive	Block-based	- Maximizing network lifetime - Minimizing packet delay	- Minimizes sink position overhead broadcast	- Knowledge of position of a node and its neighbors is required - Increased energy consumption and delay

2.6.2 Routing Based on Path Discovery Process

Depending on when the route or path discovery to a given destination is initiated, ad hoc routing protocols can be classified into *proactive and reactive protocols* [102], [44].

Proactive Routing

In proactive routing, routes are established in advance in such a way that paths to the destination are readily available when needed. Each node in the network maintains an up-to-date routing or topology information in a table by the periodic transmission of route update messages [102]. The table comprises of information on the cost as well as record of paths between a node and its neighbors (one-hop or more). Based on these information, a node selects the best path to forward its data. Examples of such protocols includes Destination-Sequenced Distance Vector (DSDV) [121], OLSR [107], TBRPF [103] etc. Proactive protocols are good in QoS-aware applications, as routes to a given destination are always available and up-to-date, thereby providing minimal latency in end-to-end packet transmission. However, the need for periodic route updates and presence of valid routes that might never be needed increases the routing overhead in the network [102].

Reactive Routing

In reactive routing protocols, routes are established on demand i.e., when a node has packet to transmit to a given destination. If no data traffic is generated by a node, routing process is completely absent. The need for periodic update of routing tables is excluded in this approach as paths are computed right before data transmission. The main procedures in reactive protocols are path discovery and maintenance as well as an optional path deletion [62]. Path discovery process is initiated whenever a node wants to transmit a packet and there are no known paths to the destination. However, this is not required for the transmission of every single packet as a discovered path can stay valid long enough for consecutive packet transmission to the same destination. Nodes then store all paths found during the discovery

Table 2.8: Comparison between proactive and reactive routing protocols modified from [111]

Proactive Protocols	Reactive protocols
Route are established in advance	Route are established on demand
Large routing information is required and maintained independently for communication	Less routing information is required, resulting in reduced energy consumption
Periodic transmission of topology update messages	Update message is sent in case of topology changes
Route acquisition time is small, making it suitable for real-time applications (+)	High route acquisition time (-)
Low energy efficiency and bandwidth under-utilization (-)	Higher energy efficiency and no bandwidth under-utilization incurred (+)
Routing information needs to be stored and maintained, thereby requiring a large node capacity	Network information need not to be stored
Suitable for high traffic load especially in static networks (+)	Unsuitable for high traffic load as high traffic might lead to increased overhead in case of frequent link breakage or topology changes (-)

Note: (+) indicates an advantage, and (-) indicates disadvantage in relation to WSDA networks

process thus acquiring new routing states. The route maintenance procedure ensures that all nodes maintain the routing information as long as its valid, otherwise deleted. Examples of some prominent reactive protocols includes AODV [106], TORA [104], Dynamic Source Routing (DSR) [122], Routing On-Demand Acyclic Multipath (ROAM) [123] e.t.c. In dynamic networks, reactive protocols are more efficient in terms of power consumption and routing overhead compared to proactive protocols, as routes are only established on demand. Though, route discovery or acquisition delay might be significantly large, which consequently results in higher latency for end-to-end packet transmission. In static networks however, this depends on the data traffic pattern. A comparison between proactive and reactive protocols, outlining some advantages and disadvantages is given in Table 2.8 [111].

Considering the static nature of WSDA networks, proactive routing protocols are best suited as routes are readily available when needed.

Table 2.9: Criteria for selecting routing protocol employed for the proposed WSDA network architecture

Feature	Reason
Proactive route establishment	<ul style="list-style-type: none"> - To ensure minimal end-to-end packet delay thereby achieving the real-time data delivery requirement in WSDA networks - To minimize route setup delay
Hierarchical protocol	<ul style="list-style-type: none"> - To ensure scalability considering the large scale deployment of geophones - To provide some form of load balancing and energy efficiency
Flexibility with underlying link layer technology	- To provide room for selecting suitable layer 2 technology that fits WSDA requirements
Self configuration and organization	To enable autonomous network configuration and management -
Multi-Point-to-Point (MP2P) and Point-to-Multi-Point (P2MP) data traffic support	<ul style="list-style-type: none"> - MP2P for communication between multiple geophones and gateway at the lower domain (establishing upward route) - P2MP for communicating acquisition or control information from gateways or CCU to geophones (establishing downward route)

2.6.3 Proposed Routing Approach

Based on the review presented above and the criteria and specifications outlined in Table 2.9 for WSDA networks, a **proactive, hierarchical, and tree-based** approach is chosen as the best routing technique to suit the traffic and application requirements for WSDA networks.

Following the review on different routing protocols that fall within the family of proactive, hierarchical and tree-based routing approach in Table 2.7, **IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL)** is chosen as the enabling routing protocol employed in this thesis due to following reasons;

- i). **Multi-objective function support:** depending on the specific requirements of the application scenario, RPL allows the utilization of different objective functions thereby enabling the prioritization of metrics like energy efficiency, reliability, hop count, delay etc.

- ii). **Energy Efficiency:** RPL is design to be energy efficient through enabling the “energy” objective function to maximize network lifetime. This is very important as WSDA networks often operate in remote areas with limited power sources.
- iii). **Less control message overhead:** RPL utilizes trickle timer algorithm to minimize the transmission of routing control messages, which is important in energy constrained networks and networks with limited bandwidth.
- iv). **Robustness:** The ability of RPL to quickly converge during route establishment as well as maintain stable routes contributes to the stability and robustness of the network. This is crucial especially when operating in a challenging environments as is the case in WSDA, and other applications like earthquake monitoring.
- v). **Loop-free routing:** RPL is designed to avoid routing loops, thereby ensuring reliable data transfer to the destination node. This is vital in WSDA networks as reliable transmission and reception of each acquired seismic data packet is crucial for reconstructing the subsurface image at the processing stage.

Others include simplicity, ease of deployment, low memory requirements etc. A preliminary evaluation and an elaborate discussion on RPL is given in Chapter 5.

2.7 Conclusion

In this chapter, a review of related work in the field of WSDA is presented. This includes information on present day devices and systems, outlining some important parameters specified by the manufacturers such as battery life time, operation mode or acquisition techniques used, technologies employed e.t.c. In addition, several architectures for WSDA networks have been proposed in literature. However, most of these architectures do not fully address the requirements and challenges outlined in Section 1.3 with regards to WSDA networks. Furthermore, no comprehensive performance evaluation of these proposed architectures is presented.

A review of technologies for WSDA is also discussed in this chapter. Based on this review, a mixture of short and long range IEEE 802.11-based technologies (IEEE 802.11n/ac and IEEE 802.11af respectively) operating in multi-hop ad hoc mode are proposed as enabling wireless technologies for WSDA networks based on the selection criteria outlined in Section 2.4. Consequently, the default random access channel access method is adopted in WSDA networks.

With multi-hop ad hoc communication proposed, a routing protocol is needed to define how geophones compute and establish routes or paths for data transmission. A large number of routing protocols for wireless ad hoc and WSNs have been proposed in literature and outlined in this chapter. Five relevant classes of routing protocols were considered and reviewed. These classification is principally based on network structure and path discovery process (see Tables 2.8, 2.5, 2.6, and 2.7). Based on this review, proactive, hierarchical, tree based approach is selected as the best routing approach with regards to the traffic and application requirements for WSDA due to reasons outlined in Table 2.9. Following a review on different routing protocols that fall within the family of proactive, hierarchical and tree-based routing approach, **RPL** is chosen as the suitable routing protocol for WSDA networks. A detailed discussion on this is presented in Chapter 5.

3 Proposed WSDA Architecture, Methodology, and Scenarios

3.1 Introduction

This chapter discusses the overall research approach and methodology applied in this thesis. A discussion on the proposed WSDA network architecture, wireless technologies, and geophone data traffic generation model employed is presented. These proposals are primarily based on addressing the challenges and requirements for WSDA outlined in Section 1.3, keeping in mind the discussion on proposed architectures, and technologies presented in literature as outlined in Chapter 2. Furthermore, an outline of the bottlenecks, research questions, as well as scenarios under which the research was carried out is presented. In addition, a brief discussion on the network simulation tool used in the research is also presented.

3.2 WSDA Proposed Architecture

With the goal of obtaining a scalable, reliable, energy efficient, self-organizing and maintaining WSDA network, a two-level network architecture comprising of geophone and gateway level or domain is proposed. The architecture entails dividing the entire survey area into subnetworks. Each subnetwork comprises of a Wireless Gateway (WG) that serves as a data sink and relay node to the group of geophones within that subnetwork. Wireless communication is enabled using the IEEE-802.11-based technologies operating in either the 2.4 or 5 GHz ISM band. Subnetworks are deployed based on frequency reuse concept in such a way that no two adjacent subnetwork use the same frequency channel. This is employed to serve as a direct approach to address interference

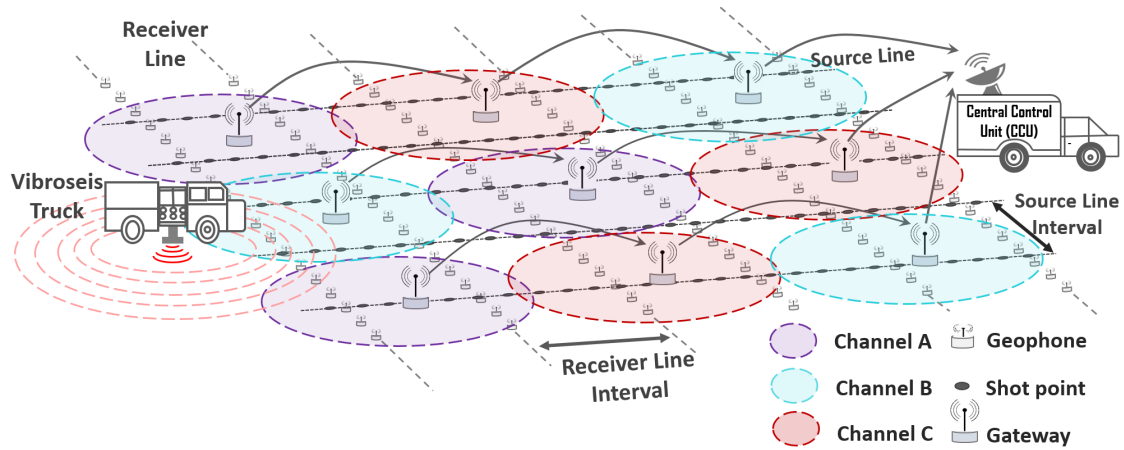


Figure 3.1: Proposed WSDA network architecture with sub-networks deployed according to frequency re-use concept

issues while ensuring reliability. Figure 3.1 illustrates the proposed WSDA network architecture. A detailed description of the geophone and gateway domains from the architecture is given in the following subsection.

3.2.1 Geophone Domain

In the geophone domain, communication between geophones and WGs is established over IEEE 802.11n/ac standard in multi-hop ad-hoc mode of operation. This mode of operation is enabled to utilize advantages such as extended coverage, robustness, enhanced capacity, self configuration and organization, as well as less spatial interference at low power levels [44]. However, a routing strategy or protocol needs to be defined to determine how geophones route their sensed data to the WG¹. With multi-hop communication enabled at the geophone level, it is imperative to avoid too many hops in which a packet has to traverse before reaching the gateway. This is more significant for the relaying or intermediate geophones, which in addition to their generated packets have to forward packets from neighboring geophones, thereby making them potential bottlenecks in terms of performance. In addition interference effects are narrowed further with reduced geophone transmit power [124]. As such, there is need to set optimal transmit power levels that will limit interference as well as minimize hop counts while ensuring required network

¹Refer to Section 2.6

performance and coverage. With regards to geophone data generation, a discussion on a proposed geophone data traffic model is given in Section 3.3.

Furthermore, geophones can have dual wireless interface to enable operation in both 2.4 or 5 GHz band employing either 20 or 40 MHz bandwidth. Each geophone is expected to have one or more antenna of at most 1 m in height in line with the state-of-the-art devices and for simulation purposes. Depending on the proximity to the gateway in a subnetwork, a geophone can transmit its acquired data in single or multi-hop form of communication. Considering the fact that data generated by geophones is quite small², in the order of 48 kbit s^{-1} , data compression is not necessary at the geophone level. However, it can be applied at the gateways to compress the aggregated data from geophones before forwarding it to the CCU. Nevertheless, as future seismic surveys are targeting better quality subsurface images by employing higher resolution ADC in geophones, data compression can also be applied on the geophone level.

3.2.2 Gateway Domain

In the upper domain, WGs in each subnetwork forward their aggregated data from member geophones down to the CCU. Depending on the proximity to the CCU, a WG can forward data either directly or via neighboring WGs. This introduces some sort of hierarchy in the WSDA network structure. Gateways are expected to have a dual interface to be able to support two communication links. One link for communication with geophones and the other for communication with the CCU. Communication between gateways and the CCU can be established via long range communication technologies like the IEEE 802.11af³. Figure 3.2 shows the logical view of the proposed network architecture.

An alternate approach is to employ cables instead of radio for the communication link between gateways and the CCU. If gateways are connected by cables and geophones via radio, around 83% of cables are saved. However, this might

²Refer to Section 1.1.3

³Refer to Section 2.5.5

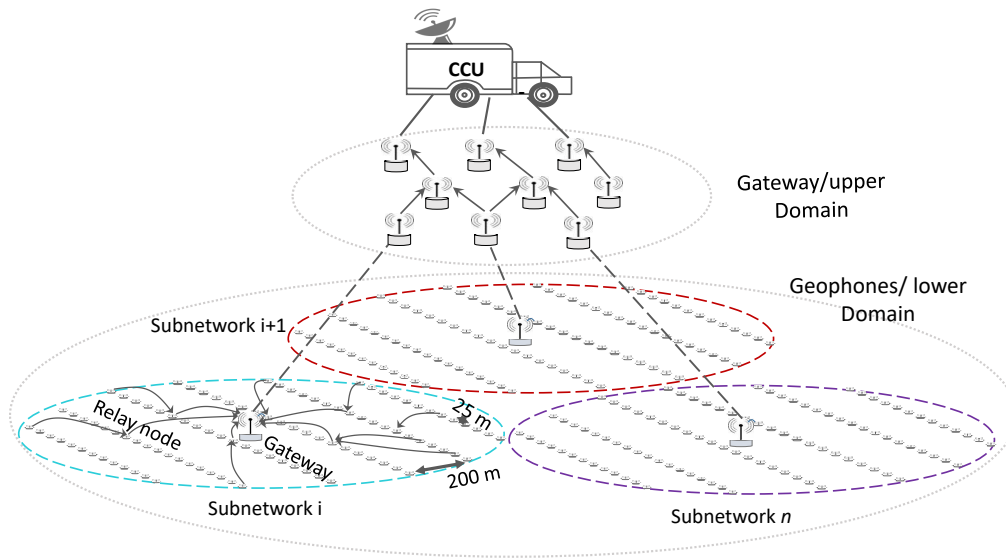


Figure 3.2: Logical topology view of the proposed network architecture depicting the two-level geophones and gateway domains

not be a good approach especially when extremely harsh and rough terrains are considered as discussed in Section 1.3.

Network Geometry

The conventional orthogonal geometry where receiver lines and source lines are placed perpendicular to each other is considered in this thesis. Geophones are placed 25 m apart along the receiver line, with the receiver lines spaced 200 m apart. Depending on the area under consideration, a typical survey can comprise of about 10,000 to 30,000 geophones [23]. However, not all geophones are active at the same time during a sweep. The number of geophones actively recording during a sweep (also referred to as “patch”) directly depends on the number of vibroseis trucks and the acquisition type⁴ employed in the survey. In other words, this determines the overall network size which is employed later in simulations as presented in chapter 7. A typical value of the distance from the edge of a patch to a shot point is 800 m [11]. In other words, this is the vibroseis truck wave propagation radius resulting from a sweep, in which the geophones within that radius are actively recording.

⁴For more details, refer to section 1.2.2 and 2.2.3

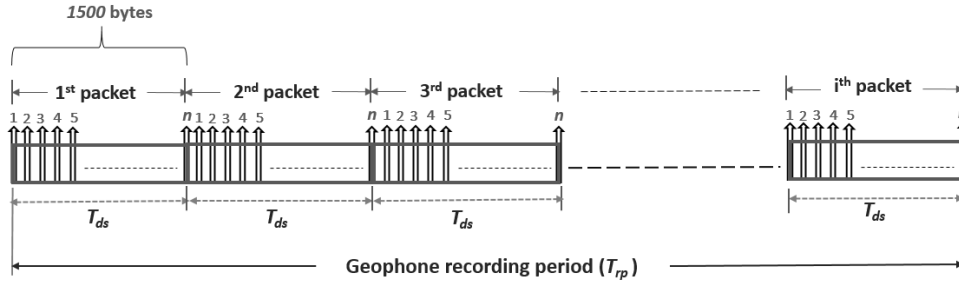


Figure 3.3: Proposed geophone recording period traffic model

3.3 Geophone Data Traffic Model

The majority of seismic data acquisition applications employ blind acquisition⁵ technique for acquiring seismic data during survey. This means that data is stored in the memory unit of geophones and later harvested by crew members during or after completion of the survey process. In other words, seismic data cannot be transmitted in real-time or near real-time during the survey. In this thesis however, we propose seismic data to be transmitted during the geophone recording or listen period (T_{rp}), referred to as “RPA”. This offers a form of real-time seismic data transfer that is expected to significantly increase the overall seismic survey productivity. Throughout the rest of this thesis, we assume each geophone has a 24-bit ADC, and seismic data is sampled at 0.5 ms interval (2000 samples s^{-1}). With this assumption, seismic data is generated at a rate of 48 kbit s^{-1} per geophone.

The geophone recording period is the duration within which all the reflected seismic signals generated during a sweep or shot from a seismic energy source are expected to be recorded by the geophones. Seismic data samples (s) collected by geophones for a given period of time (T_{ds}) during T_{rp} for a particular sweep are transmitted to the CCU at the end of every T_{ds} period prior to the next T_{ds} , until the end of T_{rp} , as depicted in Figure 3.3. T_{ds} represents the seismic sample accumulation time and defines how frequent packets are sent by geophones in the network. In this work, a typical value of $T_{rp} = 5$ s is used. Generally, the traffic model can be defined as a non-saturated periodic traffic with deterministic packet arrival rate of value T_{ds} .

⁵Refer to Section 2.2

Traffic Generation

Consider a survey in which T_{rp} of 5 s is defined and reflected seismic signals are sampled at an interval of 0.5 ms (2000 samples/s). With a 24-bit ADC geophone resolution, each seismic sample s has a size of 24 bit or 3 B, and data will be generated at a rate of 48 kbit s^{-1} (6 kB s^{-1}) per geophone. If a T_{rp} value of 5 s is used for example, a total of 240 kbit or 30 kB data will be generated over this period, which corresponds to a total seismic data samples (S_T) of 10000 per sweep per geophone. Assuming a T_{ds} of 0.5 s is defined, this means that over this duration 1000 seismic samples will be accumulated by a geophone and placed in a packet that will be sent over the network.

For any given number of seismic samples s , the packet payload size p_{sz} as well as the duration T_{ds} can be computed from Equation (3.1) and Equation (3.3), respectively.

$$p_{sz} = \frac{sP_T}{S_T} \quad (3.1)$$

where S_T is total seismic samples collected and P_T is the total data generated by a geophone over the duration T_{rp} . For a geophone with 24-bit ADC resolution, p_{sz} can be expressed as in Equation 3.2.

$$p_{sz} = s3 \text{ B} \quad (3.2)$$

$$T_{ds} = \frac{p_{sz}T_{rp}}{P_T} \quad (3.3)$$

T_{ds} can also be expressed in terms of s and S_T , as given in Equation (3.4).

$$T_{ds} = \frac{sT_{rp}}{S_T} \quad (3.4)$$

The theoretical offered load (η) in the network for different payload sizes can be computed using the relation expressed in Equation 3.5.

$$\eta = \frac{8p_{sz}NN_{ps}}{T_{rx}} \text{ bit s}^{-1} \quad (3.5)$$

where N is the number of geophones in the network, p_{sz} is the payload size, N_{ps} is the number of packets sent per node over the duration T_{rp} in bytes, and $T_{rx} = T_{rp} - T_{ds}$ is the time taken to receive all data packets at the sink. N_{ps} can be computed using the expression in Equation 3.6.

$$N_{ps} = \frac{T_{rp}}{T_{ds}} \quad (3.6)$$

The performance of this model is evaluated using simulation in Section 4.2 with the goal of investigating the optimal value of the sample size “ s ”, which is a function of the payload size “ p_{sz} ” such that $3B \leq p_{sz} < P_T$ or $1 \leq s < S_T$. This model has been published by the author of this thesis in [8].

3.4 Research Questions

A typical bottleneck in IEEE 802.11-based networks is the ***medium access***. This comes as a result of the random nature of the CSMA/CA scheme, where each geophone contends equally for access to the shared medium based on the binary exponential back off algorithm. This is even more challenging considering the large-scale deployment of geophones in the survey field, which means more probability of collisions.

Another bottleneck is the ***routing scheme***. As previously mentioned, WSDA networks are static in nature as no movement of geophones is expected after initial deployment. Several routing protocols have been proposed in literature especially for WSNs. However, WSDA networks slightly differ from WSNs in terms of the large seismic data volume generated, underlying link layer technology employed etc. Furthermore, contrary to conventional WSNs in which most of the data collected by neighboring sensors is redundant because of high correlativity between nodes, in WSDA data from each geophone is very vital especially at the processing stage to enable proper visualization and interpretation of the subsurface structure. As such, it is important to investigate the WSDA network performance in terms of these bottlenecks.

In view of the requirements and challenges outlined in Section 1.3, some of the research question put forward in this thesis include:

Research question 1: Is the default IEEE 802.11 CSMA/CA-based medium access mechanism suitable for large-scale deployment of geophones in WSDA systems?

Hypothesis: The use of random access or contention-based channel access mechanism will provide good scalability, reliability, required latency, and low complexity in WSDA networks.

Justification: Utilizing off-the-shelf, license-free IEEE 802.11 random access technologies in multi-hop ad hoc form of communication is promising in terms of extending coverage while providing required data rate to relay large volume of aggregated seismic data to the CCU. This research question seeks to investigate the performance of the default CSMA/CA channel access mechanism in the IEEE 802.11-based technologies for WSDA networks, and to test the hypothesis that contention-based channel access mechanism will provide good scalability, reliability, required latency, and low complexity in WSDA networks. This research question is addressed in chapter 4.

Research question 2: What routing strategy is more suitable for WSDA networks?

Hypothesis: In addition to extending wireless coverage, enabling routing in WSDA will ensure autonomous WSDA network configuration and improve network performance.

Justification: Self-organization and management is very crucial in WSDA networks as geophones can be left unattended for several days or weeks in unconventional areas with rough terrains. In the case where new nodes join or some fail in the network, geophones should be able to dynamically configure and manage themselves without the need of a central control entity. This research question aims to investigate a suitable routing approach/protocol for WSDA that will ensure self-configuration and maintenance of geophones, and to test the hypothesis that enabling routing in WSDA will ensure autonomous WSDA network configuration, improve network performance, and extend wireless coverage.

Research question 3: How can the issue of scalability be addressed in large-scale WSDA networks, and is the proposed architecture valid and applicable for state-of-the-art and future seismic surveys?

Hypothesis: Careful network planning, appropriate choice and optimization of wireless technologies and protocols will ensure scalability in large-scale WSDA networks.

Justification: Seismic Data Acquisition (SDA) often employ large scale deployment of geophones, with future surveys targeting hundreds of thousands of geophone nodes for better resolution of acquired seismic data. This research question aims to investigate how scalability can be ensured in WSDA networks from the network architecture as well as the underlying protocols and technology point of view, and to test the hypothesis that careful network planning and choice of technologies and protocols will improve scalability. Furthermore, the question seeks to investigate the performance, validity, and applicability of the proposed WSDA network architecture.

3.5 Methodology and Scenarios

Owing to the general complexity and expensive nature of the stages involved in realizing seismic survey, it is very difficult to utilize an experimental approach in investigating and addressing the WSDA challenges and questions raised. Thus, in this thesis, a combined approach of analytical modeling and simulation is employed to replicate the seismic survey process.

Mathematical modeling has been used in the field of WSDA research [125], [126]. These approach is used with the aim of simplifying the complex real-world scenario to obtain more reliable predictions, understanding, and conclusions regarding the WSDA system. In addition, the approach allows for better scalability as well as comparisons between different scenarios and solutions, providing an insight into which solution may be more effective. MATLAB [127] tool is used for analytical evaluation in this thesis.

Several literature have employed simulation approach in the area of WSDA research [23], [40], [43]. Similar to the mathematical modeling, the simulation

approach is utilized with the aim of studying complex scenarios, enabling the investigation and validation of multiple scenarios and outcomes, replacing the need for expensive experimentation. Furthermore, it is also utilized to make predictions about the behavior of the seismic survey system, allowing for identifying possible problems, and proposing solutions. The OMNeT++ discrete event simulator is used in this thesis. A brief discussion on OMNeT++ simulator is given in Section 3.6.

To simplify the research approach for the proposed WSDA network with the aim of investigating and addressing the medium access and routing bottlenecks, three reference scenarios (1, 2, and 3) are defined in this thesis.

3.5.1 Scenario 1

The focus in this scenario is to analytically investigate the performance of WSDA network in terms of the known medium access bottleneck of the IEEE 802.11-based technology proposed, with the aim of addressing **research question 1** outlined in Section 3.4. For simplicity of investigation, flat-based network scenario is considered whereby geophones have same functionality, operating in ad-hoc mode. Geophones transmit their data to the CCU or sink node in single-hop, with the assumption that all geophones are within communication range of the CCU. This assumption is significant especially for scalability investigation with regards to channel access of geophones in the network.

The network consists of four receiver lines positioned 200 m apart, each having geophones placed at an interval of 25 m along the line as illustrated in Figure 3.4. All geophones are assumed to employ the IEEE 802.11g link layer technology. Data is generated according to the model presented in Section 3.3 for a duration of 5 s recording period. A single sweep from a single-fleet with one vibroseis truck is assumed in this scenario.

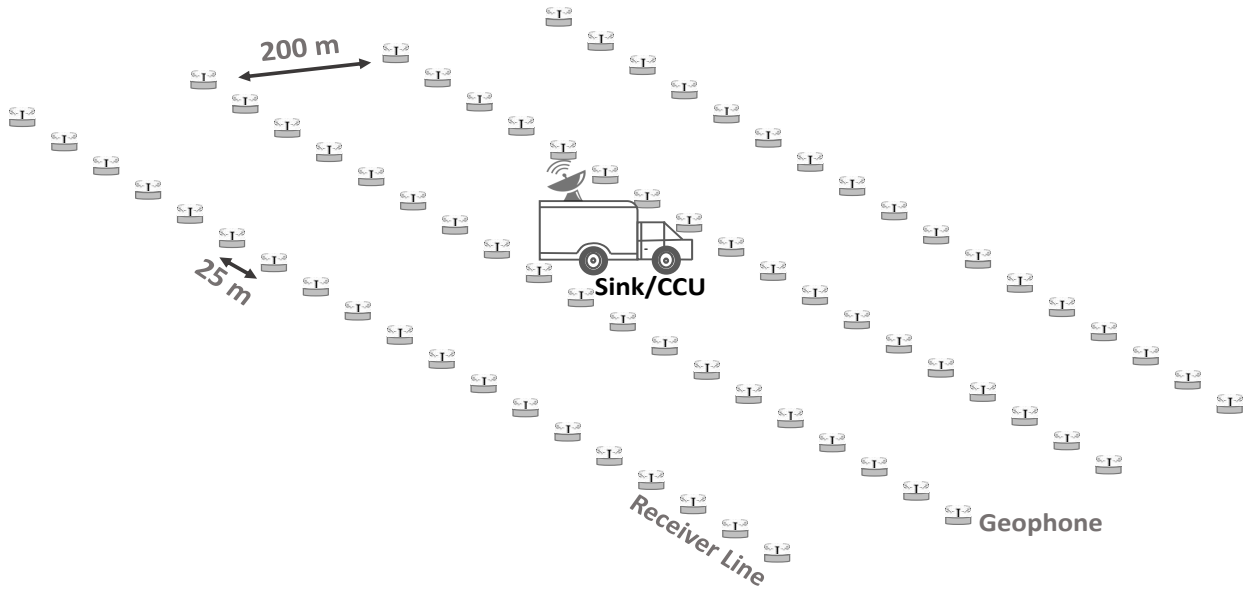


Figure 3.4: Scenario 1 depicting a flat-based single-hop WSDA for investigating the medium access bottlenecks in the IEEE802.11-based WSDA network.

3.5.2 Scenario 2

The main objective in this scenario is to conduct an investigation of the proposed routing approach discussed in Section 2.6 for the proposed architecture in Figure 3.1 using simulation, with the aim of addressing **research question 2**. For simplicity, only a single subnetwork is considered at the geophone domain, with the aim of enabling multi-hop ad hoc communication between geophones and the gateway. Considering the homogeneity of geophones in the network, this can be simply extended to the global network architecture. Figure 3.5 depicts the scenario under which the investigation is carried out⁶.

Geophones are deployed on four receiver lines placed at an interval of 200 m each, with an inter-geophone distance of 25 m. The number of geophones in the subnetwork is varied from 8 to 200 maximum. Similar to scenario 1, a single shot is assumed. IEEE 802.11g in ad hoc mode of operation is configured as the link layer technology. Geophones generate traffic according to the model presented in Section 3.3 for a duration of 5 s recording period.

⁶Refer to Chapter 5 for details of the evaluation

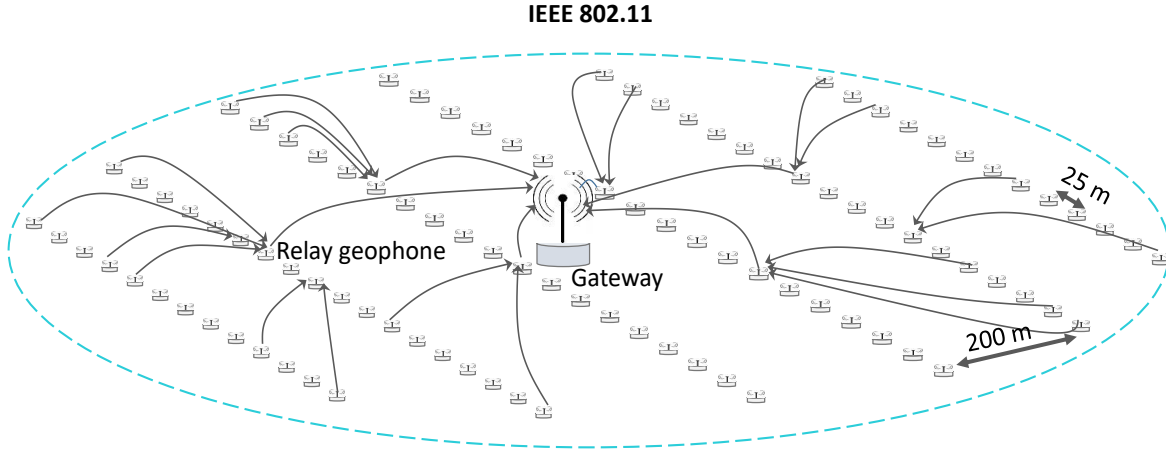


Figure 3.5: Scenario 2: depicting a single subnetwork from the proposed architecture for investigating the routing approach discussed in Section 2.6.

3.5.3 Scenario 3

This scenario represents the global network architecture for WSDA as proposed in Figure 3.1. The goal in this scenario is aimed at addressing **research question 3**, to prove the scalability and validity of the proposed WSDA architecture (including routing scheme and wireless technology employed). In addition, the real-life seismic data acquisition setup and parameters are modeled in this scenario. These includes elements like the state-of-the-art acquisition or sweep techniques outlined in Section 2.2.3, the recording period acquisition (RPA) traffic model proposed in Section 3.3, frequency re-use concept etc.

The network size is defined according to the expected number of geophones that are actively recording seismic signal as a result of an ongoing sweep from a single fleet of three vibroseis trucks, employing the flip-flop multi-vibroseis acquisition technique⁷. The network consists of six receiver lines deployed at an interval of 200 m over an area of 5 km² as illustrated in Figure 3.6. Each receiver line comprises of 200 geophones placed 25 m, giving total of

⁷Refer to Section 2.2.3 for a detailed discussion on multi-vibroseis acquisition technique

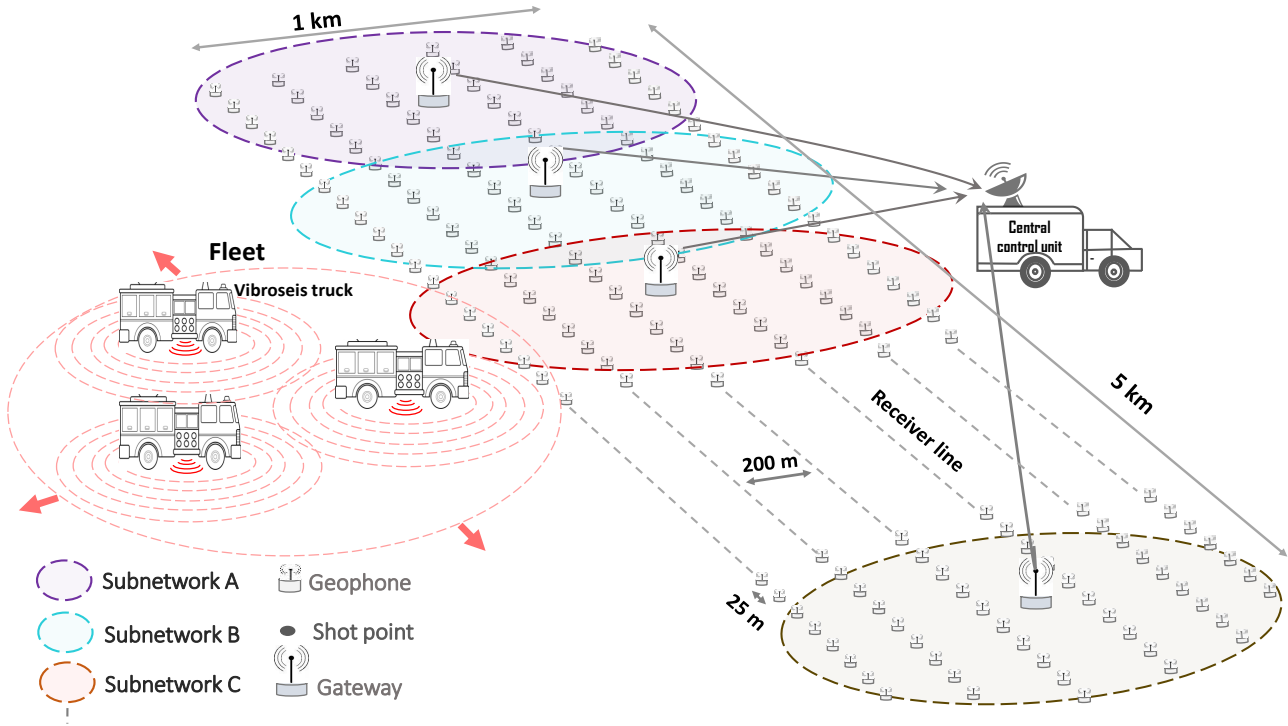


Figure 3.6: Scenario 3 depicting geophones that are actively recording as a result of a shot/sweep from a 3-vibroseis truck fleet, employing the flip-flop acquisition technique and their corresponding subnetwork. With this configuration, 86.9% of cables are discarded as compared to a full cable-based survey.

1200 active geophones in the network. The network is further divided into 10 subnetworks, each comprising of 120 geophones and a gateway that serves a relay node for forwarding the aggregated data to the CCU. Gateways are connected via cables to relay seismic data to the CCU in this scenario. The rationale behind this is to first focus the network performance investigation in the geophone domain for possible problems and bottlenecks while assuming an ideal connection between gateways and the CCU (gateway domain).

Furthermore, using cables for the connections between gateways and the CCU might be more advantageous compared to wireless connections, especially in terms reliability and survey costs. Besides, the connections between geophones account for the highest percentage drawbacks brought about by cables. For example, a typical survey with 30,000 geophones, where gateways are connected via cables to the CCU and geophones have wireless connection to gateways, about 83.3% of cable is saved when compared to a full cable-based seismic survey.

3.6 OMNeT++ Simulator

OMNeT++ [128] is a discrete event network simulator developed with the primary goal of building and simulating networks. These networks can be queuing networks, on-chips network, wireless or wired communication networks etc. It is a component-based C++ simulation framework and library designed with the flexibility to support the addition of new functionalities and enhancements. Independent projects referred to as *frameworks* can be modeled and integrated in the OMNeT++ simulation platform. Furthermore, it provides support for field-specific operations like WSN, internet protocols, performance modeling, wireless ad hoc networks, photonic networks e.t.c., as provided by the corresponding framework.

Models are represented by a component (module) architecture in OMNeT++, programmed in C++. A high level network descriptor (NED) language is used to assemble the modules into larger components. To summarize, the major component of OMNeT++ includes:

- i). Simulation kernel C++ library
- ii). NED language
- iii). Simulation integrated development environment (IDE), based on the Eclipse platform
- iv). Simulation execution using command-line interface (Cmdenv)
- v). Utilities like makefile creation tool

The main protocol model library in OMNeT++ is the INET framework, which is used as a foundation that extends to many other application frameworks such as (Veins, CoRE), LTE (simuLTE), peer-to-peer networks (OverSim), INETMANET, LEACH, Framework for LoRa (FLoRa) e.t.c. Furthermore, the RPL protocol implementation in OMNeT++ by authors in [129] is employed.

3.7 Conclusion

In this chapter, an outline of the methodology and approach used in this thesis is presented. A detailed discussion on the architecture proposed for WSDA networks with the goal of addressing the research challenges is also presented. This architecture involves dividing the network into subnetworks, deployed based on the frequency reuse concept. Furthermore, the bottlenecks as well as the research questions along side the hypothesis and justifications are outlined. Analytical modeling and simulation approach are employed to investigate the WSDA network bottlenecks and research questions. For simplicity of these investigations, three different scenarios outlined in Section 3.5 are employed. These scenarios form the basis for the subsequent chapters in this thesis. In addition, a brief introduction to the OMNeT++ simulation tool is presented.

4 MAC Modeling for WSDA Networks

This chapter discusses an analytical model developed for WSDA networks with regards to the default medium access in the IEEE 802.11-based wireless technology using a bi-dimensional Markov Model. Sequel to the discussion in chapter 3 on the bottlenecks in IEEE 802.11-based technologies, it is imperative to analytically estimate the performance of WSDA networks based on the IEEE 802.11 DCF using **scenario 1** discussed in Section 3.5, prior to setting up the overall simulation. In addition, the model is expected to serve as a tool to undertake quick parameter studies as well as investigate network performance in the survey planning phase before deploying geophones in the field. The model is extended to the global proposed WSDA network. Obtaining the desired WSDA network parameter sets as well as expected performance can be done much faster using analytical models as compared to simulations. Furthermore, an evaluation on the performance of the RPA traffic model presented in Section 3.3 is carried out in this chapter using reference scenario 1. The goal is to investigate an optimal value of the seismic data sample size “ s ” or packet payload “ p_{sz} ” to be transmitted over the network using simulation.

4.1 Single-hop Modeling and Analysis of the DCF

The IEEE 802.11 DCF protocol was first modeled using a two dimensional Markov chain by Bianchi in [130]. The model was the foundation for many IEEE 802.11 DCF analytical models in literature today. It provides the basis for analytically computing the saturation throughput for 802.11 DCF single hop networks under the assumption of ideal channel, no hidden terminals, and saturated buffer conditions. However, some attributes of the IEEE 802.11 DCF

protocol like freezing of the back-off counter when the channels is sensed busy, and retransmission limits were not considered in the model. Improvements to the model presented in [130] have been put forward in literature with regard to a more generalized and realistic network settings.

For improvements with the assumption of saturated traffic conditions, authors in [131] presented an analytical expression to compute the system capacity, packet drop probabilities, and the mean frame delays in an error-prone radio channel. In [132], an analytical model to compute the saturation system throughput and delay for different frame aggregation techniques in the IEEE 802.11n under error-prone channel conditions was presented. They compared the analytical model with simulation using the uni-directional and bi-directional methods of transferring data of the A-MSDU and A-MPDU frame aggregation schemes. In [133], the Bianchi model was extended to analyze the performance of the 802.11 under jamming. Authors analyzed the saturation throughput under channel aware and channel-oblivious jammer models, characterizing the optimal omniscient jamming that establishes a lower bound on the throughput of the IEEE 802.11 protocol under jammer attacks. In [134], authors presented a performance analysis of the IEEE 802.11ac under hidden nodes and saturated traffic conditions. They investigated the effect of using different primary channels and different bandwidth as new features in the 802.11ac DCF. Authors in [135] study the impact of grouping strategy introduced in the 802.11ah standard for channel contention alleviation in dense IEEE 802.11 networks. They proposed an analytical model to monitor the performance of a no-crossing group-synchronized DCF under saturated traffic conditions. An extension of the latter is presented in [136] to analyze the saturation throughput of the group-synchronized DCF employing the centralized uniform grouping and decentralized random grouping techniques for a given number of groups in a network. Authors in [137] proposed a model to analyze the saturated throughput of IEEE 802.11ad Enhanced distributed channel access (EDCA) under ideal channel conditions using a 5-dimensional Markov chain model. They investigated the effect of minimum contention window size, packet length, number of stations, arbitration inter-frame space (AIFS), and number of sectors on the throughput service categories presented in the EDCA.

The assumption of saturated traffic condition is however unrealistic in most IEEE 802.11 networks as majority of real data traffic transmission is irregular with considerable idle periods and far from saturated. As such, various articles proposed a model extension of [130] that takes into account unsaturated traffic condition. Different approaches were employed in the literature to model the unsaturated traffic behavior of a station.

An approach to extend the discrete-time Markov chain model presented in [130] was given in [138], [139], [140], [141], [142]. Their models incorporate an additional state to account for the situation where a node has an empty queue i.e. has no any packet in its buffer to be transmitted. Another approach in [143], [144] employs applying queuing theory analysis to estimate probability that the stations queue is zero, which denotes the corresponding station will not compete for the medium access. However, in all the above literature, the probability to drop a packet after m number of retries was not considered in the modeling.

Some literature focus on extending [130] to properly estimate the time duration spent by a node during the backoff procedure. Authors in [145], [146], [147] take into account the effect of back-off counter freezing in their models i.e. the busy medium condition during the back-off procedure. However, they did not consider the circumstance where the packet is been dropped after the maximum retransmission limit is reached. Authors in [148] considered the packet drop probability in their model in addition to back-off counter freezing, but however fail to incorporate an additional state to account for the situation where a station has an empty queue, and also assumed ideal channel conditions. Authors in [149], [150], [151] included the maximum retransmission limit and packet drop in their models and did not consider the back-off counter freezing situation during the back-off procedure. Authors in [138] incorporate network coding to analyze the performance of the 802.11 DCF protocol while addressing the packet drop and back-off counter freezing probabilities.

Nonetheless, to properly analyze an IEEE 802.11-based geophone station under the proposed WSDA traffic model aimed at offering a form of real-time seismic data transfer as described in section 3.3, the model has to take into account unsaturated traffic conditions because of the periodic generation of seismic data by geophones during the recording period. Real channel conditions,

back-off counter decrementing probability, as well as probability to drop a packet are taken into account in accordance with the standard.

Therefore, this thesis focus on combining and extending the models presented in [130], [142], [148] to incorporate all features of the IEEE 802.11 DCF as defined by the standard (like packet drop after certain transmission retries, counter freezing and decrementing probability during backoff procedure). The contributions in this thesis are three folded:

- i). First a model that investigates the general behavior of a single-hop IEEE 802.11 DCF based on the WSDA specific network attributes is presented. This will serve as a general tool for faster performance investigation of IEEE 802.11-based WGNs as compared to simulation.
- ii). Secondly, an analysis and modeling of the wireless channel behavior when a reference geophone enters backoff procedure is presented. This is to estimate the average duration a node spends before decrementing its counter during the backoff procedure.
- iii). Finally, an expressions for the probability that a packet transmission fails, throughput, and MAC delay is presented. These expressions can be applied to estimate network performance as well as perform scalability and parameter investigation within the proposed WSDA network topology.

4.1.1 Markov Model for a Geophone Node

As discussed in Section 2.5.1, the DCF is the fundamental channel access mechanism in the IEEE 802.11 standards which is based on the CSMA/CA scheme that employs the binary exponential backoff algorithm. It comprises of two schemes; basic access and Request-to-send (RTS) clear-to-send (CTS) access scheme. However, in this thesis only the basic access mechanism is considered. The Markov model presented is a extension of the classical Bianchi model [130] and two other models ([142], [148]) presented in literature. The model consist of two main states of a geophone;

- i). State S_E : this denotes the state of a geophone when it has no packet awaiting transmission in its buffer.

- ii). $S_{i,j}$ which is a bi-dimensional state with one dimension “ i ” ($0 \leq i \leq m$) representing the transmission stages and “ j ” ($0 \leq j \leq W_i - 1$) representing the backoff counter value at the i^{th} transmission stage. m denotes the maximum retransmission limit beyond which the packet is dropped. W_i is the contention window value at the i^{th} transmission stage and is given by the expression;

$$W_i = \begin{cases} CW_{min} & i = 0 \\ 2^i CW_{min} & 0 < i \leq m' - 1 \\ CW_{max} & m' \leq i \leq m \end{cases} \quad (4.1)$$

$$m' = \log_2 \left(\frac{CW_{max} + 1}{CW_{min} + 1} \right) \quad (4.2)$$

Model Assumption

The model is developed based on the following postulations in relation to the proposed network architecture and geophone traffic model:

- i). Fixed number of homogeneous geophone nodes with fixed packet size under unsaturated traffic and real channel conditions in accordance with the proposed traffic model in Section 3.3.
- ii). The geophone has at least one packet in its buffer with probability q , and an empty buffer with the probability $1 - q$.
- iii). A packet transmission fails either due to collision with probability P_c , which is independent of the previous number of retransmission suffered, or due to channel errors with the probability P_{ce} , which is independent of the previous channel errors.
- iv). A geophone transmits packet in a randomly chosen time slot with probability τ .

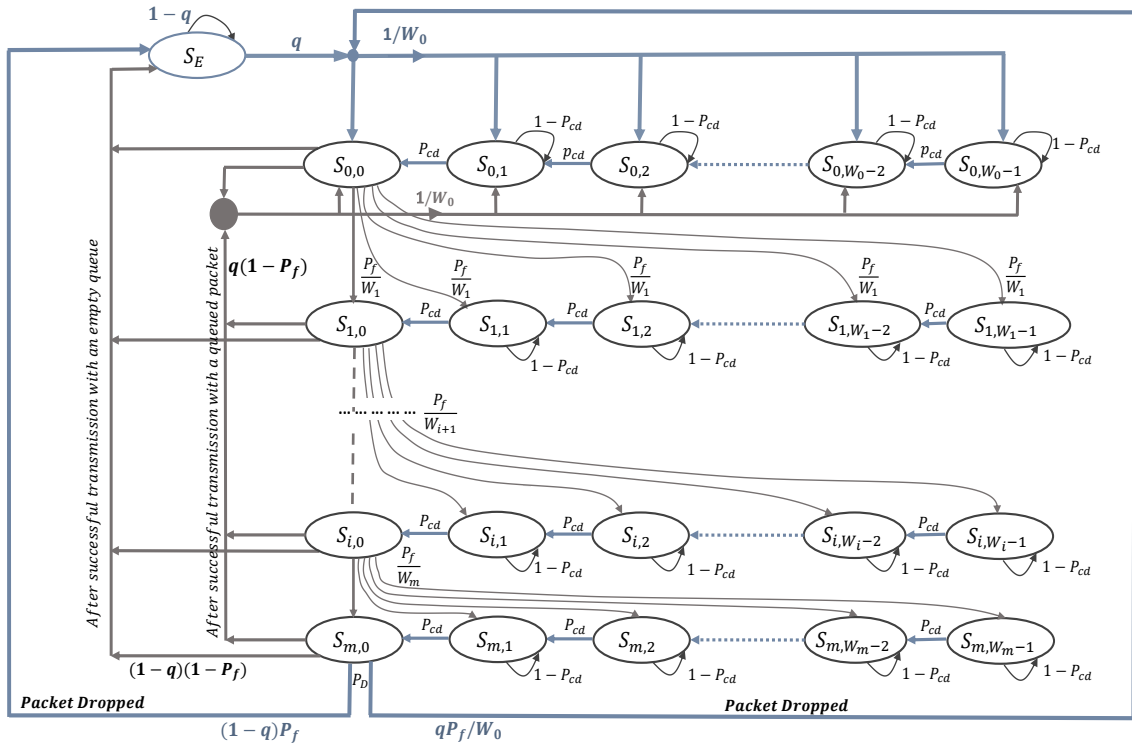


Figure 4.1: Markov model for a single geophone node

Figure 4.1 shows the Markov model for a geophone station under unsaturated traffic conditions. A packet is successfully transmitted if no channel errors and no packet collision occurs. This event happens with a probability

$$P_s = (1 - P_c)(1 - P_{ce}) \quad (4.3)$$

The packet transmission then fails with a probability

$$P_f = 1 - P_s = P_c + P_{ce} - P_c P_{ce} \quad (4.4)$$

A geophone is at state S_E when it has no packet in its queue with the probability $1 - q$ and exits this state with the probability q . At this point, the geophone then senses the channels for an ongoing activity. If the channel is sensed idle for a DIFS duration and also has zero as its backoff counter value, it then directly transmits at state $S_{0,0}$ and goes back to state S_E if it has no packet awaiting transmission in its buffer. If the channel is sensed busy however, the geophone defers its transmission according to the binary exponential backoff algorithm and draws a random backoff counter value uniformly between $[0, W_0 - 1]$. During the backoff process, the counter value

decrements from state S_{i,W_i-1} to S_{i,W_i-2} only when the channels is sensed idle by the geophone with the probability P_{cd} and freezes with the probability $1 - P_{cd}$.

A geophone can only attempt transmission at state $S_{i,0}$ when the backoff counter value reaches zero. At state $S_{0,0}$, if the transmission attempt fails either due to collision or channel errors, the node then move to state $S_{1,j}$ and draws a random backoff value uniformly from $[0, W_1 - 1]$ with probability P_f/W_1 . The same process is repeated for each successive failed transmission attempt until state $S_{m,0}$ is reached. If the packet transmission attempt failed at this state, the packet is dropped with the probability $P_D = P_f^{m+1}$. If the geophone has another packet in its buffer it then moves back to the initial transmission state $S_{0,j}$ with probability $(qP_f)/W_0$, otherwise goes to state S_E with probability $(1 - q)P_f$. Furthermore, if the transmission attempt is successful in any of the state $S_{i,0}$ and the geophone has a packet in its buffer awaiting transmission, the geophone moves to state $S_{0,j}$ with probability $q(1 - P_f)/W_0$. If the buffer is empty however, the geophone moves to state S_E with probability $(1 - q)(1 - P_f)$ and awaits the arrival of a packet. Equation 4.5 and 4.6 shows the transition probabilities and duration from all possible states in the model respectively.

$$\left\{ \begin{array}{ll} P\{S_{i,j-1}|S_{i,j}\} = P_{cd} \\ P\{S_{i,j}|S_{i,j}\} = 1 - P_{cd} \\ P\{S_{i+1,j}|S_{i,0}\} = P_f/W_{i+1} & 1 \leq i \leq m \\ P\{S_{0,j}|S_{i,0}\} = \frac{q(1 - P_f)}{W_0} & 1 \leq j \leq W_0 \\ P\{S_E|S_{i,0}\} = (1 - q)(1 - P_f) & 0 \leq i < m \\ P\{S_{0,j}|S_E\} = q/W_0 & j \in (0, W_0 - 1) \\ P\{S_E|S_E\} = 1 - q \\ P\{S_{0,j}|S_{m,0}\} = qP_f/W_0 & j \in (0, W_0 - 1) \\ P\{S_E|S_{m,0}\} = (1 - q)P_f \end{array} \right. \quad (4.5)$$

Table 4.1: Notations and corresponding definitions used.

Notation	Description
q	Probability that a geophone has at least one packet in its buffer
$1 - q$	Probability that a geophone has an empty queue
P_c	Collision probability
P_{ce}	Probability of error due to channel conditions
P_s	Probability of successful packet transmission
P_f	Probability that the packet transmission fails
P_{cd}	Probability that the backoff counter value decrements
$P_{f rz}$	Probability that the backoff counter freezes
P_D	Probability that a geophone drops a packet after m retries
τ	Probability that a geophone transmits in a random time slot
i	Transmission stage
W_i	Contention window value at the i^{th} transmission stage
m	Maximum transmission stage
j	Backoff counter value at i^{th} transmission stage value
$S_{i,j}$	State of a geophone in terms of i, j
S_E	State of a geophone with an empty buffer
σ	Slot time
T_s	Time taken for successful packet transmission
T_c	Time taken for a duration of collision
T_f	Time taken due to failed packet transmission
λ	Packet arrival rate
$\gamma_{i,j}$	Probability that a geophone occupies a given state $S_{i,j}$

$$\begin{cases}
T\{S_{i,j-1}|S_{i,j}\} = \sigma \\
T\{S_{i,j}|S_{i,j}\} = \frac{T_s p_s + T_c p_c}{1 - p_{cd}} \\
T\{S_{i+1,j}|S_{i,0}\} = T_c \\
T\{S_{0,j}|S_{i,0}\} = T_s \\
T\{S_E|S_{i,0}\} = T_s \\
T\{S_{0,j}|S_E\} = \frac{1}{\lambda}
\end{cases} \quad 0 \leq i \leq m \quad (4.6)$$

T_s is the duration the channel is sensed busy due to a successful transmission, T_c is the duration the channel is sensed busy during a failed packet transmission, λ is the packet arrival rate and $1/\lambda$ is the inter-arrival time.

Table 4.1 gives the summary of the notations used in the model and their corresponding definitions.

4.1.2 Stationary Transmission Probability

In view of the transition probabilities summarized in Equation 4.5, the probability “ τ ” that a geophone transmits packet in a randomly chosen time slot can be obtained applying normalization conditions.

$$\sum_{i=0}^m \sum_{j=0}^{W_i-1} \Upsilon_{(i,j)} + \Upsilon_{S_E} = 1 \quad (4.7)$$

Equation 4.7 states that the sum of the probabilities of been in all possible states should add up to one. To determine the stationary distribution of the Markov chain in Figure 4.1, let $\Upsilon_{i,j}$ represent the probability that in any given time slot, a geophone occupies a given state $S_{i,j}$.

$$\Upsilon_{i,j} = \lim_{t \rightarrow \infty} P[s(t) = i, \Upsilon(t) = j] \quad \forall \quad i \in [0, m], \quad \forall \quad j \in [0, W_i - 1] \quad (4.8)$$

Noting the relations;

$$\begin{cases} \Upsilon_{i,0} = P_f \Upsilon_{i-1,0} = P_f^i \Upsilon_{0,0} & \forall \quad i \in [1, m] \\ \Upsilon_{i,j} = \frac{W_i - j}{P_{cd} W_i} P_f^i \Upsilon_{i-1,0} & 1 \leq i \leq m, \quad 1 \leq j \leq W_i - 1 \\ \Upsilon_{m,0} = \frac{P_f^m}{1 - P_f} \Upsilon_{0,0} & i = m \\ \sum_{i=0}^m \Upsilon_{(i,0)} = \frac{1 - P_f^{m+1}}{1 - P_f} \Upsilon_{0,0} \end{cases} \quad (4.9)$$

Let Υ_{S_E} represent the stationary probability of been in state S_E . Υ_{S_E} accounts for the fact that after a successful transmission at any of the state $S_{i,0}$, state S_E can be reached with probability $(1 - q)(1 - P_f)$.

$$\Upsilon_{S_E} = (1 - q)(1 - P_f) \sum_{i=0}^m \Upsilon_{(i,0)} + (1 - q)\Upsilon_{S_E} + (1 - q)P_f \Upsilon_{m,0} \quad (4.10)$$

Substituting $\Upsilon_{(i,0)}$ and $\Upsilon_{(m,0)}$ from Equation 4.9 in Equation 4.10 and applying some mathematical simplifications, Υ_{S_E} can be expressed as:

$$\Upsilon_{S_E} = \frac{1 - q}{q} \Upsilon_{(0,0)} \quad (4.11)$$

The stationary probabilities of being in the other states are expressed in Equation 4.12.

$$\Upsilon_{0,j} = q(1 - P_f) \sum_{i=0}^m \Upsilon_{(i,0)} + q\Upsilon_{S_E} + qP_f\Upsilon_{m,0} \quad (4.12)$$

$$\Upsilon_{0,j} = P_f\Upsilon_{m-1,0} \quad (4.13)$$

Equation 4.7 gives an expression for the normalization conditions, which yields the solution for $\Upsilon_{0,0}$ in Equation 4.14 [152].

$$\Upsilon_{0,0} = \frac{2qP_{cd}(1 - P_f)(1 - 2P_f)}{q\left[W(1 - P_f)(1 - (2P_f)^{m+1}) + (1 - 2P_f)(2P_{cd} - 1)(1 - (P_f)^{m+1})\right] + 2(1 - q)P_{cd}(1 - P_f)(1 - 2P_f)} \quad (4.14)$$

Therefore, the stationary probability τ that a geophone transmits a packet in a randomly chosen time slot is expressed in Equation 4.15, which can be further expressed as in Equation 4.16 [142].

$$\tau = \sum_{i=0}^m \Upsilon_{(i,0)} = \Upsilon_{0,0} \frac{1 - P_f^{m+1}}{1 - P_f} \quad (4.15)$$

$$\tau = \frac{2qP_{cd}(1 - 2P_f)(1 - P_f^{m+1})}{q\left[W(1 - P_f)(1 - (2P_f)^{m+1}) + (1 - 2P_f)(2P_{cd} - 1)(1 - (P_f)^{m+1})\right] + 2(1 - q)P_{cd}(1 - P_f)(1 - 2P_f)} \quad (4.16)$$

Considering the WSDA traffic model described in Section 3.3 where geophones generate packet at a fixed interval T_{ds} , we assume the packet arrival process to be deterministic. Furthermore, due to the stochastic nature of the CSMA/CA based MAC scheme in IEEE 802.11 DCF, it is appropriate to assume the packet departure process as Markovian. Thus, we assume a D/M/1 queue model in our analysis.

However, the probability q that a geophone has at least one packet in its buffer is approximated as expressed in Equation 4.17.

$$q = \frac{\lambda}{E[s]} \quad (4.17)$$

λ represents the packet arrival rate, and $E[s]$ is the mean service rate computed as sum of the time to successfully transmit a packet T_s , collision time T_c and mean backoff duration over the average number of retransmission.

$$E[s] = (T_s + T_c + \delta)m/2 + \sigma \left(\sum_{i=0}^{m/2} 2^i \frac{CW_{min} - 1}{2} \right) \quad (4.18)$$

δ is the propagation delay and σ represents the slot time.

4.1.3 System Throughput

Throughput describes the amount of data successfully received at the gateway within a given period of time. Prior to presenting an expression for the throughput, an expression for some important probabilities for N number of geophones in the network is obtained. This includes probabilities for both successful (P_{suc}) and failed packet transmission (P_f). Note that a transmission attempt can fail either due to collision with probability P_c or due to channel errors with probability P_{ce} .

A packet transmitted from a source geophone suffers collision if one or more of the remaining $N - 1$ geophones transmits at the same time.

$$P_c = 1 - (1 - \tau)^{N-1} \quad (4.19)$$

Thus, the packet is lost either due to channel errors or collision with the probability

$$P_f = P_c + P_{ce} - P_c P_{ce}$$

The probability that a geophone transmits its packet successfully is the probability that exactly one geophone transmits on the channel as given in Equation 4.20.

$$P_{T_{xG}} = N\tau(1 - \tau)^{N-1} \quad (4.20)$$

P_{T_x} is the probability that there is at least one transmission in a considered slot time as expressed in Equation 4.21.

$$P_{T_x} = 1 - (1 - \tau)^N \quad (4.21)$$

P_{suc} is the probability that a packet transmission ongoing on the channel is successful. This is equivalent to the probability that a packet transmission is successful given that there is at least one transmission in the considered time slot as expressed in Equation 4.22.

$$P_{suc} = \frac{P_{T_{xG}}}{P_{T_x}} = \frac{N\tau(1 - \tau)^{N-1}}{1 - (1 - \tau)^N} \quad (4.22)$$

Therefore the normalized system throughput can be expressed as in Equation 4.23.

$$U = \frac{L_P}{E[D]} = \frac{P_{suc}P_{T_x}L_P}{(1 - P_{T_x})\sigma + P_{T_{xG}}T_s + P_fP_{T_x}T_c} \quad (4.23)$$

where L_P is the length of packet transmitted over the channel, $E[D]$ is the expected duration of successful packet transmission, σ is the slot time, T_s is the duration of a successful packet transmission, and T_c is the duration of a collision for the DCF basic access scheme as given in Equation 4.24.

$$\begin{cases} T_s = DIFS + T_H + T_{L[P]} + SIFS + 2\delta + T_{ACK} \\ T_c = DIFS + T_H + T_{L[P]} + \delta \end{cases} \quad (4.24)$$

T_H represents the PHY and MAC header duration, $T_{E[P]}$ is the packet transmission time, T_{ACK} is the ACK packet transmission time, and δ is the propagation delay.

To properly model the average delay experienced by a packet before it is successfully received at the destination, it is important to look at the average duration a geophone spend during the backoff procedure before decrementing

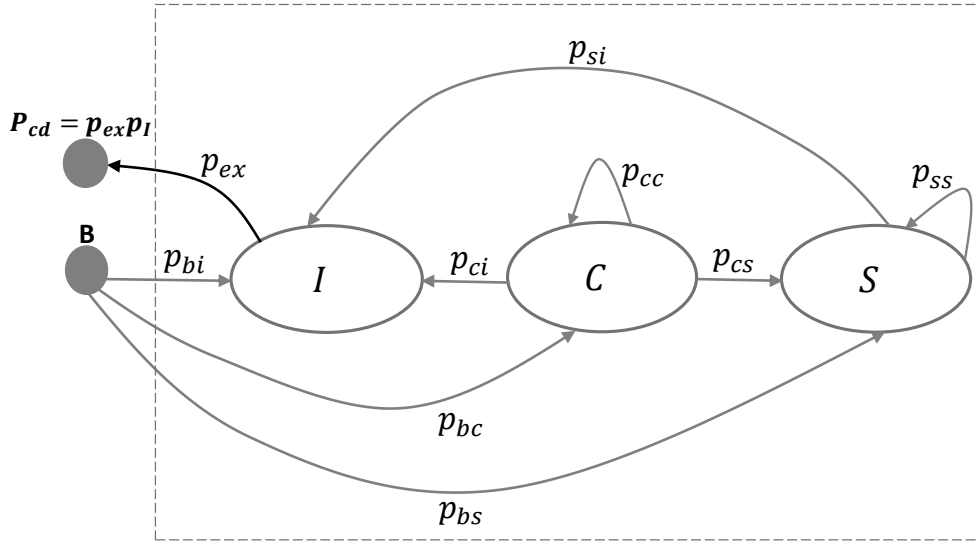


Figure 4.2: Channel state Markov model during backoff process

its counter value. In other words, the duration a backoff counter remains frozen during the backoff process. As such, a Markov model that describes the state of the wireless channel during backoff procedure from a reference geophone point of view is presented in Section 4.1.4.

4.1.4 Channel State Markov Model

Figure 4.2 shows the Markov model that represents the channel state behavior during the backoff procedure, which is an extension of the model presented in [148]. The model consist of three main states I , C , and S which represents the channel being idle, having a failed transmission attempt due collision or channel errors, and successful transmission respectively. B denotes the point where the considered geophone enters the backoff process.

The reference geophone enters backoff and finds the channel in the idle state I with the probability P_{bi} . This happens when all the remaining $(N - 1)$ geophones are not transmitting a packet. Thus, P_{bi} can be expressed as Equation 4.25. The channel exits state I with the probability $P_{ex} = 1$.

$$P_{bi} = (1 - \tau)^{N-1} \quad (4.25)$$

P_{bs} represents the probability that the considered geophone enters backoff and encounters the channel busy due to a successful transmission. This happens with the probability that only one out of the remaining $(N - 1)$ geophones is transmitting a packet as expressed in Equation 4.26. The channel remains in this state with the probability P_{ss} which represents the probability that the current transmitting geophone draws zero as a backoff counter value in the next transmission attempt as expressed in Equation 4.27. The channel moves from state S to I with probability P_{si} as expressed in Equation 4.28 when there is no activity on the channel.

$$P_{bs} = \binom{N-1}{1} \tau (1 - \tau)^{N-2} \quad (4.26)$$

$$P_{ss} = 1/W_0 \quad (4.27)$$

$$P_{si} = 1 - p_{ss} \quad (4.28)$$

P_{bc} represents the probability that the geophone enters backoff and finds the channel busy with a failed transmission either due to a collision or channel errors. This happens with the probability that two or more of the remaining $(N - 1)$ geophones transmit at the same time as given in Equation 4.29.

$$P_{bc} = 1 - P_{bi} - P_{bs} \quad (4.29)$$

The channel moves from state C to I with the probability P_{ci} when none of the colliding nodes selects zero as their backoff counter value as expressed in Equation 4.30. c denotes the number of colliding nodes.

$$P_{ci} = \sum_{c=2}^{N-1} \left(1 - \frac{1}{CW_{avg}}\right)^c \quad (4.30)$$

where CW_{avg} is the average contention window size over all transmission stages and is given as Equation 4.31.

$$CW_{avg} = \frac{(1 - P_f)}{(1 - P_D)} \sum_{i=0}^m P_f^i W_i \quad (4.31)$$

Similarly, the channel moves from state C to S with the probability P_{cs} when one out of the two or more colliding nodes selects zero as a backoff counter value as expressed in Equation 4.32. The channel remains in state C with probability P_{cc} as expressed in Equation 4.33.

$$P_{cs} = \sum_{c=2}^{N-1} c \left(\frac{1}{CW_{avg}} \right) \left(1 - \frac{1}{CW_{avg}} \right)^{c-1} \quad (4.32)$$

$$P_{cc} = 1 - P_{ci} - P_{cs} \quad (4.33)$$

Equation 4.34 gives a summary of the transition probabilities to all possible states in the model from Figure 4.2.

$$\left\{ \begin{array}{l} P\{I|B\} = P_{bi} = (1 - \tau)^{N-1} \\ P\{S|B\} = P_{bs} = \binom{N-1}{1} \tau (1 - \tau)^{N-2} \\ P\{C|B\} = P_{bc} = 1 - P_{bi} - P_{bs} \\ P\{S|S\} = P_{ss} = 1/w_0 \\ P\{I|S\} = P_{si} = 1 - P_{ss} \\ P\{I|C\} = P_{ci} = \sum_{c=2}^{N-1} \left(1 - \frac{1}{CW_{avg}} \right)^c \\ P\{S|C\} = P_{cs} = \sum_{c=2}^{N-1} c \left(\frac{1}{CW_{avg}} \right) \left(1 - \frac{1}{CW_{avg}} \right)^{c-1} \\ P\{C|C\} = P_{cc} = 1 - P_{ci} - P_{cs} \\ P\{C|S\} = P_{sc} = 0 \end{array} \right. \quad (4.34)$$

Backoff Counter Freeze Duration ($\bar{\sigma}$)

We define $\bar{\sigma}$ as the average duration taken by a geophone before decrementing its counter (or remains frozen) during a backoff procedure. To compute $\bar{\sigma}$, we first consider the duration a reference geophone spends when the state of the channel is idle (σ_I), having successful transmission (σ_S), or collision (σ_C) during a given backoff procedure.

The reference geophone awaits one time slot before decrementing its counter for σ_I .

$$\implies \sigma_I = 1$$

If the reference geophone encounters the channel busy with an ongoing successful transmission, the geophone has to wait for a duration of the successful transmission of packet (T_s) and an additional time slot. Thus, σ_S can be expressed as in Equation 4.35.

$$\sigma_S = \frac{1}{1 - P_{ss}} T_s + \frac{P_{si}}{1 - P_{ss}} \sigma_I \quad (4.35)$$

If the channel is found busy due to a failed packet transmission, it awaits the duration of a collision or packet error (T_c) and any other successive failed or successful transmission, and an idle slot time. Thus, σ_C can then be expressed as in Equation 4.36.

$$\sigma_C = \left(\sum_{i=1}^m i P_{cc}^i \right) T_c + \frac{P_{cs}}{1 - P_{cc}} \sigma_S + \frac{P_{ci}}{1 - P_{cc}} \sigma_I \quad (4.36)$$

Furthermore, there are two cases in which the reference geophone can enter backoff process. Either from a previous backoff state with the probability $1 - \tau$ or a transmission state with the probability τ .

If the node enters from a previous backoff state, the average duration ($\bar{\sigma}_B$) can be expressed as in Equation 4.37.

$$\bar{\sigma}_B = \frac{1}{P_{cd}} \left[P_{bi} \sigma_I + P_{bs} \sigma_S + P_{bc} \sigma_C \right] \quad (4.37)$$

If the node enters backoff procedure from a transmission state, the average slot duration ($\bar{\delta}_T$) can be expressed as in Equation 4.38.

$$\bar{\delta}_T = q \left(1 - \frac{1}{CW_{avg}} \right) [p_{bi}\sigma_I + p_{bs}\sigma_S + p_{bc}\sigma_C] \quad (4.38)$$

Thus, $\bar{\delta}$ can be expressed as in Equation 4.39.

$$\bar{\delta} = (1 - \tau)\bar{\delta}_B + \tau\bar{\delta}_T \quad (4.39)$$

4.1.5 Average Packet Delay

We define average packet delay (D_{pkt}) as the time taken by a packet before it is successfully received at the destination. It comprises of different delay components such as medium access control (D_{MAC}), queuing T_q , and average duration a node spends during the backoff process before decrementing its counter ($\bar{\delta}$).

Medium Access Delay (D_{MAC})

D_{MAC} is defined as the delay experienced by a frame from the instant it arrives at head of the queue in the geophone buffer till its successful transmission to the intended receiver. If a geophone transmits a packet at the initial transmission attempt, D_{MAC} can be expressed as in Equation 4.40.

$$D_{MAC(0)} = T_s + \left(\frac{W_0 - 1}{2} \right) \bar{\delta} \quad (4.40)$$

For all consecutive successful transmissions at stage i likewise, D_{MAC} can be expressed as in Equation 4.41.

$$D_{MAC(i)} = T_s + iT_c + \sum_{j=0}^i \bar{W}_j \bar{\delta} \quad 0 < i \leq m \quad (4.41)$$

where $\overline{W}_j$ is the average contention window value at a given transmission stage $j \in i$ expressed as $\frac{W_j - 1}{2}$.

Conditioning Equation 4.41 over the probability that the packet is successfully transmitted (P_{suc}) in any of the transmission stages i , given that the packet is not dropped with the probability $1 - P_D$, the medium access delay D_{MAC} can be generally expressed as in Equation 4.42.

$$D_{MAC} = \frac{1}{1 - P_D} \sum_{i=0}^m P_{suc}^{(i)} \left[T_s + iT_c + \sum_{j=0}^i \overline{W}_j \delta \right] \quad (4.42)$$

The Average packet delay can then be expressed as in Equation 4.43.

$$D_{pkt} = \frac{1}{1 - P_D} \sum_{i=0}^m P_{suc}^{(i)} \left[T_s + iT_c + T_q + \sum_{j=0}^i \overline{W}_j \delta \right] \quad (4.43)$$

where T_q is the average queue waiting time.

Note that we assumed T_q to be negligible in this model because of the large inter-arrival time of packets in our proposed traffic model discussed in Chapter 5.

4.1.6 Model Validation

OMNeT++ discrete event simulation tool is used in the model validation. Table 4.2 shows the list of parameters used for both analytical and simulation evaluation. These parameters are in accordance with both the proposed WSDA system in Chapter 5 and the orthogonal frequency division multiplexing (OFDM) based WLANs in the best effort or background access traffic categories, employed in the IEEE 802.11a/g/n standards.

Traffic is generated according to the model described in Section 4.1. With the fixed payload size of 1500 B, each geophone will generate a packet deterministically every 250 ms, and 20 packets for the 5 s recording period duration. For simplicity, we assume a constant probability that a packet is lost due to channel errors of value ($P_{ce} = 0.05$).

Table 4.2: Simulation Parameters

Parameter	Value
Packet Payload	1500 B
MAC Header	224 bit
PHY Header	192 bit
ACK	112 bit+PHY Header
CW_{min}	32
CW_{max}	1024
Bit Rate	12 & 54Mbit s ⁻¹
Packet retransmission limit	7
Propagation delay	1 μ s
SIFS	10 μ s
slotTime	20 μ s
DIFS	50 μ s

Figure 4.3 shows the offered load to the network along with the analytical and simulated throughput behavior as a function of number of geophones for different data rates (12 and 54 Mbit s⁻¹).

The simulated throughput closely matches the analytical results for both data rates. With 12Mbit s⁻¹ data rate however, it can be noticed that the throughput begins to drop when the number of geophones in the network reaches a certain value (176). This is because, the offered load as well as packet transmission failure probability P_f increases with increase in number of geophones in the network. This subsequently leads to increased congestion as can be seen in Figure 4.4 showing how the probability q that the queue is non-empty increases with network size for both data rates, and subsequently increased collisions. As a result, this leads to an increase in packet retransmissions as can be seen in Figure 4.5 computed from simulation as the ratio of total number of packets successfully sent with retransmissions to the number of packets received at the destination.

Thus, with an exponential increase in packet retransmissions beyond 176 geophones in Figure 4.5, some packets are dropped due to the fact that retransmission limit has been exceeded. Note that 134% packet retransmission from Figure 4.5 means every packet in the network is retransmitted 1.34 times on the average as is the case for the network size of 200 geophones. For the network size of 120, only 3% of the packets are retransmitted.

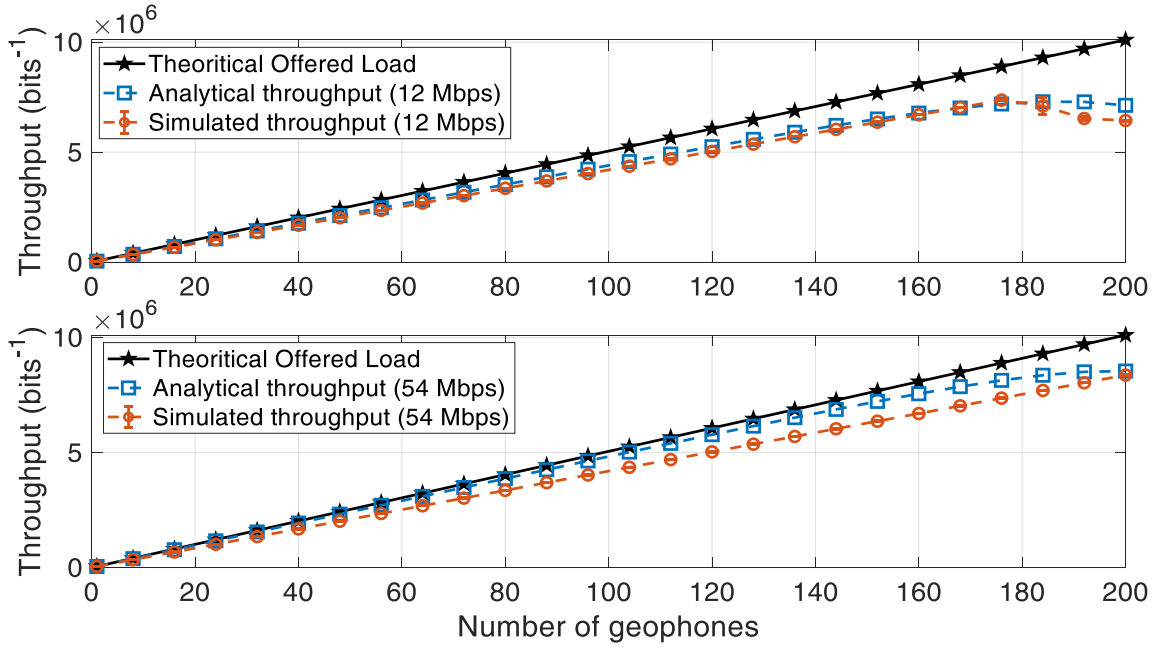


Figure 4.3: Theoretical and simulated throughput for basic access mechanism as a function of number of nodes.

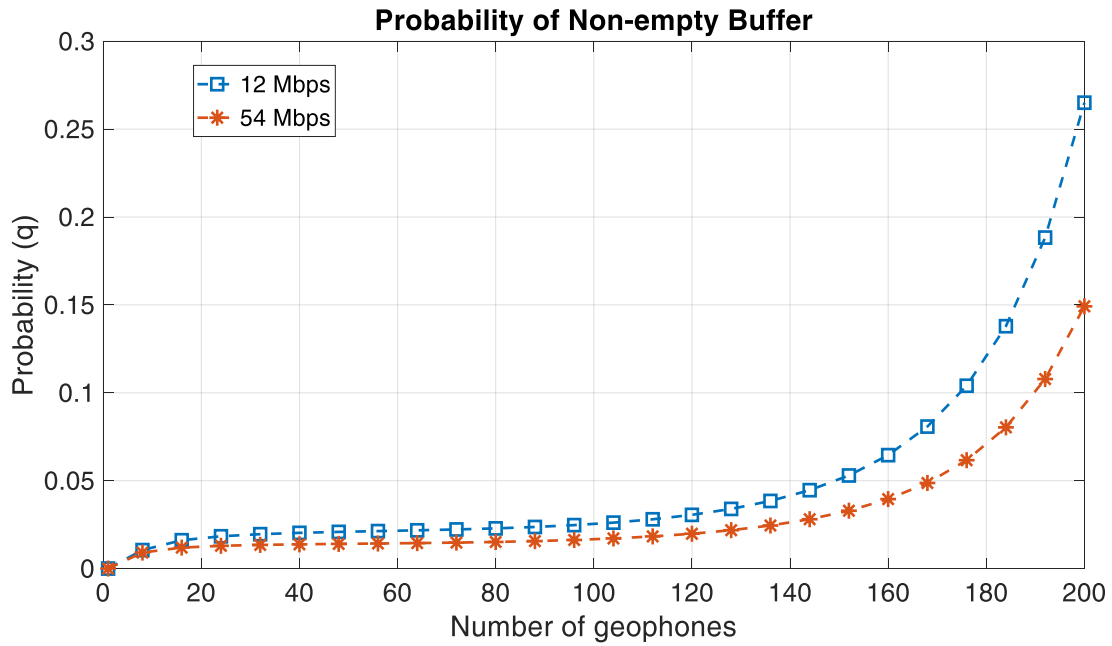


Figure 4.4: Probability that the geophone buffer is non-empty obtained from analytical model.

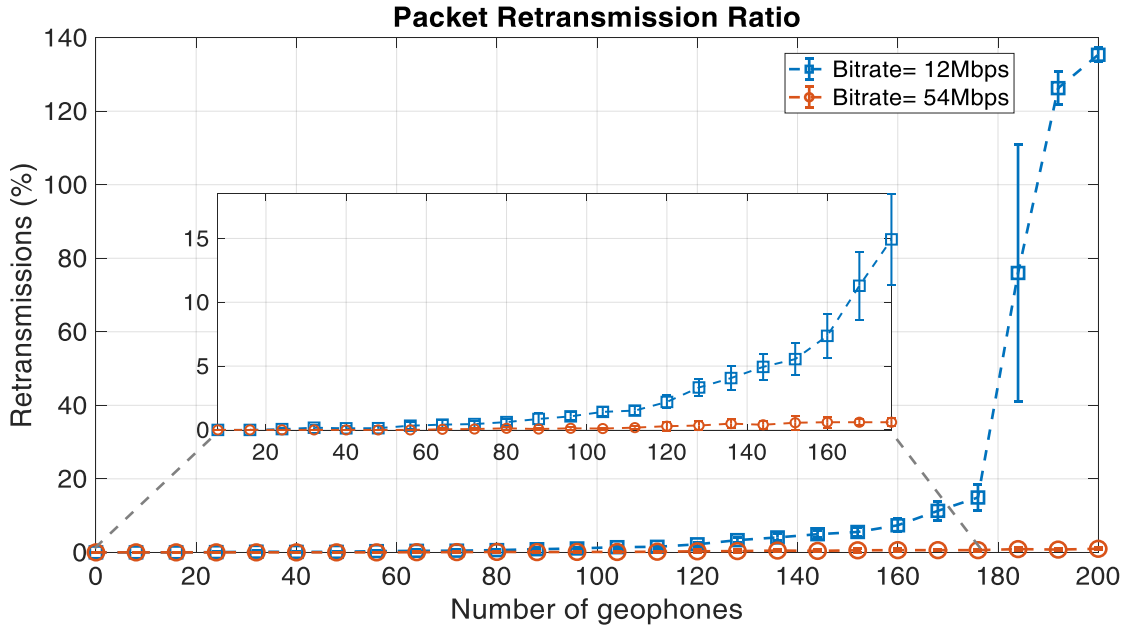


Figure 4.5: Packet retransmission ratio captured from the simulation model as a function of number of nodes in the network.

Therefore, it can be deduced that for lower data rates and increased network size, our model assumption of geophone unsaturated traffic condition and binary queue size does not hold because the offered load closely approaches the maximum network capacity (e.g., 8.9 Mbit s^{-1} for a network size of 176 nodes).

Furthermore, with the proposed WSDA architecture discussed in Chapter 3, it is important to avoid perfect synchronization of geophones in real-life seismic surveys in order to reduce packet collision or transmission failure probability (P_f). To validate this assertion both analytically and using simulations, two different cases (1 and 2) are considered for 12 Mbit s^{-1} data rate.

In case 1, the transmission of packets in all geophones is perfectly synchronized i.e., all geophones start at exactly the same time. For the analytical model, geophones immediately attempt packet transmission with the probability “ q ” of having a packet in the buffer. Case 2 on the contrary, represents the scenario where geophones are not synchronized i.e., are configured to have a different, uniformly distributed packet transmission start times. To account for this in the analytical model, the geophones begin packet transmission with the probability q/W_o where W_o is the initial contention window value.

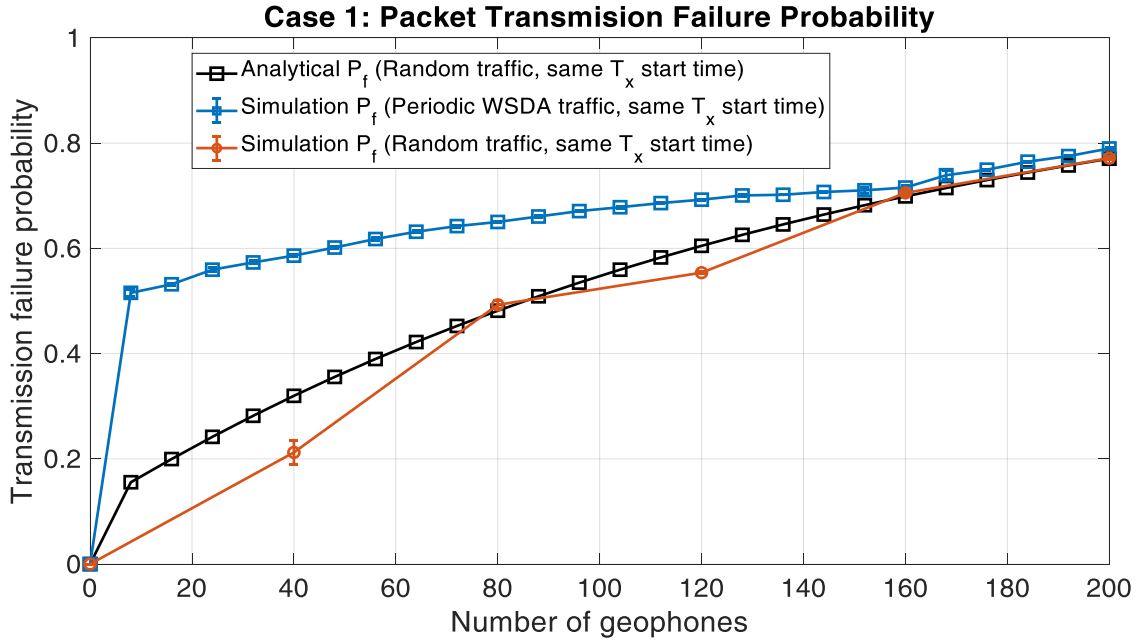


Figure 4.6: Analytical vs simulated P_f for case 1 with synchronized packet transmission start times.

For the simulation in both cases, packet transmission in geophones is configured to follow the proposed WSDA periodic traffic model described in Section 3.3 where a geophone directly transmits a packet after accumulating seismic samples for a given duration. However, in case 1, an additional simulation was carried out to show the impact of packet collision when random traffic is used, which is also valid for the analytical model.

Figure 4.6 shows the analytical P_f compared against simulated P_f for case 1, with different number of geophones in the network. In the figure it is shown that the analytical model, assuming a random traffic gives an upper bound for case 2 with non-synchronized start time. Figure 4.6 additionally shows the case for synchronized start time obtained from simulations. This clearly shows the strong and adverse effect of geophone synchronization, especially for the scenario with periodic WSDA traffic in which each of the first packet transmission always collide irrespective of the network size. Therefore, it is strongly recommended to include a random start time delay in the protocol to avoid this situation. Case 2 in Figure 4.7 illustrates this point.

Figure 4.7 shows the analytical P_f compared against simulated P_f for case 2, which captures the realistic traffic in WSDA networks. It can be seen from the figure that the simulated P_f closely follows the analytical model irrespective

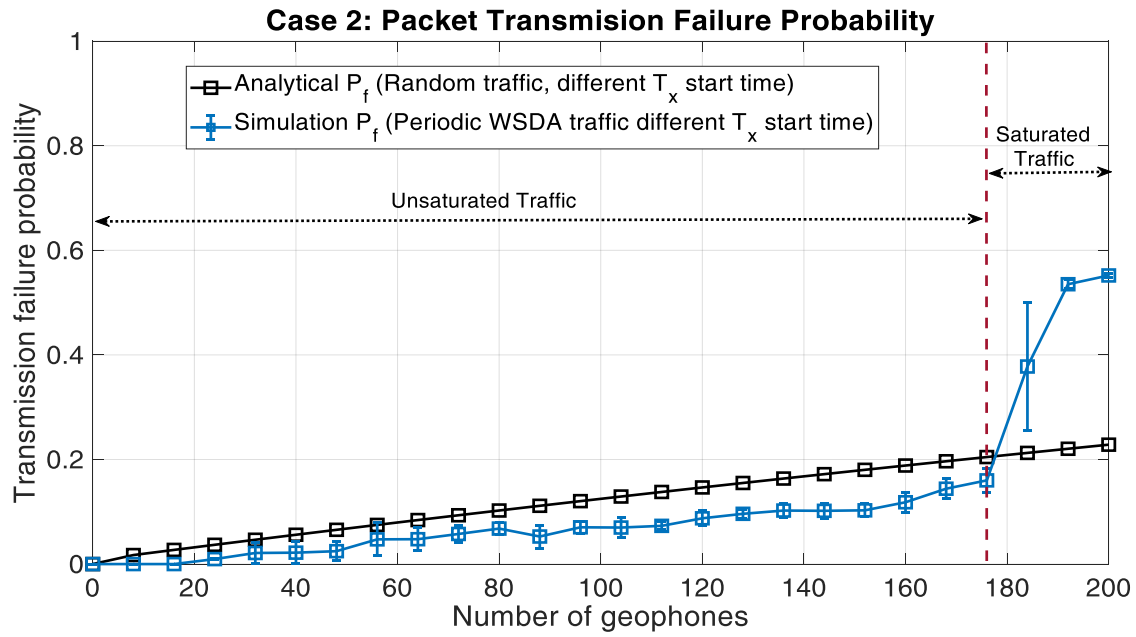


Figure 4.7: Analytical vs simulated P_f obtained for case 2 simulated with different, uniformly distributed, packet transmission start times.

of the traffic type considered. This is due to the fact that geophones are configured to have different packet transmission start times, thereby resulting in a significant decrease in collisions as compared to case 1, even for the periodic WSDA traffic. Beyond a certain number of geophones in the network (176) from simulations, the geophone queue begins to build up due to network congestion and insufficient link data rate, thereby approaches saturated traffic condition. This violates the assumption of unsaturated traffic used in the analytical model, consequently resulting in the deviation with simulations. This proves the validity of the proposed model for unsaturated WSDA traffic. Generally, saturated traffic condition needs to be avoided in any case as it does not provide the required QoS for WSDA networks.

Therefore, from these results shown, it is imperative that in real-life WSDA networks, geophones should be configured with a random starting time offset, in the order of few slot lengths, to significantly reduce high channel contention, thereby increasing overall network reliability.

Figure 4.8 shows the analytical and simulated MAC delay as a function of number of geophones for different data rates (12 and 54 Mbit s⁻¹) employed in the network. The delay is computed analytically from Equation 4.42 for each packet generated by a geophone over all nodes in the network, which

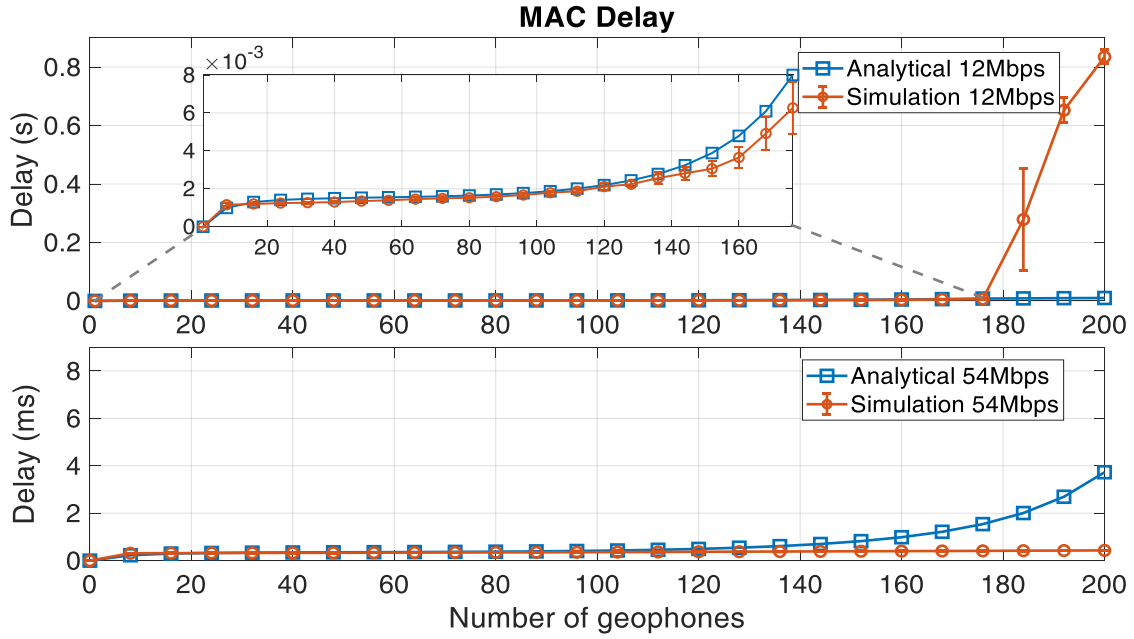


Figure 4.8: Theoretical and simulated MAC delay for basic access mechanism as a function of number of nodes.

also include the delay added due to retransmission suffered by each packet, propagation, and transmission delays. The analytical results closely follows the simulation with lower network size for both data rates. A slight deviation between the analytical and simulated results can be noticed with increase in network size which at the same time increases the offered load in the network and consequently leads to increased congestion. This is because probability P_f (computed as a function of P_c and P_{ce} in the model) increases with increase in network size, thereby resulting in more retransmissions as can be seen in Figure 4.5. This effect can be seen clearly from the 12 Mbit s⁻¹ data rate plot where the simulation results increases exponentially beyond the network size of 176 as compared to the analytical results.

Thus, beyond this point our model assumption of geophone unsaturated traffic condition and binary queue size does not hold because the offered load closely approaches the maximum capacity the network can handle.

Therefore, based on these results validation, it can be deduced that the analytical model presented can effectively be employed to evaluate the performance of a single-hop IEEE 802.11-based WSDA network. With this model, the throughput and delay are well captured. However, once the network is congested due to larger network size, the delay estimation no longer holds because

of the assumption of binary queue and unsaturated traffic condition. The model presented in this section has been published by the author of this thesis in [153].

In the following sections, an investigation of RPA traffic model is presented. The goal is to determine optimal parameter sets (e.g., packet size, send interval etc.) to be configured based on the underlying IEEE 802.11-based MAC layer.

4.2 Evaluation of Recording Period Acquisition (RPA) Traffic Model

In view of the traffic model presented in the Section 3.3, it is imperial to investigate an optimal value of the sample size “ s ”, which is a function of the payload size p_{sz} such that $3B \leq p_{sz} < P_T$ or $1 \leq s < S_T$. The optimal value of p_{sz} should be able to uphold required seismic QoS parameters such as minimal or no packet loss as well as low latency to meet up with real-time data acquisition. Such acquisition methods require that data should be transferred instantly or within a reasonable amount of time before the energy source moves to the next shot point. As such, a delay upper bound of 1 s is employed in this investigation.

With reference to the proposed architecture in Section 3.2, the parameter studies is carried out by considering a single subnetwork with fixed number of geophones transmitting their acquired data to the gateway within that subnetwork as depicted in Figure 4.10. Figure 4.9 shows the various packet sizes chosen with their corresponding traffic load and send interval. The evaluation is carried out in OMNeT++ discrete event simulation tool [128] for 10 runs and results are evaluated with 95% confidence level. IEEE 802.11g wireless standard is employed in infrastructure mode of operation. Table 4.3 summarizes the parameters used to setup the simulation.

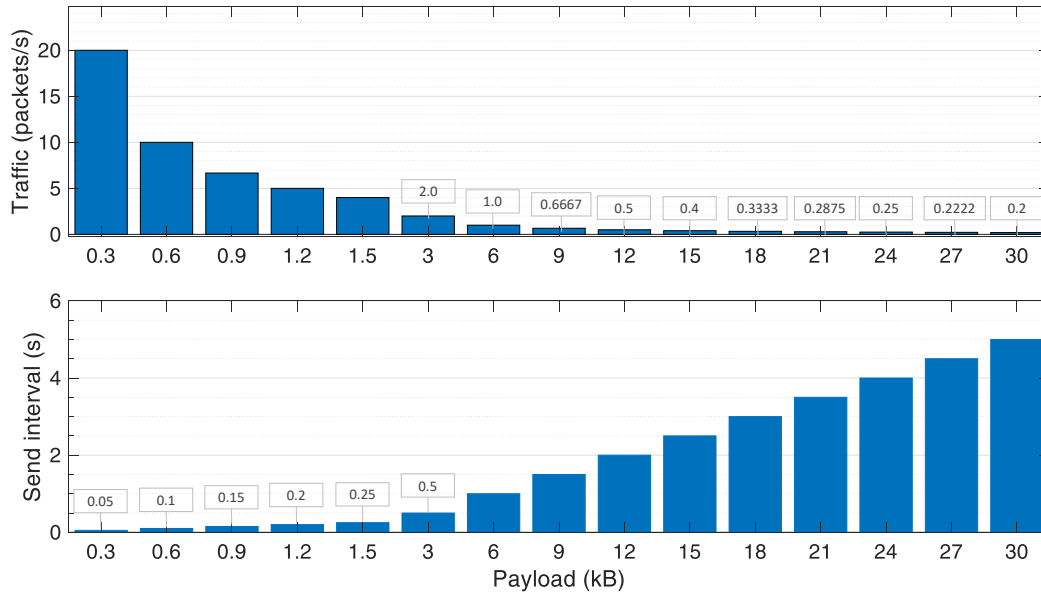


Figure 4.9: Chosen packet sizes for the evaluation with their corresponding traffic load and sending interval plots

Table 4.3: Parameters for traffic model simulation

Parameter	Value
Number of geophones	100
Operating Frequency	2.4 GHz
Recording Period T_{rp}	5 s
Simulation Time	15 s
WLAN MTU	1500 B
Physical Environment	Flat ground
Propagation Model	Free space path loss
Background Noise	Isotropic scalar
Node Max. Transmit Power	20 dBm
Bandwidth	20 MHz
Traffic Type	Periodic (UDP based)
PHY Bit Rate	54 Mbit s ⁻¹
Packet retransmission limit	7
Beacon Interval	100 ms
SIFS	10 μ s
slotTime	20 μ s
DIFS	50 μ s

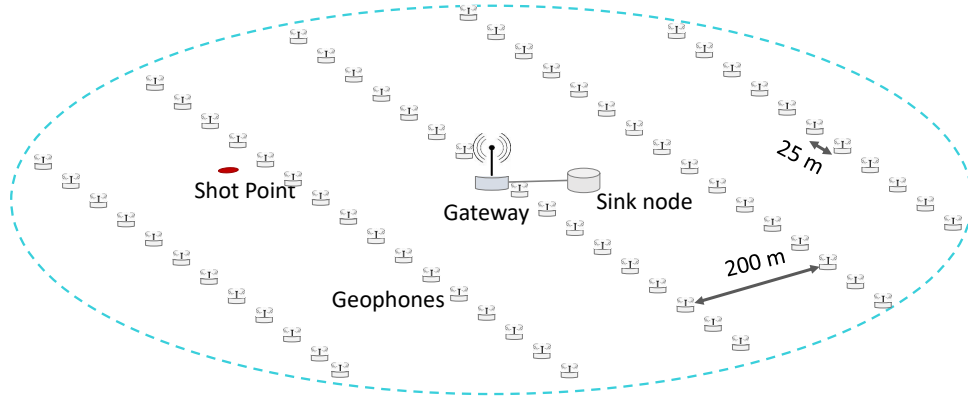


Figure 4.10: Parameter studies network scenario setup in accordance with infrastructure-based IEEE 802.11g standard

4.2.1 Key Performance Indicators (KPIs)

Various metrics are used to measure the network performance which includes [8]:

Throughput (Γ)

Is the amount of data successfully received at the sink node from geophones over a given period of time T . For P number of packets received at the sink, each of size K bit, the throughput can be expressed as given in Equation 4.44.

$$\Gamma = \frac{PK}{T} \text{ bit s}^{-1} \quad (4.44)$$

where T is the total time required to transmit all data packets from geophones to the sink node. T can be computed as the difference between the timestamp when the last and first packets are received.

Average End-to-End Delay ($E2E$)

This metric measures the average time it takes to transmit a data packet from all geophones in the network to the sink or gateway node. This comprises

of the transmission, propagation, queuing, backoff and processing time. It is expressed as given in Equation 4.45.

$$E2E = \frac{1}{K} \sum_{i=1}^K (T_i^{rx} - T_i^{tx}) \quad (4.45)$$

where T_i^{tx} is the instant the i th packet is generated and sent out by a geophone, T_i^{rx} is the time the i th packet is received at the sink node, and K is the total number of packets received at the sink node from all geophones.

Packet Loss Due to Retransmission Failure Ratio (Pl_r)

This metric measures the amount of dropped packets by a geophone at the link layer due to failed retransmission. This occurs as a result of exceeding the retransmission attempt limit due to multiple collisions. It is expressed as given in Equation 4.46.

$$Pl_r = \frac{\sum_{j=1}^N p_{d_j}}{\sum_{j=1}^N p_{u_j}} \quad (4.46)$$

where p_{d_j} is the number of packets dropped by the j^{th} geophone due to retransmission failure, p_{u_j} is the total number of packets sent from upper layer to the link layer of the j^{th} geophone, and N is the total number of geophones.

Retransmission Ratio (R_r)

Authors in [154] (RFC 6551 document) define the number of expected transmissions a node needs to make in order to successfully transmit a packet at a given destination as:

$$ETX = \frac{1}{(D_f D_r)} \quad (4.47)$$

where D_f is the probability that a packet is received by the neighbor and D_r the probability that an acknowledgment packet is successfully received.

However, the metric retransmission ratio (R_r) in this thesis is defined as the ratio of number of packets retransmitted per geophone (p_r) as a result of failure to reach the destination during their initial transmission to the total

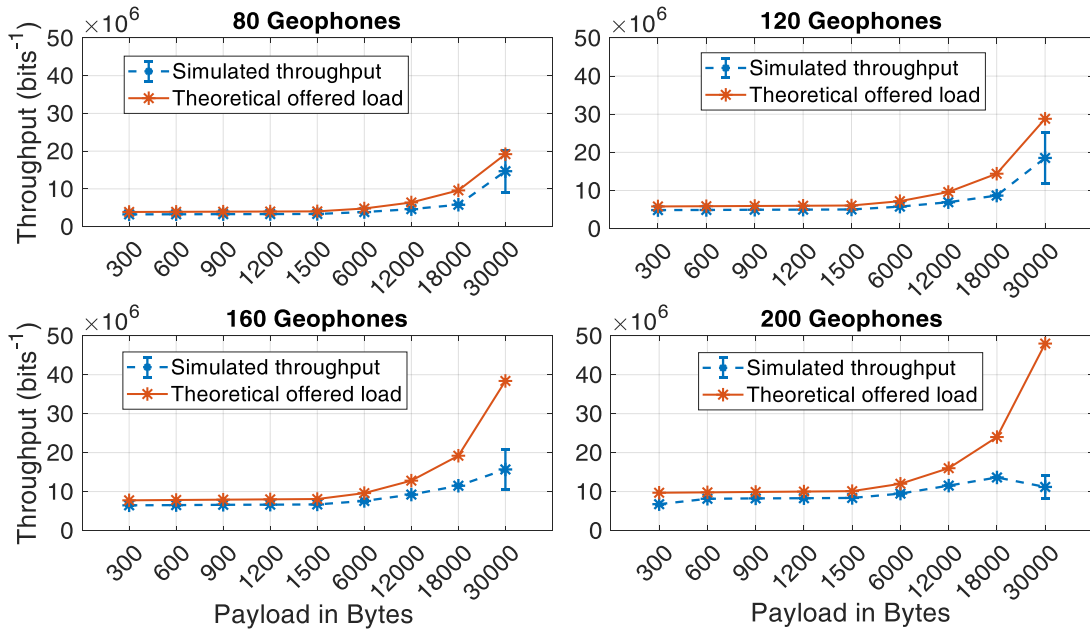


Figure 4.11: Throughput vs offered load for different payload sizes

number of successfully transmitted packets (p_s) by the geophones to the sink or gateway node during both initial transmission and retransmission attempt. This metric shows the percentage retransmission of packets in the network.

$$R_r = \frac{\sum_{j=1}^N p_{r_j}}{\sum_{j=1}^N p_{s_j}} \quad (4.48)$$

4.2.2 Results

Figure 4.11 shows the relationship between simulated throughput and theoretical offered load to the network computed using Equation 3.5 as a function of the payload size. The offered load increases with increase in network size. The throughput closely follows the theoretical offered load up to 15 kB, beyond which it starts to deviate. This is because the payload size exceeds the WLAN maximum transmission unit (MTU), mostly of size 1500 B resulting in fragmentation of packets at the network layer. Each of these fragmented packets has its header and contends for access to the channel, thereby resulting in increased overhead as well as congestion at the link layer. This subsequently leads to some of the packets been dropped as a result of exceeding the maximum number of retransmission specified in the IEEE 802.11 DCF as shown in Figure 4.12. With 30 kB payload size, the throughput is a bit higher. 30 kB

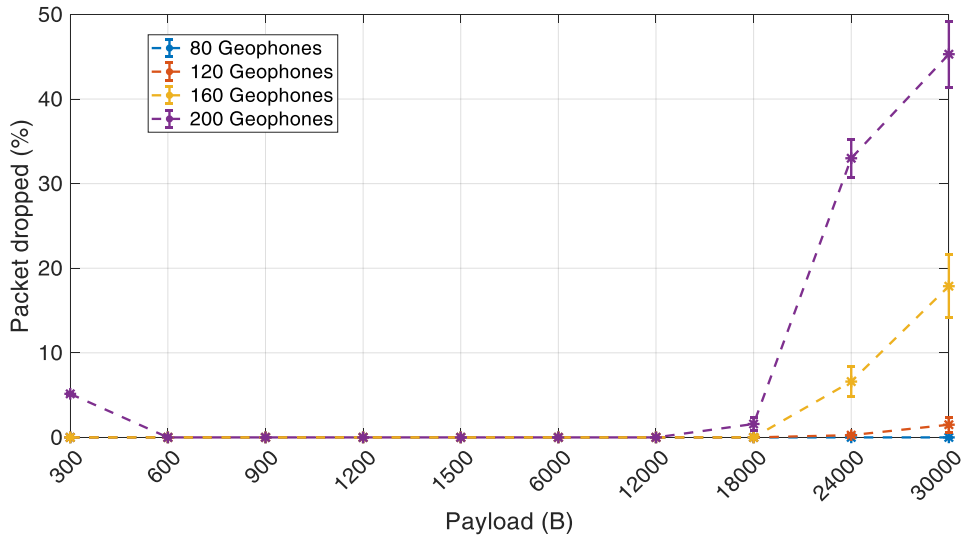


Figure 4.12: Average packets dropped as a result of retransmission limit been exceeded

represents the entire data acquired for the duration T_{rp} of 5 s placed in a single packet and sent once over the network, which also gets fragmented at the network layer. For lower payload sizes, the packet needs to be sent more the once in the network.

Figure 4.13 shows the Empirical Cumulative Distribution Function (ECDF) of packet end-to-end delay in the network captured from simulations at the sink node. The delay increases with increase in payload size. This is because of the proportional relationship between payload size and number of fragmented packets, which results in an increased congestion at the link layer as explained previously. More congestion leads to more collisions and subsequently more retransmission as shown in Figure 4.14. This consequently increases the duration a node spends during the CSMA/CA backoff procedure and hence the increased end-to-end delay. In addition, as expected, the delay also increases with increase in network size with packets reaching up to 400 ms for a network size with 80 geophones and 1.4 s with 160 geophones.

Furthermore, it can be noticed from Figure 4.14 that the percentage retransmission at the smallest payload size (300 B) is greater than that of 600, 900, and 1200B. This is because with smaller payload sizes larger number of packets are sent with shorter sending interval (T_{ds}) over the period (T_{rp}). This results in more link layer congestion and consequently more collisions and increased delay due to retransmissions. This effect can be seen in the plot with 200 geophones and 300 B payload size, where packets reach up to 4 s end-to-end

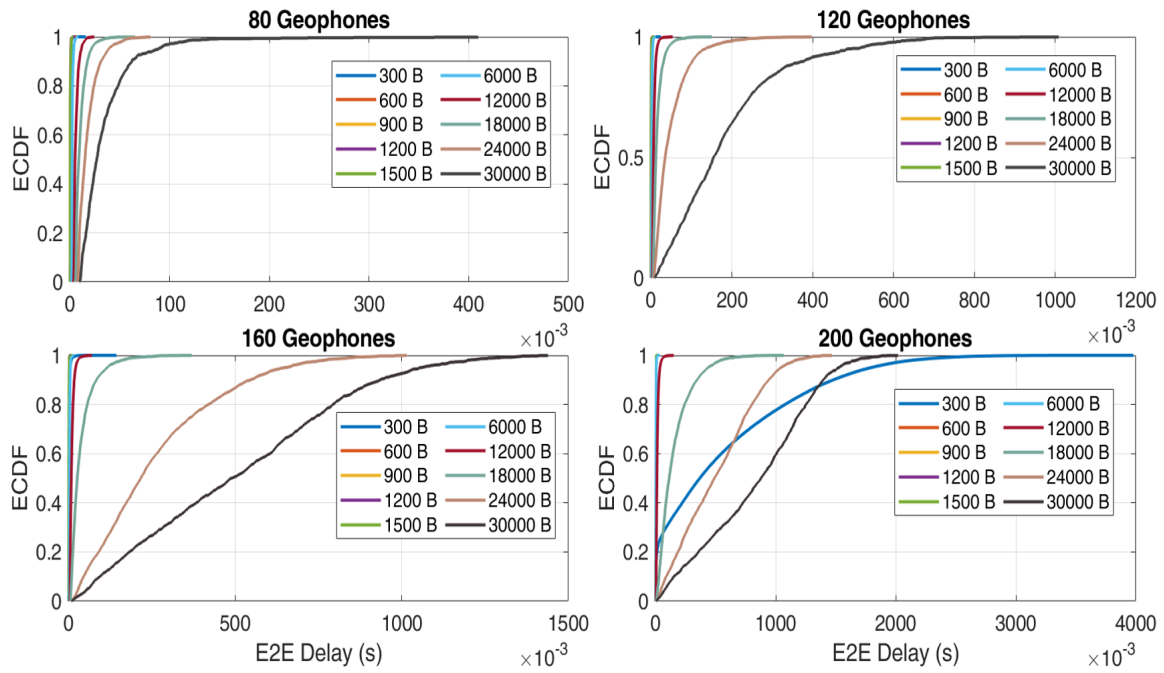


Figure 4.13: Probability distribution of packet end-to-end delay

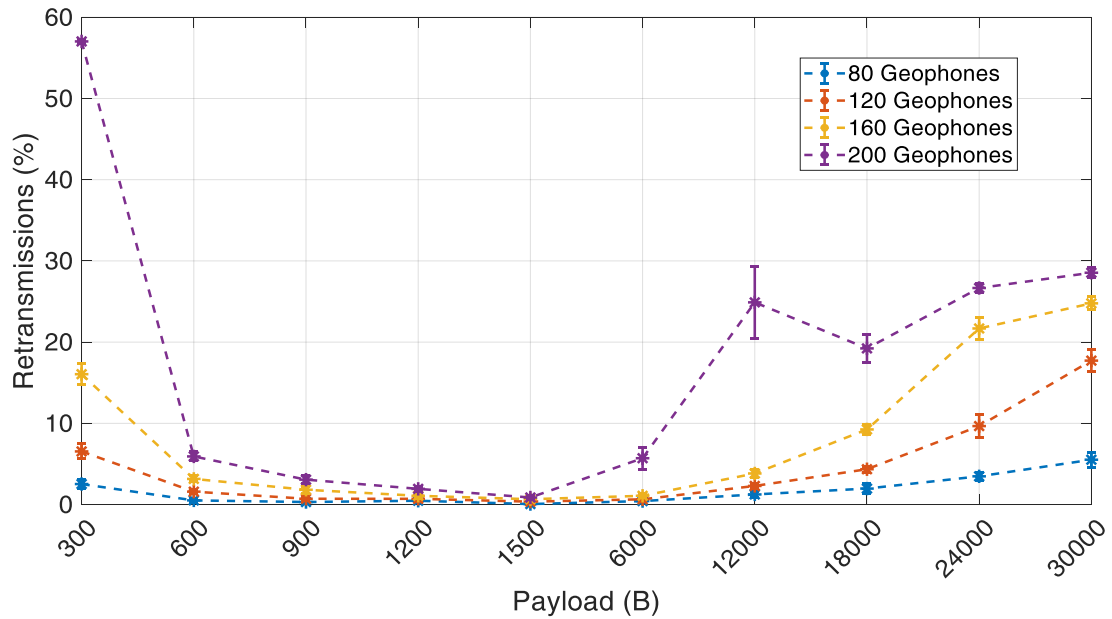


Figure 4.14: Average number of packets received with retransmissions at the gateway

delay. Thus, to achieve better reliability and required QoS in the proposed WSDA network, it is generally recommended to avoid lower payload sizes. Therefore, from the results obtained, a payload size of 1500 B is optimal as it has the least retransmissions, and also delay falls within the 1 s bound.

4.3 Conclusion

In this chapter, an analytical model for the IEEE 802.11 DCF is presented for WSDA networks. The model serves as a general tool for performance evaluation of single-hop WSDA networks, and for scalability as well as quick parameter studies. The model is an extension of the classical Bianchi model that accounts for unsaturated traffic conditions, backoff counter decrementing probability, packet drop probability, and the duration a node spends during the backoff procedure before decrementing its counter. The model is validated using simulation in OMNeT++ discrete event simulator for different data rates and varying network size. Results show that more number of geophones can be accommodated with higher data rate. However, the model assumption of binary queue and unsaturated traffic does not hold for larger network size with lower link data rate. In addition, to increase overall reliability in WSDA networks, it is shown that perfect synchronization of geophones and saturated traffic conditions should be avoided.

Furthermore, an evaluation of the proposed RPA traffic model for seismic applications is presented. The evaluation is carried out in OMNeT++ discrete event simulator for different seismic data payload sizes and varying network size. Results show that the required QoS for WSDA networks can be achieved with the optimal payload and subnetwork size configurations.

5 RPL for WSDA Networks

5.1 Introduction

Following the discussion on routing protocols for WSDA and the adoption of IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) in Section 2.6, this chapter presents a discussion on routing as applied in the proposed WSDA architecture. An elaborate overview of RPL and how it is applied to the proposed WSDA logical topology is presented. In addition, an evaluation of the proposed routing protocol (RPL), compared to the most prominent ad hoc routing protocols (OLSR and AODV) as introduced in Section 2.6.2 is presented. Furthermore, the chapter presents a geophone hop count distribution model based on RPL with respect to scenario 2 presented in Section 3.5. The model serves as a tool to determine the expected network performance and coverage as well as perform other parameter optimization at the survey planning stage by estimating the hop count of geophones in the network given a certain transmit power level.

5.2 RPL Overview for WSDA Networks

RPL is an IPv6 distance vector routing protocol designed for Low Power and Lossy Networks (LLNs). It is mainly employed in networks that are collection-based, where nodes periodically send data to a central collection point. RPL supports Multi-Point-to-Point (MP2P), Point-to-Multi-Point (P2MP), and Point-to-Point (P2P) traffic flows. It employs hierarchical topology as it compels nodes in the network to self-organize based on the concept of parent and child [155].

In LLNss, routers are constrained in terms of energy or battery, processing power, and memory. Similarly, their interconnects are attributed to low data rates, high loss, and instability [120]. RPL uses the concept of Destination Oriented Directed Acyclic Graph (DODAG) to construct the network topology in such a way that no cycles are present in all the graph edges orientation. The network graph is built using the concept of Objective Function (OF) that describes how routing metrics and constraints are computed and taken into account during the process of constructing the network topology. This allows for a network to be optimized for different deployments, applications, and scenarios. The protocol detects and avoids routing loops by computing a node rank, which defines the nodes particular position with respect to the DODAG root node relative to other nodes in the network. RPL uses the trickle algorithm to optimize the dissemination of control information over the network topology. This permits nodes running RPL to operate mostly *autonomously*, enabling minimal configuration in the nodes [120].

With regards to expectations of link layer type, RPL does not rely on a particular link layer technology. It is designed to operate over variety of link layers [120]. This flexibility makes it suitable for WSDA networks, especially considering scalability and data rate requirements as discussed in Chapter 1.

5.2.1 Control Messages

For information exchange and topology control, RPL defines four types of control messages [120] which include:

- i). DODAG Information Object (DIO): is the main control message that originates from a DODAG root node to establish a new Directed Acyclic Graph (DAG). DIO is transmitted through the DODAG structure in a multicast manner. It contains routing information such as the RPL instance, node rank, version number, DODAG ID etc. DIO allows for a node to detect configuration parameters, discover the RPL instance, choose a parent set from the DODAG and maintain the DODAG.
- ii). Destination Advertisement Object (DAO): is an optional control message sent by an RPL node in unicast mode to establish downward route for

applications requiring P2MP or P2P traffic flow. It is used to disseminate reverse route information along the upward path, registering the nodes visited along that path. A complete path between the node and DODAG root is set up after passing a DAO message via the path from the node to the DODAG root. It contains information fields such as DAO sequence, DODAG ID, RPL Instance ID etc.

- iii). DODAG Information Solicitation (DIS): enables an RPL node to inquire its neighborhood for nearby DODAGs. In other words, it is used to seek DIO messages from an RPL node. Its service is similar to that of router solicitation in IPv6 neighbor discovery.
- iv). DAO-ACK: is used to acknowledge the reception of a DAO message by its destination in a unicast mode.

5.2.2 RPL Topology construction

Generally, RPL network constitute of three types of nodes; the root, parent, and the leaf node [156]. The root represents the sink node that serves as a data collection point. It can also be a gateway that provides connection to another network. DIO control messages originate from this node. The parent node acts as a router and may advertise topology information to their neighbors. The leaf nodes are child nodes that have the ability to join a DODAG and must advertise a DAG rank of infinity [120].

A DODAG is constructed based on the Neighbor Discovery process. RPL provides upwards routes toward the DODAG root, and an optional downward route away from the DODAG route, thereby forming a DODAG optimized according to an OF.

Upward Routes Construction

Upward routes are normally employed for applications that require MP2P traffic flow. It enables routes to be built from the DODAG root to child nodes in downward direction. The root node sends out a DIO message, announcing important topology information like RPL Instance, DODAG ID, OF, rank

information etc. The OF determines how nodes chose and optimize route formation within a RPL Instance using defined metrics and constraints, and also how nodes select parents. The rank of a node is a scalar value that monotonically decreases towards the DODAG root, representing the position of that node within a DODAG version. It is used for detecting and avoiding routing loops [155].

An RPL node that receives a DIO message can either be willing to join the DODAG or an already joined node. For a node willing to join the DODAG, upon receiving the DIO message, it adds the address of the DIO sender to its parent list, then computes its rank in such a way that it is greater than that of its parents from the list. This computation is done according to the OF specified. The node then forwards the DIO message containing the updated rank information to its neighbor sets. Finally, the node then selects the preferred parent from its parent list through which incoming traffic will be forwarded [156].

If a node has already joined a DODAG and receives another DIO message, it can either discard or process the DIO message received. In case of the latter, the node can process the DIO to either maintain its position in the current DODAG, or enhance its position by computing the past cost according to the OF defined via obtaining a lower rank in the DODAG. Once the DODAG construction is complete, each node would have a route through which incoming traffic can be routed via its preferred parent towards the DODAG root. The DODAG topology is maintained by the periodic transmission of DIO messages by each RPL node that is triggered using the *trickle timer* algorithm. The concept behind trickle timer is to optimize the control message transmission frequency by nodes as a result of variations in network conditions e.g., in the case of an inconsistent network management information reception [120]. Figure 5.1 illustrates the formation of an RPL network with three DODAGs under a single RPL instance.

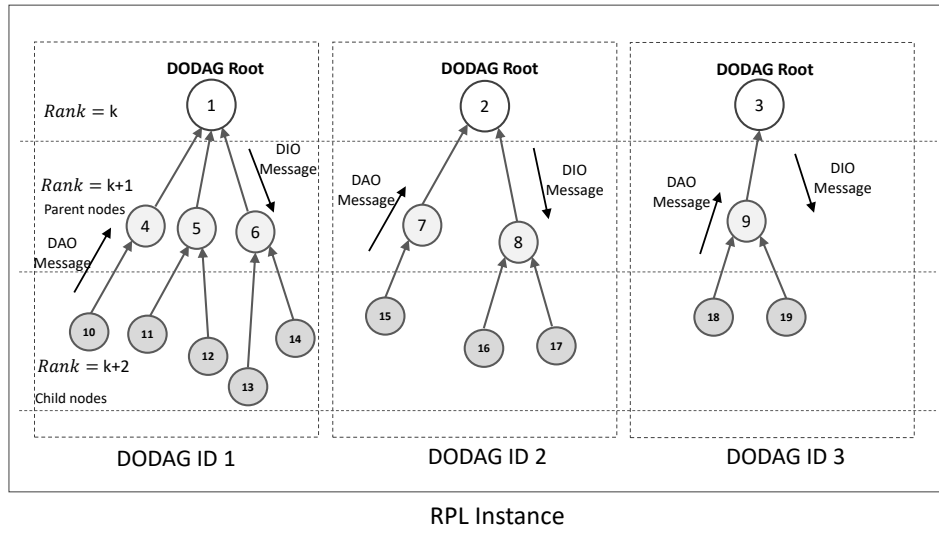


Figure 5.1: RPL network with three DODAGs within a single instance. The downward and upward pointing arrows in black show the direction of propagation of DIO and DAO messages respectively via the DAG.

In relation to the proposed WSDA network architecture, the RPL upward route is suitable for establishing routes between geophones and their associated gateway within any given subnetwork, to support MP2P traffic flow type.

Downward Routes Construction

Downward routes are mainly utilized by applications that employ P2MP or P2P traffic flow. DAO messages are used by RPL to construct and maintain downward routes. Each node send a DAO in unicast mode to determine the route information. Nodes visited along the upward route are recorded in the packet when traveling back to the DODAG root. Thus, a complete path is established between the RPL nodes and the root node. For maintaining downward routes in an RPL instance, two modes of operation are specified, *non-storing* and *storing* mode [120].

Non-storing mode: in this mode, DAO messages are not stored by intermediate parents of a node. Instead, the parents include their own addresses in the received DAO message to set up the reverse route, and then forward it to its own parent until it reaches the DODAG root node.

Storing mode: In this mode, unlike the Non-storing mode, DAO messages are not propagated to the DODAG root. It is sent by child nodes to all their selected parents which maintains additional routing table to setup downward routes. Each parent then store the DAO message received from its child before forwarding the new DAO to its parent.

In relation to the proposed WSDA architecture, downward routes will be suitable for monitoring geophones from the CCU. Furthermore, it can be used to communicate acquisition and quality control information from gateways or the CCU to geophones deployed in the field.

5.2.3 Trickle Algorithm

Trickle algorithm [157] is a mechanism used to dynamically adjust the dissemination of information or message updates in a network to avoid unnecessary message transmission. With trickle algorithm, each node in a network is associated with a timer referred to as *trickle timer* which controls how often a node sends updates or information to its neighbors. When a router receives an update message, it checks its local timer associated with the received message and compares with its own information. If its the same, it resets its trickle timer. However, if it contains new information, an update is immediately sent to its neighbors and then resets its trickle timer.

In relation to RPL [120], trickle algorithm uses two constants i.e., minimum interval duration I_{min} and a redundancy constant k to define how often a node will send DIO messages. If the same DIO message is received multiple times by a node within a short period of time usually less than I_{min} , it enters an *increase phase* during which the trickle timer is reset and the DIO message is disseminated to its neighbors. If the same DIO message is continuously received by the node during the increase phase, the DIO message send interval is doubled to reduce overhead. However, if no DIO message is received by the node for a duration more than I_{min} , it enters a *decrease phase* and the DIO message send interval is halved. If the same DIO message is received by the node during the decrease phase, the timer remains the same to maintain network stability by avoiding unnecessary transmissions.

5.2.4 RPL Routing Metrics

RPL provides support for constraint-based routing applied to both link and nodes. The metrics used to compute the constrained path are specified by an OF. Nodes select their preferred parents based on the metrics and constraints advertised in a DIO message [120].

The working group in [154] has defined a set of routing metrics for link as well as nodes to be used by RPL. However some of these metrics defined are optional from the implementation point of view of RPL. As such, the discussion will be limited to only three metric computations as specified in the document for RPL metric. These includes the *expected number of transmission (ETX)*, *energy consumption*, and *hop count* metrics.

Expected Number of Transmission (ETX)

ETX is a one-hop link quality estimation metric between two neighboring nodes that is bi-directional [158]. It approximates the number of transmissions a data packet experience before successfully reaching the root or destination node. A node may have an ETX value of 1 if its one hop away from the root with minimal interference and strong signal strength. A higher ETX value is expected for nodes with less reliable link to the root node. Packet reception rate metric, calculated at the receiver for each packet received window as expressed in Equation 5.1, can be used for ETX computation [156].

$$PRR = \frac{\text{No. of received packets}}{\text{Number of sent packets}} \quad (5.1)$$

However, according to the working group in [154], the ETX can be calculated using the relation expressed in Equation 5.2.

$$ETX = \frac{1}{P_r A_r} \quad (5.2)$$

where P_r is the measured probability that a packet is received by the neighbor and A_r is the measured probability that the acknowledgment packet is successfully received.

Energy Consumption

The energy metric aims at providing an option for RPL nodes to avoid selecting a parent or forwarding node with low residual energy. For this reason, the routing protocol may compute a longer path for some data traffic in an effort to maximize the network life time. Depending on how power is supplied to a node, RPL considers three possible states for a node power source which includes; *powered, running on batteries, or scavenging for energy*. For a powered node or device, RPL considers it to be the DODAG root node or some special collector node. Such nodes are more preferable during parent selection as they report maximum Energy Estimation (EE) value [156]. For a node running on batteries, the EE value has to be computed using the expression shown in Equation 5.3.

$$EE = \frac{P_{now}}{P_{max}}.100 \quad (5.3)$$

where P_{now} is the current remaining node energy and P_{max} is the starting energy of the node reported at the initialization phase. If the node scavenge for energy from an outside sources, the EE value is reported as a quantity computed from dividing the amount of energy acquired by the node with the energy it consumed.

Hop Count

The hop count metric shows the number of traversed nodes along a path to the destination. The DAG root may indicate the maximum number of hops that can be traversed along a path, when hop count is used as a constraint. No other node can join this path when the defined maximum number of hops is reached. Each node visited may just simply increments its hop count field. The hop count field value must be set to 1 by the first node along the path [154].

As regards to utilizing these three metrics in the proposed architecture, the idea is to investigate for bottlenecks and challenges when the default RPL metrics are employed. A thorough discussion on RPL and how its topology is interpreted into the proposed topology in Figure 3.1 is presented in the subsequent sections.

5.3 RPL Topology as Applied to the Proposed WSDA Architecture

Recall that the proposed architecture previously discussed in Section 3.2 involves dividing the entire survey area into subnetworks, with each subnetwork having a gateway that serves as a data aggregator and relay node to the CCU. In relation to the RPL topology, each subnetwork is considered as a DODAG at the lower or geophone domain of the proposed architecture. These subnetworks are configured to be running within the same RPL instance, with the same objective function but different DODAG IDs. This is because, subnetworks are deployed based on frequency reuse concept, meaning that no two adjacent DODAGs are operating on the same frequency channel. This will significantly reduce the reception of multiple control messages by reachable nodes from neighboring DODAGs.

Furthermore, the gateways in each subnetwork represent the DODAG root, and the member geophones represent either the parent or child nodes, forming a tree-like topology. Depending on the proximity to the gateway, geophones within the DODAG can reach the gateway in one, two, three etc., hops. This configuration is determined from the transmit power set for the nodes in the network as will be discussed further in chapter 6. Therefore with respect to the node rank, gateways will always have a rank equals to 1, and geophones will have either rank 2, 3, 4 etc. Gateways will initiate the DIO transmission, advertising important topology information and its operating frequency channel. Nodes configured on that channel will received and process the DIO message to join the DODAG, thereby constructing the upward route for MP2P seismic data traffic flow.

For the upper/gateway domain of the proposed architecture, gateways can utilize the other wireless interface to establish connectivity with the gateway using a separate, long range wireless technology (e.g., IEEE 802.11 af). RPL can also be employed to enable routing at this level.

Figure 5.2 depicts how the logical connection of the proposed architecture is interpreted into RPL topology.

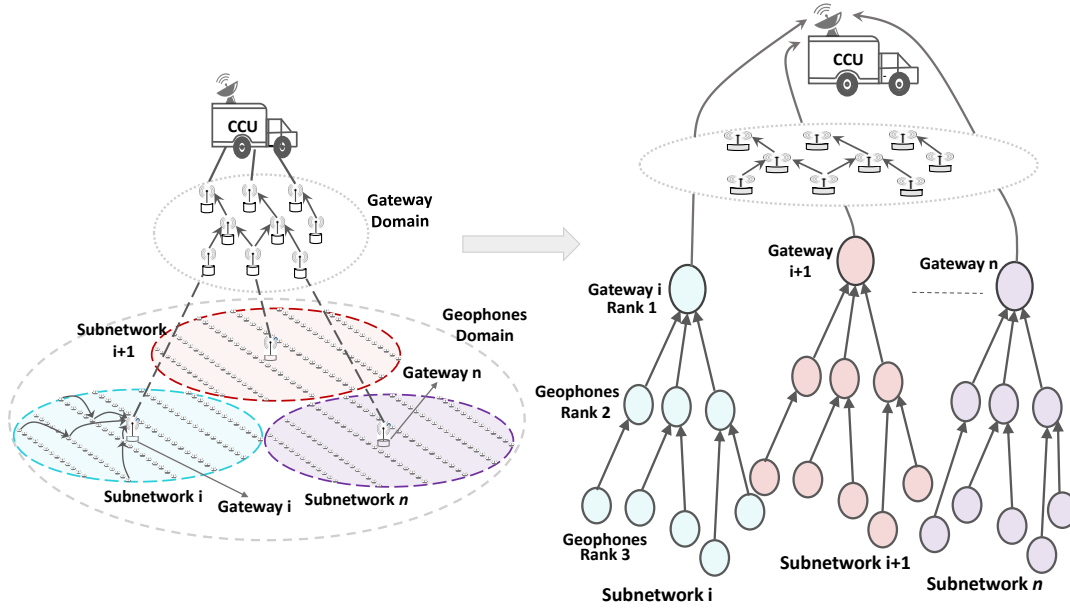


Figure 5.2: Logical connection of the proposed architecture as interpreted in RPL topology

In the following subsection, a preliminary evaluation of RPL as compared to some major ad hoc routing protocols (OLSR and AODV) is presented.

5.4 Evaluation of RPL in WSDA Subnetwork

Infrastructure-based WSDA architectures have been proposed in literature, whereby a group of geophones transmit their sensed data directly to a wireless gateway (GW) in star topology. Considering the large scale deployment of geophones in WSDA networks (tens of thousands), proper communication coverage will entail significant number of infrastructures, consequently leading to increased survey cost. Thus, the need for self-organization and independence between geophones is conspicuous, with the potential of adopting a multi-hop ad-hoc communication in WSDA, to support MP2P seismic data traffic flow. Geophones can communicate with other geophones within its communication range in a distributed manner without the need for central coordination or fixed infrastructure. Throughout the rest of the thesis, ad-hoc refers to infrastructure-less communication. This can prove to be more suitable in terms of data rate, as the furthest away nodes from the gateway can be transmitting data at a very low rate compared to nodes closer to the gateway.

Forwarding data to such nodes can introduce some form of load balancing in the network.

Nevertheless, this raises the question of which routing protocol should be employed in these networks as nodes need to facilitate and calculate the best routes to the destination in the network. This question has been addressed in Section 2.6 of the thesis, proposing RPL as the most suitable routing protocol for WSDA networks. An initial scalability investigation and evaluation on the performance of RPL, benchmarked against some prominent routing protocols used in multi-hop ad-hoc communication is carried out in the following subsections.

As discussed in Section 2.6, various routing protocols for wireless ad-hoc networks have been classified based on the fundamental routing strategy used in initiating route discovery into reactive and proactive routing protocols. In proactive protocols, route is established and maintained in advance by the periodic exchange of control messages. In reactive protocols, route establishment is triggered only on demand from source nodes. A widely used proactive protocol i.e., Optimized Link State Routing (OLSR), as well as a prominent reactive protocol i.e., AODV are considered.

OLSR is an extension of the classical link state routing that uses the concept of Multi-Point Relays (MPR) to minimize the number of control messages in the network as compared to the classical flooding mechanism. MPRs are nodes selected to forward broadcast messages during the flooding process, and are the only nodes that generate routing information in the network. MPR selection, link sensing, and neighborhood detection is done by a node via periodic exchange of hello messages [159].

AODV is a distance vector routing protocol in which routes are created on-demand. A source node wanting to transmit in the network broadcasts a route request message (RREQ). If the RREQ message reaches the destination or finds an intermediate node with a route to the destination, a route is found and the destination sends a route reply message back to the source in a unicast mode. In case of link breakages, a route error (RERR) message is used to alert other nodes that the link is no longer reachable. Destination sequence numbers are used for each route entry to avoid loops and problems related to classical distance vector protocols such as count to infinity problem [160].

5.4.1 Simulation model

With reference to the architecture proposed in Figure 3.1, a single subnetwork is considered for this evaluation. Geophones are deployed on four receiver lines placed at an interval of 200 m each, and an inter-geophone interval of 25 m. The number of geophones in the subnetwork is varied from 8 to 200 maximum. A single shot is assumed with geophone recording period of 5 s. Figure 5.3 depicts the scenario under which the simulation is carried out in OMNeT++ simulator. IEEE 802.11 in ad hoc mode of operation is configured as the link layer technology with 11 Mbit s^{-1} as the recommended data rate in ad hoc mode of operation [161]. However, as 11 Mbit s^{-1} might insufficient to address the required network capacity, especially for larger network size over several hops, 54 Mbit s^{-1} data rate is also considered in the evaluation. The simulation is repeated for 10 runs, and the 95% confidence level is computed.

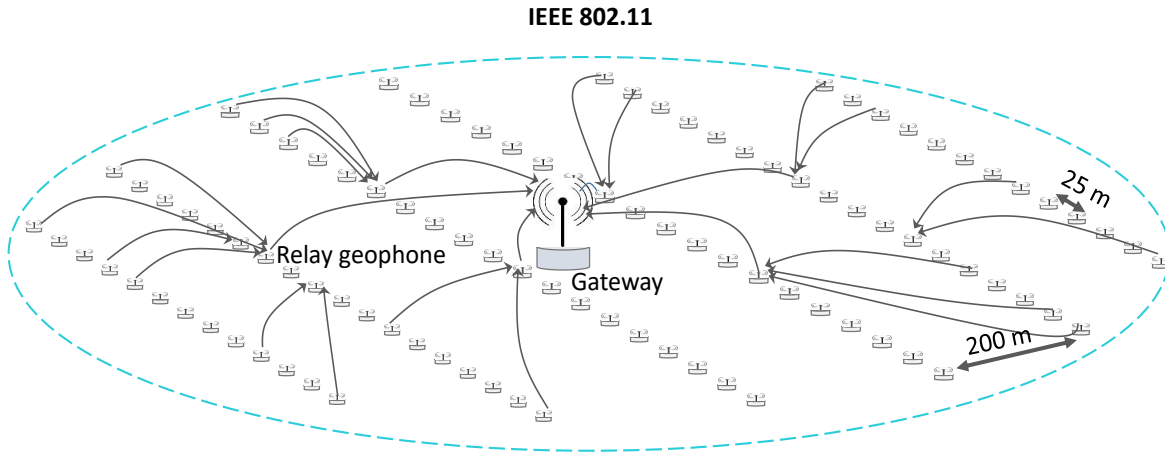


Figure 5.3: Multi-hop ad-hoc communication

5.4.2 Traffic generation

Geophones generate traffic according to the model described in Section 3.3. With the assumption of a 24-bit ADC and seismic data sampling interval of

0.5 ms, data is generated at a rate of 48 kbit s^{-1} . Depending on the number of hops a packet has to travel to reach the gateway from a geophone, a relaying geophone could generate data at twice this rate or more. Since the number of geophones in the considered subnetwork is varied from 8 to 200 maximum, a capacity of around 9.6 Mbit s^{-1} of the network is required if all geophones are assumed to reach the gateway in single-hop. This value doubles or triples with 2 or 3 hops respectively. In this evaluation, a packet of size 1500 B corresponding to a sample accumulation time of $T_{ds} = 250 \text{ ms}$ is considered.

5.4.3 Result analysis

From Figure 5.4, it can be noticed that, for 11 Mbit s^{-1} , a PDR of 100% can be achieved with only up to 20 geophones, regardless of the protocol used. This is because the traffic generated in the network increases as the number of geophones increase, thereby resulting in the offered load approaching the maximum capacity the network can handle, leading to packet loss. This effect has been discussed in the analytical modeling presented in Section 4.1.6, only that in this case packets may need to traverse multiple hops before reaching the gateway. In addition, protocol overheads further takes up the capacity of the network. Furthermore, as collision probability increases with increase in number of nodes, packets are also dropped at the MAC layer due to retransmission limit been exceeded in all the three protocols.

However, with 54 Mbit s^{-1} , RPL shows better PDR performance compared to OLSR and AODV. The PDR of all protocols follows closely till the network size of 80. Beyond this, it can be noticed that the PDR for AODV significantly dropped to almost 50%. This effect could be described from our traffic model point of view. In this model, geophones initiate packet transmission at almost the same time. This is a bottleneck for AODV as route discovery process is initiated whenever a node wants to transmit a packet, thereby leading to route request (RREQ) packets collisions. Subsequently, more packets are dropped due to route discovery failure. For larger network sizes beyond 100, RPL shows better PDR performance compared to OLSR as it uses the trickle timer algorithm to dynamically adjust the rate of sending control packets.

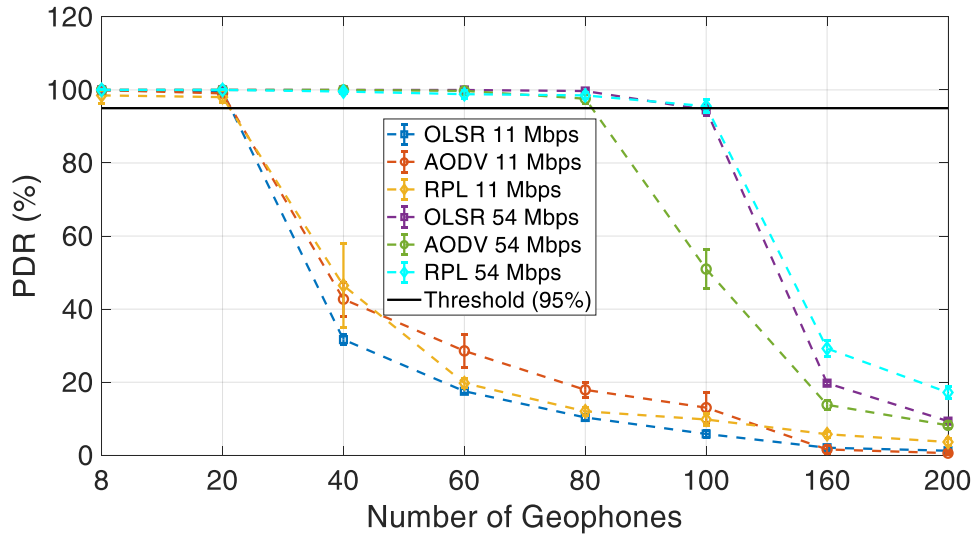


Figure 5.4: Packet delivery ratio for different number of geophones

Figure 5.5 shows the average packet end-to-end delay in the network. The delay increases with increase in network size and decreases with higher data rate as expected. A lower data rate implies longer packet transmission time. Moreover, with increase in network size, a packet might have to travel via two or three hops before it reach the sink. This means at least double or triple the transmission time is required, thereby leading to higher overall delay. In addition, packets will take longer time in the queue due to the CSMA/CA back-off algorithm, especially in AODV protocol.

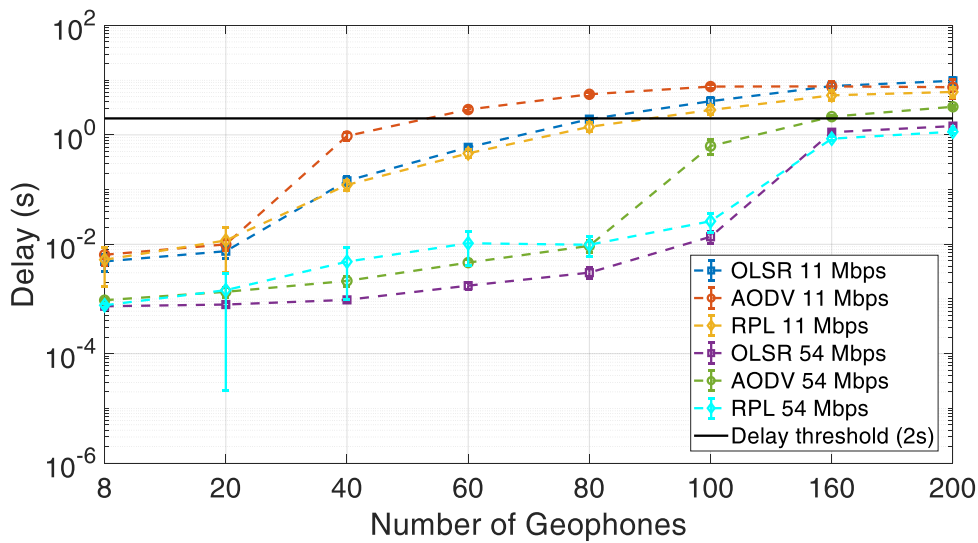


Figure 5.5: Average packet end-to-end delay for different number of geophones

Therefore, it can be deduced from these results that, the performance of these protocols evidently depends on factors such as underlying routing strategy of the protocol and data rate. Considering our proposed traffic model, employing AODV is clearly not a good idea as routes are established on demand. However, results from RPL and OLSR are more promising as routes are immediately available when transmission begins, thus offering low delay during route establishment. Nevertheless, a major drawback in OLSR is higher bandwidth requirements, as amount of control overhead is proportional to the number of geophones in the network. In RPL however, trickle algorithm¹ is employed to optimize the dissemination of control and topology messages, thereby significantly minimizing overhead. Thus, these results obtained confirm the choice of RPL as the suitable enabling routing protocol for WSDA networks. The evaluation presented in this section has been published by the author of this thesis in [162].

5.5 Modeling Geophone Hop Count Distribution in Relation to RPL

Prior to the commencement of seismic data acquisition, it is crucial for surveyors to evaluate some expected network performance for better decision making at the planning stage. This is done to adjust some of the predefined parameters according to the survey requirements before the actual deployment of devices in the field. With the proposed multi-hop ad hoc based network architecture for WSDA, modeling the hop count distribution is useful in evaluating and optimizing for some key WSDA challenges outlined in Chapter 1. For example knowing the expected hop count in advance will help in optimizing geophone transmit power settings to ensure better connectivity and coverage while minimizing interference and power consumption etc. In addition, it can be useful in optimizing for reliability through determining network configurations that may lead to regions with high hop count indicating possible bottlenecks, subsequently leading to increased interference, latency, and channel contention.

¹see section 5.2.3 for more information

Thus, in this section, a model that serves as a tool for estimating the hop count distribution of geophones with respect to the network architecture discussed in Chapter 3 is presented. The model is based on the configuration in scenario 2 of Section 3.5 that estimates the number of hops required by geophones to reach a gateway in the subnetwork. The model takes into account the following inputs or factors:

- i). Radio propagation model
- ii). Operating frequency
- iii). Device antenna specifications
- iv). Device transmit power and minimum received power threshold

As most seismic surveys are carried out in remote areas, it is assumed that the radio signals experience less obstacles when propagating from a transmitter to receiver. As such, multipath fading, shadowing and doppler effects are also assumed to be dominated by ground reflection of signals. In addition, geophones antennas are considered to be near ground with height of at most 1 m, which will result in the probability of having a ground reflected components in the received signal.

Thus, ***Two-Ray Ground Reflection*** model is employed as the propagation model for signal from geophones, which considers the line-of-sight and reflected component of the transmitted signal in modeling the path loss [44]. The two ray model assumes that the transmitting and receiving antennas are omnidirectional, as well as an ideal ground reflection of the propagating signal over flat earth surfaces. Equation (5.4) gives an expression for the power of signal received by a node (P_r) located at a distance d from the transmitter.

$$P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \quad (5.4)$$

where P_t is the node transmit power, G_t and G_r represents the transmitter and receiver antenna gain respectively, h_r and h_t denotes the heights of the receiving and transmitting antennas respectively, and L is the system loss factor independent of the propagation or Free-Space Path Loss (FSPL) as expressed in Equation 5.5.

$$L = \left(\frac{4\pi df}{c} \right)^2 \quad (5.5)$$

where d is the distance between transmitter and receiver, f is the operating frequency, and c represents the speed of light.

To model the geophone hop count distribution with respect to the gateway, the effective communication range of the gateway (d_{GW}) is first determined from the two ray ground reflection model using Equation 5.6.

$$d_{GW} = \left(\frac{P_t G_t G_r h_t^2 h_r^2}{P_r L} \right)^{1/4} \quad (5.6)$$

The distance of each geophone from the gateway in the subnetwork d_i is then determined using Equation 5.7.

$$d_i = \sqrt{(x_i - x_{GW})^2 + (y_i - y_{GW})^2} \quad \forall \quad 1 \leq i \leq N \quad (5.7)$$

x_i and y_i are the Cartesian coordinates of the i^{th} geophone which are easily determined giving the static grid nature of the network with fixed inter-geophone and receiver line distances. x_{GW} and y_{GW} are the gateway coordinates. Figure 5.6 illustrates the hop count distribution model.

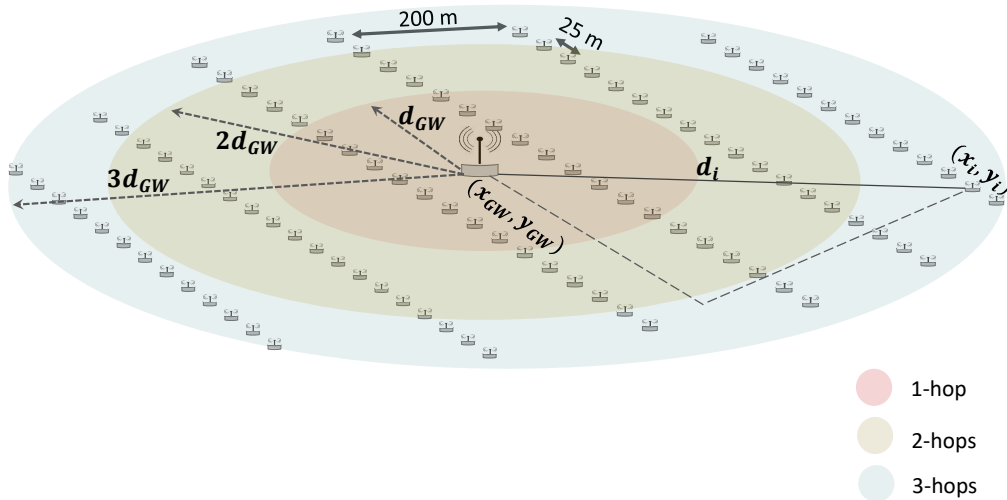


Figure 5.6: Hop count distribution model scenario

The distance d_i of the i^{th} geophone to the gateway is then compared with the gateway's effective communication range d_{GW} . If the d_i is less than or equals to d_{GW} , this means that the i^{th} geophone is within the communication range of the gateway and has a hop count of 1. d_{GW} is then doubled to $2d_{GW}$ indicating twice the communication range of the gateway and compared against d_i . All geophones that fall in the region between the two concentric circles of radius d_{GW} and $2d_{GW}$ as illustrated in Figure 5.6 will have a hop count of 2.

The same procedure is repeated with $3d_{GW}$, $4d_{GW}$ etc., and the corresponding hop count of each geophone in the network is recorded as expressed in Equation (5.8). A distribution can then be obtained based on the recorded hop count values of geophones in the network.

$$H_i = \begin{cases} 1 & d_i \leq d_{GW} \\ 2 & d_{GW} < d_i \leq 2d_{GW} \\ 3 & 2d_{GW} < d_i \leq 3d_{GW} \\ 4 & 3d_{GW} < d_i \leq 4d_{GW} \\ \dots & \end{cases} \quad (5.8)$$

Model Validation

The model is validated using simulation in OMNeT++ discrete event simulator. Table 5.1 summarizes the parameters used for both the analytical model and simulations. The evaluation is carried out in the two most commonly used license-free bands (2.4 & 5 GHz). Following an optimization evaluation in simulations as presented in Chapter 6, a geophone transmit power level of 5 and 25 mW are used in the 2.4 & 5 GHz bands to maintain minimal level of interference while ensuring required network performance and coverage.

Figure 5.7 shows the analytical and simulated geophone hop count distribution in the 2.4 GHz band with a transmit power of 5 mW. The analytical model matches the simulation, with 66.7% of geophones having a hop count of 1, while the remaining 33.3% having 2.

Table 5.1: Analytical and Simulation Parameters

Parameter	Value
Subnetwork	1 (120 nodes)
Frequency band	2.4 & 5 GHz
Transmit power (P_t)	5 & 25mW
Bandwidth	20 MHz
Data rate	65 Mbit s ⁻¹
T_x, R_x antenna gain	2 dB
T_x, R_x antenna height	1 m
$P_{threshold}$	-85 dBm
RPL OF	Hop Count
Simulation time	30 s
Simulation runs	10
Physical environment	Flat ground
Propagation model	Two-ray ground reflection

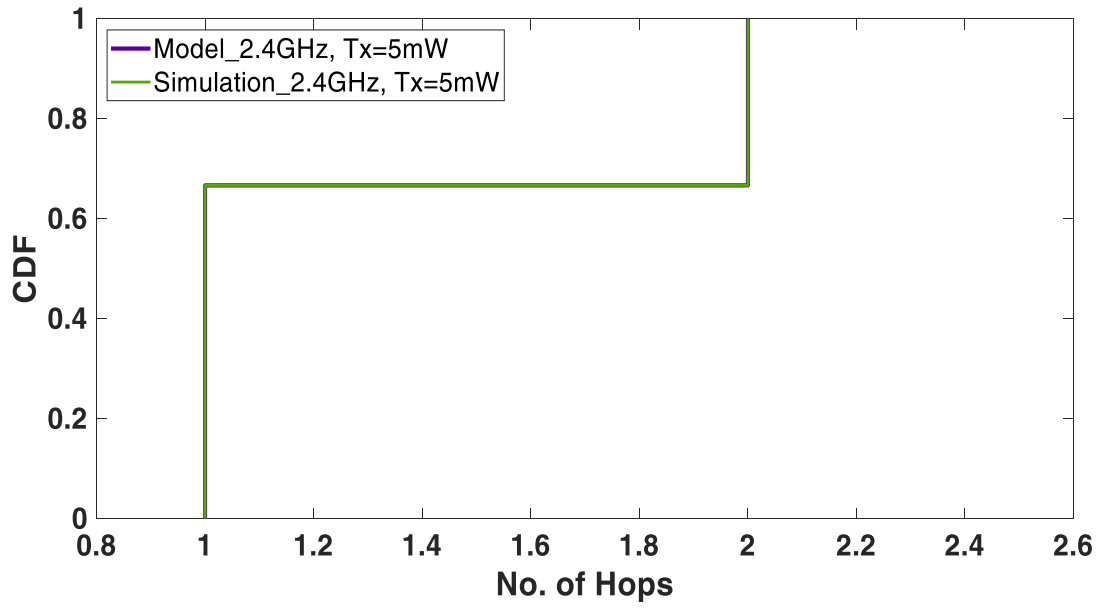


Figure 5.7: Hop count distribution in a subnetwork with Tx=5mW in the 2.4 GHz band

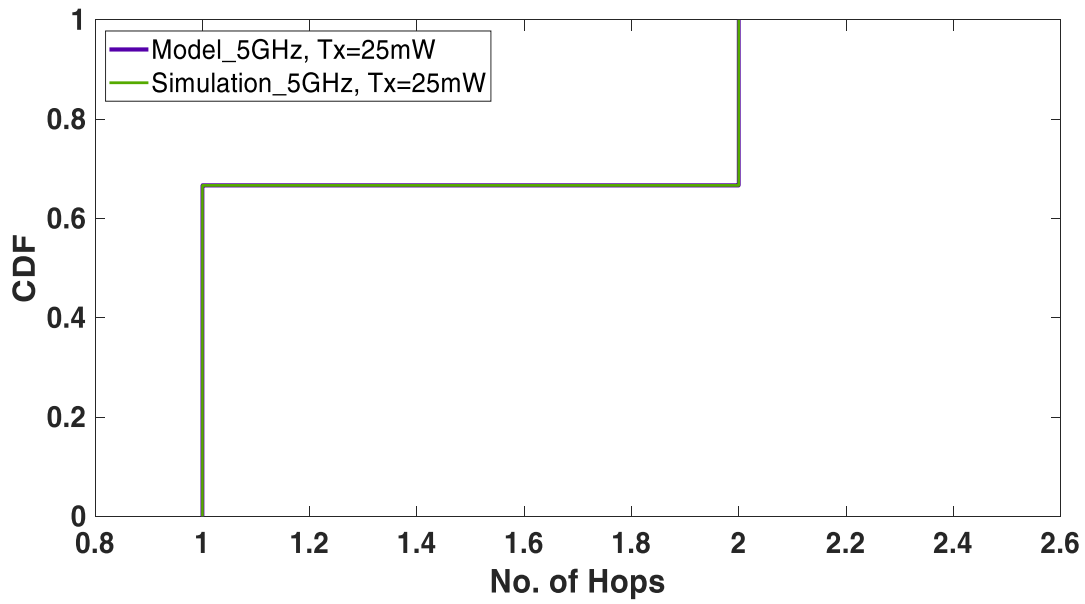


Figure 5.8: Hop count distribution in a subnetwork with Tx=25mW in the 5 GHz band

Figure 5.8 shows the analytical and simulated geophone hop count distribution in the 5 GHz band with a transmit power of 25 mW. The transmit power is adjusted to 25 mW in this case to achieve similar coverage as in the 2.4 GHz band. This is because of the 6.6 dB band gap loss between the two bands [163] that arises due to increased path loss at higher frequencies leading to reduced communication coverage. A more detailed discussion is given in Section 6.3. Similar to the 2.4 GHz case, the model matches the simulation, also with $\sim 66.7\%$ of geophones having a hop count of 1, while the remaining $\sim 33.3\%$ having 2.

5.6 Conclusion

In this chapter, a discussion and evaluation of RPL as the enabling routing protocol in the proposed WSDA network architecture is presented, with the goal of addressing the routing bottleneck and challenges outlined for WSDA networks. An elaborate overview of RPL protocol is presented in terms of topology, basic operation, control messages, and routing metrics employed. Moreover, discussions on how RPL topology interprets to the logical topology in the proposed WSDA architecture is presented. Furthermore, an evaluation of the performance of RPL is carried out using simulation, benchmarked

against two prominent ad hoc routing protocols (OLSR and AODV). Results confirm the choice of RPL as the suitable candidate for enabling routing in WSDA networks.

Based on the proposed WSDA architecture, a geophone hop count distribution model is proposed. The model is validated using simulations in OMNeT++ simulator. The model serves as a tool to determine the expected network performance and coverage at the survey planning stage by estimating the hop count of geophones in the network given a certain transmit power level.

6 WSDA Network Performance Evaluation

6.1 Introduction

Following the conclusions deduced from Chapter 4 and 5 with regards to the bottlenecks outlined for Wireless Seismic Data Acquisition (WSDA), this chapter aims at employing simulations to provide a proof of concept to the third research question described in Chapter 3. The evaluation is based on the proposed WSDA network architecture relative to *scenario 3* outlined in Section 3.6. The chapter investigates the feasibility and validity of the proposed architecture, wireless technology, and protocol put forward in this thesis with respect to addressing challenges and requirements outlined in Section 1.3. An evaluation of the network performance in the 2.4 and 5 GHz band is presented, with focus on investigating the effect of interference under different scenario configurations. Furthermore, geophone energy consumption analysis and modeling, as well as discussions on the results obtained and what it generally implies as regards to WSDA is presented.

6.2 Performance Metrics

Several metrics are used in this chapter for evaluating the performance of the proposed WSDA network architecture, which includes;

Packet Delivery Ratio (PDR)

This metric defines the ratio of the total number of data packets successfully received at the CCU (P_{rx}) to the total number of packets sent from all geophones in the network (P_{sg}). It is expressed as shown in Equation (6.1).

$$PDR = \frac{P_{rx}}{P_{sg}} \quad (6.1)$$

As one of the requirements for WSDA is to provide reliability that is close to or even match that provided by cable based surveys, a lower bound PDR value of 95% is specified.

Average End-to-End Delay (E2ED)

E2ED defines the average time taken to transmit data packets from all geophones in the network to the CCU. This includes delay components such as propagation, processing, queuing, and transmission delay. It is expressed as shown in Equation (6.2).

$$E2ED = \frac{1}{K} \sum_{i=1}^K (T_i^{rx} - T_i^{st}) \quad (6.2)$$

where T_i^{st} is the time instance at which the i^{th} packet is generated and sent out by a geophone, T_i^{rx} is the time instance at which the i^{th} packet is received at the CCU, and K is the total number of packets received at the CCU from all geophones. Equation (6.2) is similar to Equation (4.45) except that (6.2) is with reference to the CCU not the sink or gateway node as is the case in (4.45).

Packet Error Rate (PER)

This metric defines the probability of receiving an erroneous packet by nodes in the network due to some impairment on the wireless channel such as signal interference, collisions, noise, attenuation etc. It is defined as the ratio of

the number of packets received with errors ($P_{rx_{err}}$) to the total number of transmitted packets (P_{tx}) as shown in equation (6.3).

$$PER = \frac{P_{rx_{err}}}{P_{tx}} \quad (6.3)$$

Signal-to-Interference Plus Noise Ratio (SINR)

SINR metric describes the quality of the wireless connectivity in the network by quantifying the quality of a received signal. It is defined as the ratio of the signal of interest power (S_{power}) to the interference (I_{power}) plus noise power (N_{power}) at the receiver. It is expressed as shown in Equation (6.4).

$$SNIR = \frac{S_{power}}{I_{power} + N_{power}} \quad (6.4)$$

Retransmission Ratio (RTR)

This metric shows the percentage of packets retransmitted by geophones in the network received at the CCU. It is defined as the ratio of number of packets received at the CCU from subsequent retransmissions (not from initial transmission) (p_{rtx}), to the total number of packets successfully received at the CCU both from initial and subsequent retransmissions (p_{rx}) as expressed in equation (6.5).

$$RTR = \frac{p_{rtx}}{p_{rx}} \quad (6.5)$$

Equation (6.5) is similar to Equation (4.48) except that (6.5) is with reference to the CCU not the sink or gateway node as is the case in (4.48).

Average Packet Dropped Retry Limit Reached (PD_{RLR})

This metric shows the percentage of dropped packets at the link layer when a geophone exceeds the maximum retransmission attempt limit. It is expressed as shown in equation (6.6).

$$PD_{RLR} = \frac{1}{N} \sum_{i=1}^N \left(\frac{p_i^d}{p_i^{sg}} \right) \quad (6.6)$$

where N is the number of geophones in the network, p_i^d is the number of packets dropped due to retransmission limit been exceeded by the i^{th} geophone, and p_i^{sg} is the number of packets sent by the i^{th} geophone.

Energy Consumption (EC)

This metric defines the amount of energy consumed as the ratio of the current remaining energy of a geophone or gateway (E_{rmn}) to the initial energy of a geophone or gateway (i.e., the initial battery capacity value) at the starting phase or commencement of the acquisition process (E_{int}). It is expressed as shown in equation (6.7).

$$EC = \frac{E_{rmn}}{E_{int}} \quad (6.7)$$

Network Life-time

This metric defines the time or number of sweeps to be carried out until the first geophone node runs out of battery power (i.e., 100% of energy is consumed). It is expressed either as a unit of time or number of sweeps (shots).

6.3 Performance Evaluation in the 2.4 and 5 GHz Band

The IEEE 802.11 or WLAN usually operates in two frequency bands, the 2.4 and 5 GHz bands. Although these bands are similar in terms of their operational characteristic some of their major differences are in frequency range, channel availability, communication range, and speed or data rate. Due to its lower frequency range, the 2.4 GHz band has longer communication range and better penetration via obstacle than 5 GHz band. In terms of channel

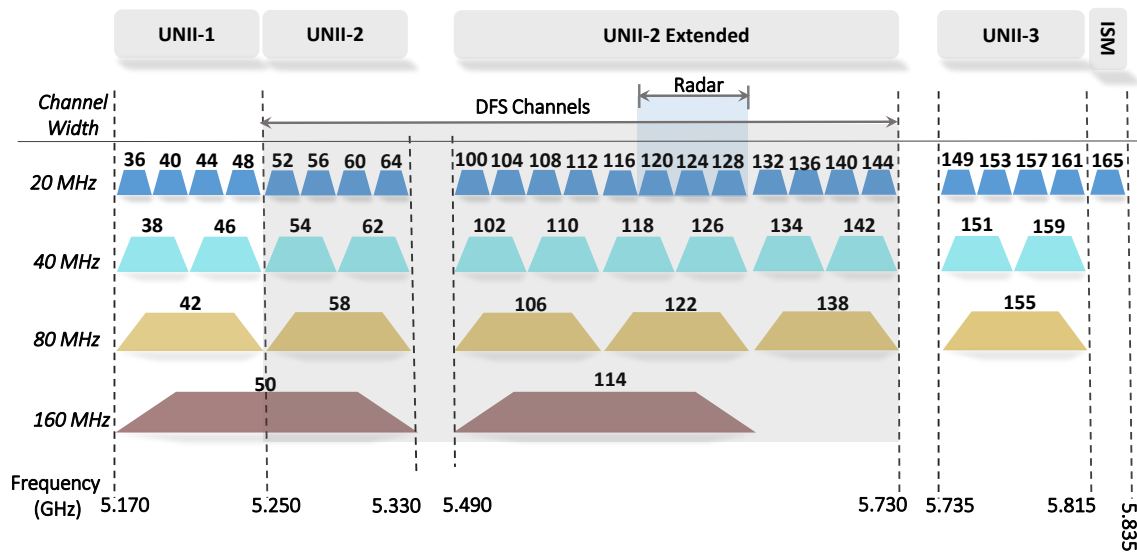


Figure 6.2: Illustration of the 5GHz band available channels over various channel width adapted from [164].

availability, the 2.4 GHz band has 3 non-overlapping channels as compared to 5 GHz which has 25, as illustrated in Figure 6.1 and 6.2 respectively, making the latter the less crowded band.

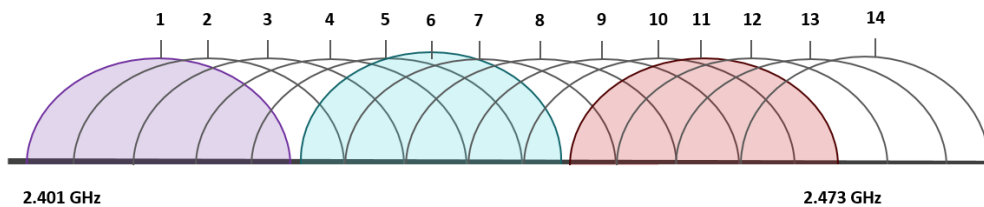


Figure 6.1: Illustration of the 2.4 GHz channel overlay depicting the non-overlapping channels (1, 6, and 11) adapted from [164].

However, some of the channels in the 5 GHz band are Dynamic Frequency Selection (DFS) channels designed with the feature of detecting and avoiding radar signals (from military or weather radar system) in the same frequency range. Additionally, the 5 GHz band offers higher data rate because of its broader frequency range [165].

Although the 2.4 GHz band is the most commonly used band for WLAN operations, one of its major drawback is its susceptibility to interference [164]. Thus it is important to investigate the effect of interference on the WSDA network in these two bands.

6.3.1 Interference Effect

IEEE 802.11 ad hoc networks are susceptible to interference, which can result in significant packet loss, increased latency, reduced throughput, and consequently low QoS. Interference can arise from different factors, some of which include other wireless devices operating on the same frequency band, other external wireless devices emitting radio waves, physical obstructions from the environment etc., [165]. However, seismic data acquisition is often carried out in remote areas where interference from external devices, or obstruction from physical environment like buildings are not expected. Thus, in this thesis the focus is on two common types of interference which include:

- i). Co-Channel Interference (CCI): caused due to overlapping signals from two or more nodes operating on the same frequency channel.
- ii). Adjacent Channel Interference (ACI): occurs when two or more nodes are operating on adjacent frequency channels, which causes signals to leak into each others channel.

As outlined in Chapter 3, careful network planning and appropriate choice or configuration of frequency channels can contribute in minimizing interference in the WSDA network. Another technique used to mitigate interference is *transmit power control* [166]. The transmit power level of a node is directly proportional to its effective communication range. Higher transmit power means better received signal strength (SINR) value at the receiver, and lower packet error, but also means more energy consumption as well as more likelihood of interference occurring in the network and vice versa.

Besides impacting the network connectivity or communication range, transmit power level also affects how nodes contend for the shared wireless medium. With the CSMA/CA protocol, carrier sense threshold specifies the level of the signal strength at which a node believes the medium is busy and will not transmit [167]. The number of concurrent transmissions is reduced with a low carrier sense threshold, while a high carrier sense threshold increases interference among concurrent transmissions. Thus, it is equally important to investigate the impact of *geophone transmit power* on interference. Therefore, an investigation on the effect of interference in the popular 2.4 and 5 GHz

Table 6.1: Simulation Parameters

Parameter	Value
Network size	1200 geophones
No. of subnetworks	10
Subnetwork size	120 geophones
Packet Payload	1500 B
Send interval	250 ms
Frequency bands	2.4 & 5 GHz
CW_{min}	32
CW_{max}	1024
Bit Rate	65 Mbit s ⁻¹
Max. retransmission limit	7
SIFS	10 μ s
slotTime	20 μ s
DIFS	50 μ s
Propagation model	Two-ray

license free bands with regards to the proposed WSDA network architecture, technology, and protocol is carried out using simulations for different transmit power levels.

6.3.2 Simulations

As mentioned earlier, **scenario 3** as illustrated in Figure 3.6 of Section 3.5 is used as the simulation reference scenario. The simulation is carried out for 10 runs and results are evaluated with 95% confidence level. Table 6.1 gives a summary of some important parameters used in the simulation.

To properly analyze the WSDA network performance in the presence of the different interference effects in simulation, four cases are investigated. Each of these cases are simulated for different geophone transmit power level of 5, 10, 25, and 40 mW with “hop count” as the RPL OF metric.

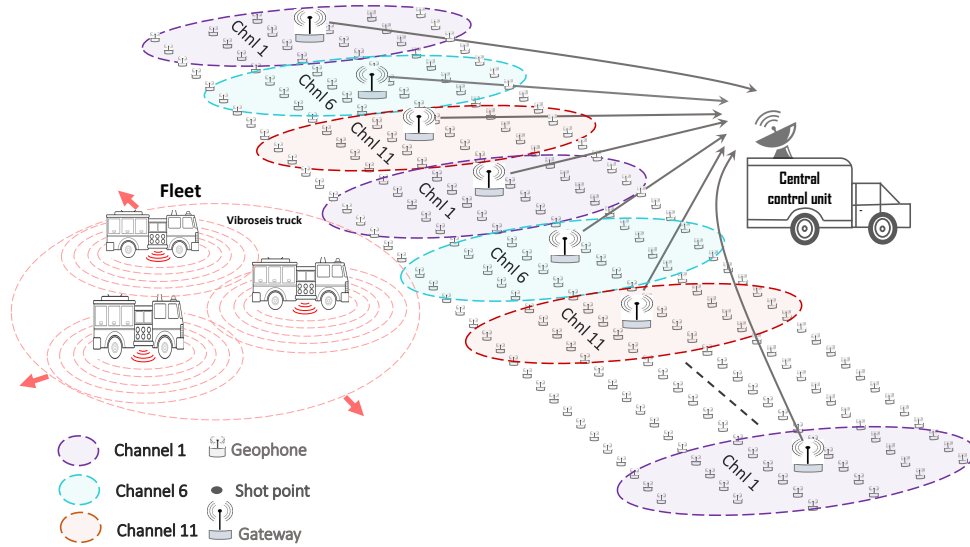


Figure 6.3: Illustration of CCI simulation setup depicting the deployment of the 3 non-overlapping channels in the 2.4 GHz band

Case 1: Non-overlapping Channels in the 2.4 GHz Band

The goal in this setup is to investigate the effect of Co-Channel Interference (CCI) on the network performance in the 2.4 GHz band with respect to scenario 3. Subnetworks are configured to use the three non-overlapping channels (1, 6, and 11) in the 2.4 GHz band, repeated over the 10 subnetworks, and deployed according to the frequency reuse concept as illustrated in Figure 6.3.

Case 2: Overlapping channels in the 2.4 GHz Band

The goal in this setup is to investigate the effect of Adjacent Channel Interference (ACI) on the network performance when subnetworks are configured to operate on adjacent overlapping channels in the 2.4 GHz band as depicted in Figure 6.4. Figure 6.5 illustrates the simulation scenario, which is configured to show the worst case performance of the WSDA network under heavy interference effect.

Case 3: Partially over-lapping 40 MHz channels in the 2.4 GHz Band

This setup aims at investigating the effect of combining two 20 MHz non-overlapping channels in the 2.4 GHz band to form two 40 MHz channels that

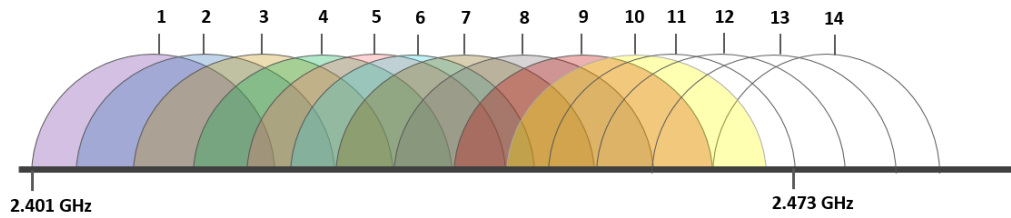


Figure 6.4: Illustration of the 2.4 GHz channel overlay depicting the completely overlapping channels simulation setup.

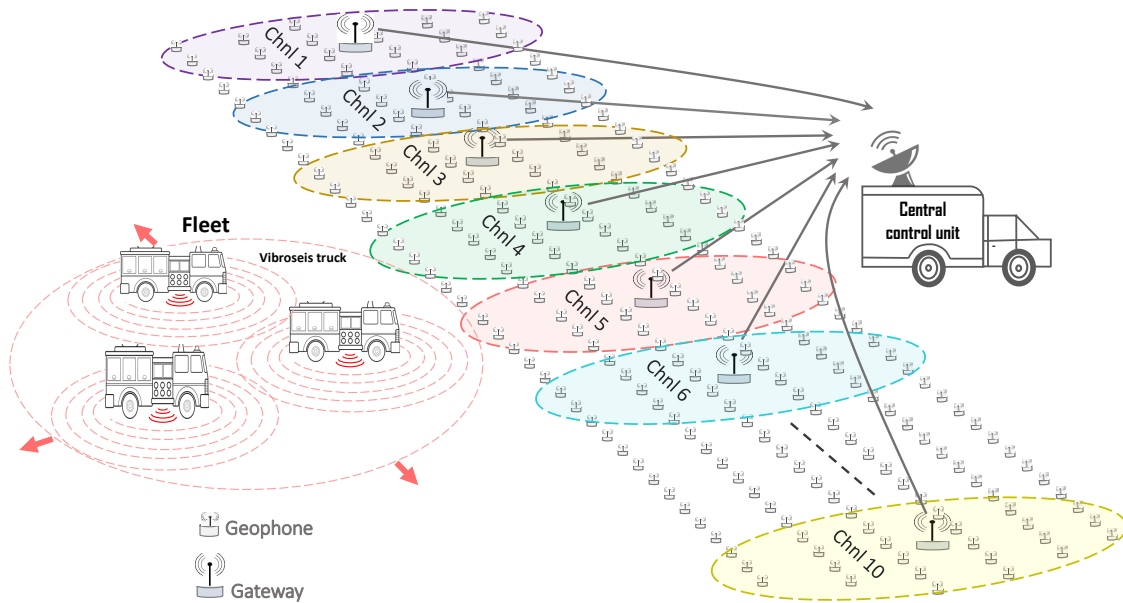


Figure 6.5: Illustration of ACI simulation setup depicting the deployment of adjacent overlapping channels in the 2.4 GHz band.

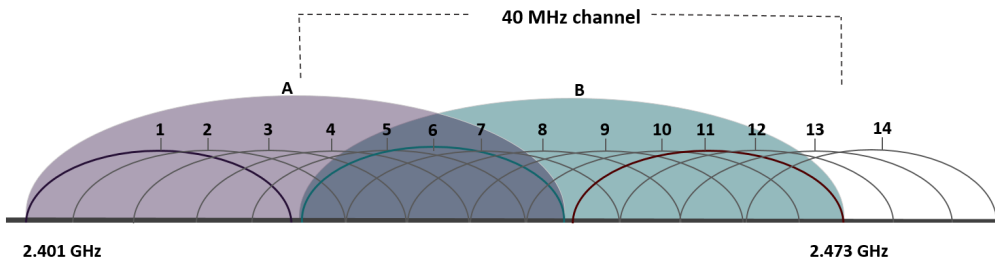


Figure 6.6: Illustration of the 2.4 GHz channel overlay depicting the partially overlapping channels with 40 MHz bandwidth simulation setup.

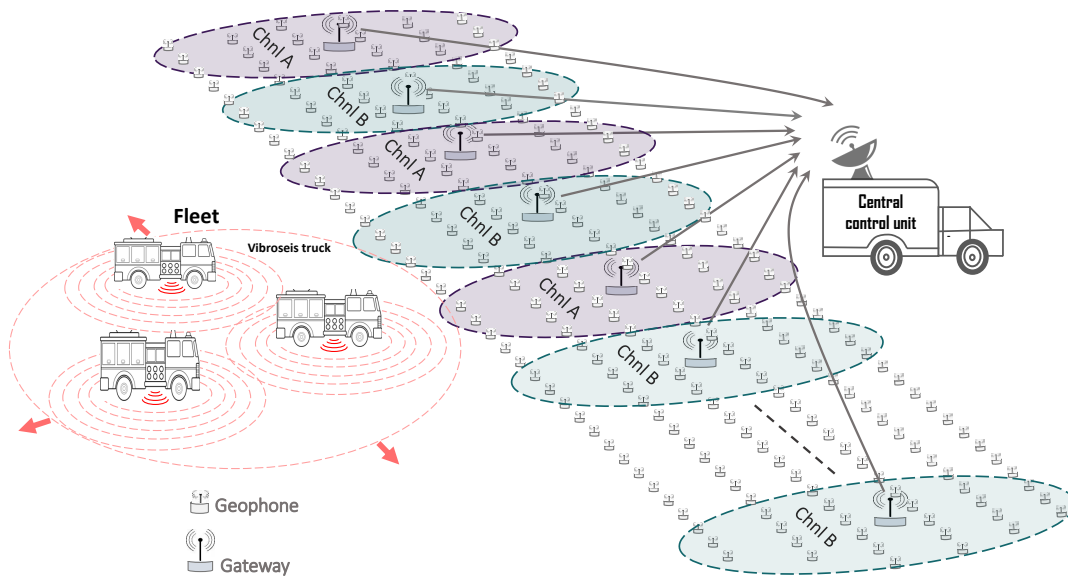


Figure 6.7: Illustration of ACI simulation setup depicting the deployment of partially overlapping 40 MHz channels in the 2.4 GHz band.

are partially overlapping with each other as shown in Figure 6.6. These 40 MHz channels are then deploy based on the frequency re-use concept over the ten subnetworks as depicted in Figure 6.7.

Case 4: Non-overlapping Channels in the 5 GHz Band

In this setup, an investigation on the effect of CCI on the network performance in the 5 GHz band is carried out. Due to the availability of non-overlapping channels in this band, each of the ten subnetworks deployed is configured to use a different non-overlapping channel as illustrated in Figure 6.8.

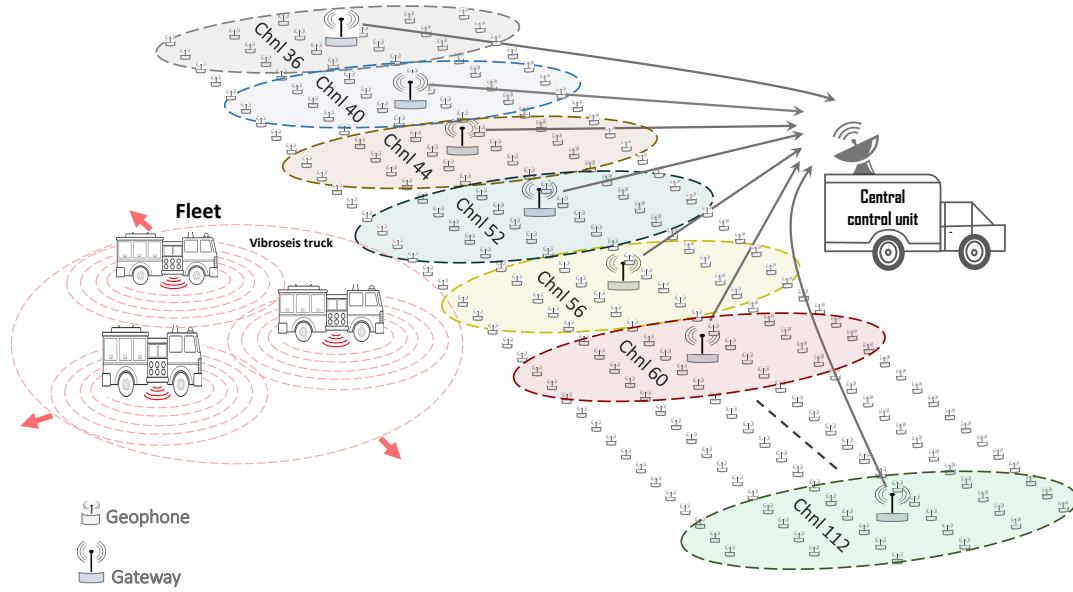


Figure 6.8: Illustration of CCI simulation setup depicting the deployment of the non-overlapping 20 MHz channels in the 5 GHz band.

6.3.3 Results

Figure 6.9 shows the packet delivery ratio (PDR) computed at the CCU. In general, the PDR for case 1, 2, and 3 is considerably lower (below 40%) compared to that of case 4 (above 60%) for transmit power values of 10, 25, and 40 mW. This is because of the increased CCI from within a subnetwork experienced by packets in the 2.4 GHz band in case 1, 2, and 3 as compared to case 4 which is configured to operate in the 5 GHz less congested band. For case 4 with 5 mW transmit power, the PDR is below 40%. An explanation for this is because of the 6.6 dB band gap loss between the 2.4 GHz and 5 GHz bands that arises from the increased path loss at higher frequencies leading to reduced communication coverage [163]. Consequently, the communication coverage in the 5 GHz band is lower than that of the 2.4 GHz band even though the transmit power levels are the same. Hence, most of the leaf geophones in a subnetwork will be out of communication range of their parent geophones, and subsequently cannot relay data packets to their respective gateways. However, it is important to note that the 6.6 dB value can vary depending on factors like physical environment, antenna design or specification, regulatory domain etc.

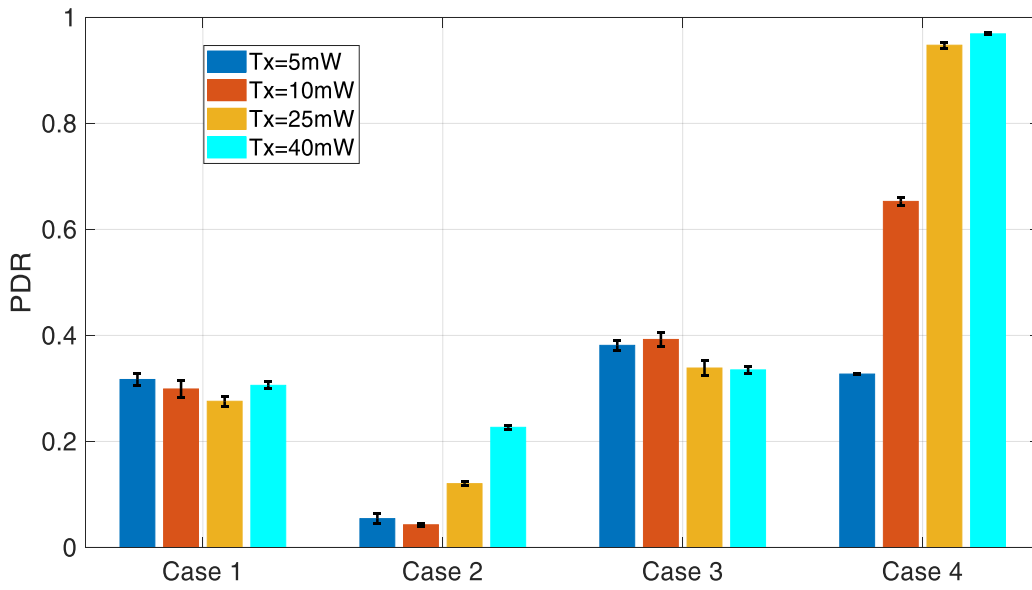


Figure 6.9: Packet Delivery ratio for all cases and different Tx power captured at the CCU

Furthermore, it can be noticed in case 1 that the PDR slightly drops with increase in transmit power levels (10 and 25 mW). This is because higher transmit powers result in increased CCI within a subnetwork as more geophones contend for access to the channel leading to increased retransmission and subsequently some packets are dropped due to retransmission limit reached as can be seen in Figures 6.10 and 6.11 respectively. The PDR with 40 mW transmit power in this case is slightly better compared to that of 10 and 25 mW. This is because in addition to hidden node problem, lower transmit power results in more number of hops, thereby increasing the depth of RPL tree within a subnetwork and subsequently increases the probability of collision in the network. With 40 mW transmit power however, all geophones within a subnetwork are 1-hop away from their respective gateway can be seen in Figure 6.15.

As expected, case 2 depicts the worst case PDR performance (below 30%) for all transmit power levels, in accordance with the configuration shown in Figure 6.5. As a result of the high impact of ACI interference from the completely overlapping channels in addition to the CCI from within a subnetwork, most of the packets in the network experience collision thereby resulting in increased retransmission as can be seen in Figure 6.10. Consequently packets are been dropped as a result of retransmission limit reached as shown in Figure 6.11. Higher transmit power in this case result in better PDR as more geophone

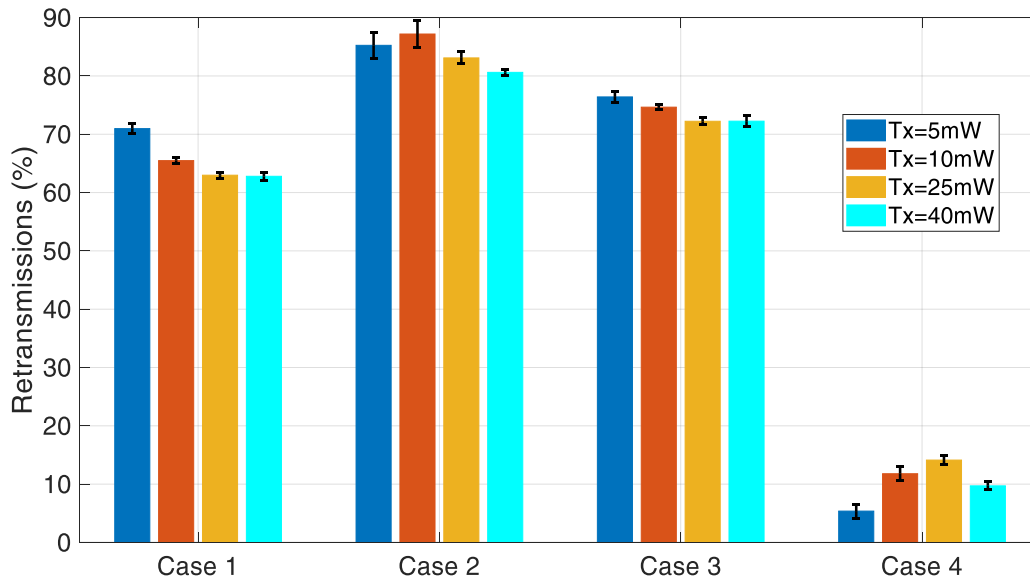


Figure 6.10: Geophones packet retransmission ratio in the network for all simulation cases and different transmit power levels.

sense the transmission of each other thereby reducing the effect of ACI from neighboring subnetworks.

Although the PDR in case 3 is slightly higher than that of case 1, similar explanation of the latter can be applied. The major difference is that in case 3, two partially overlapping 40 MHz channels are configured as illustrated in Figure 6.7, as compared to the 20 MHz channels used in case 1 and 2. As wider channel widths (40 MHz in this case) lead to reduced communication range due to factors like increased path loss, multipath fading, reduced SINR due to higher noise floor etc., the effect of CCI from within a subnetwork is lowered as compared to that of case 1. This explanation is supported further with the average retransmission ratio and PER cumulative probability distribution plot as shown in Figures 6.10 and 6.12 respectively. The PER in the network is significantly higher (normally distributed between 43% to 90%) for case 1, 2, and 3 because of increased interference as discussed above, leading to increased packet retransmission (figure 6.10). Subsequently, packets are dropped due to retransmission limit is reached as shown in Figure 6.11. Furthermore, in case 3 lower transmit power shows better PDR compared to higher transmit power due to lower CCI at lower transmit power level.

The PER in case 4 is lower (normally distributed between 0 to 50 %) due to advantage of reduced CCI from within subnetworks and utilization of high

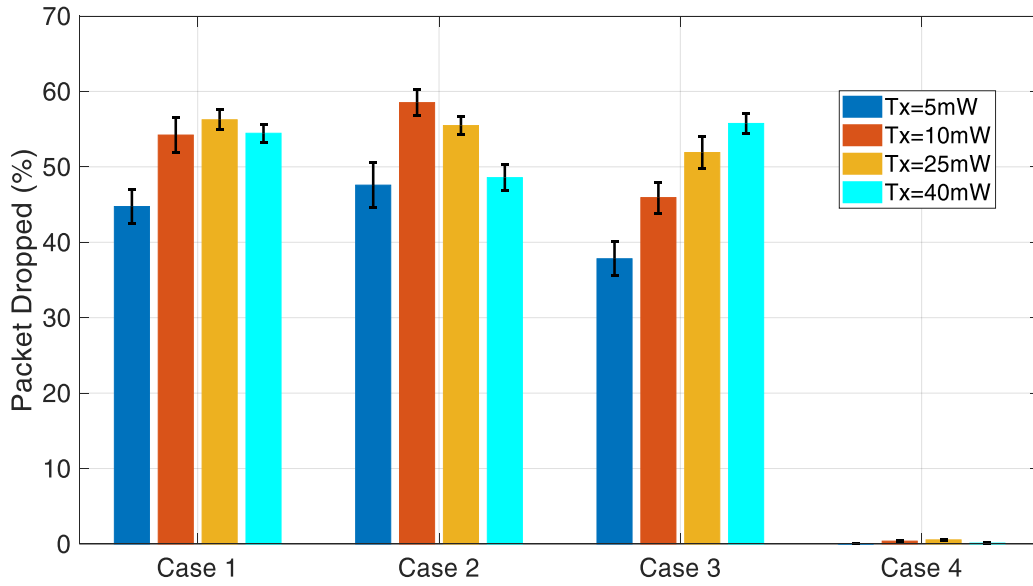


Figure 6.11: Packets dropped by geophones in the network due to retransmission limit been exceeded for all simulation cases and different transmit power levels.

number of non-overlapping channels from the configuration in the 5 GHz band.

Similar explanation can be projected to the packet end-to-end delay. Figure 6.13 shows the cumulative probability distribution of packet delays in the network. Observing the delay values that corresponds to the 90th percentile in the network, 90% of the values fall below 1.2s for all transmit power levels in case 1, with remaining packets having a value of up to 5s maximum. For case 2, 90% of the values fall below 4s with the remaining extending up to 5.9s maximum. Similarly for case 3, 90% of the values fall below 2s with the remaining extending up to 4.9s maximum. In case 4 however, 90% of the packet delay values fall below 10 ms with remaining packets having a value of up to 2s maximum. The delay is higher in case 2 due to increased retransmissions resulting from the high adjacent channel interference, which increases with increase in transmit power as expected. This can be seen more clearly from the average packet end-to-end delay plot in Figure 6.14. However, with the 40 mW transmit power in this case, there are no leaf (rank 3) geophones present in a subnetwork as all geophones are within the range of the gateway in a subnetwork as 1-hop neighbors (as can be seen in Figure 6.15), making the delay lower than that of 25 mW transmit power.

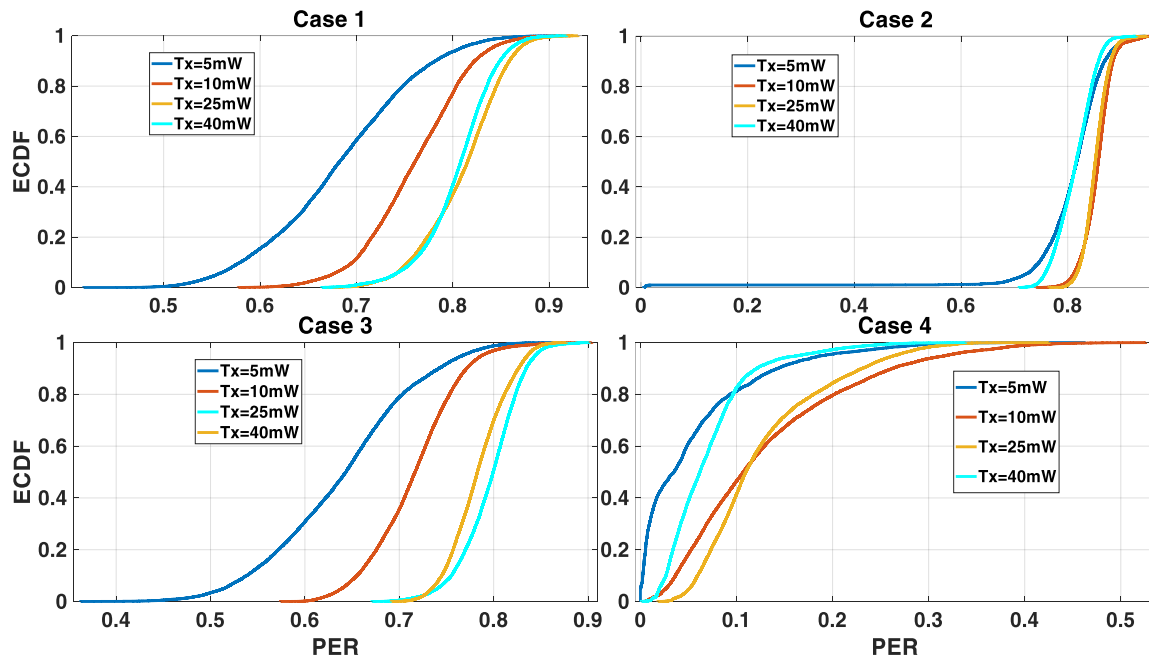


Figure 6.12: Geophones packet error rate distribution for all simulation cases and different transmit power level.

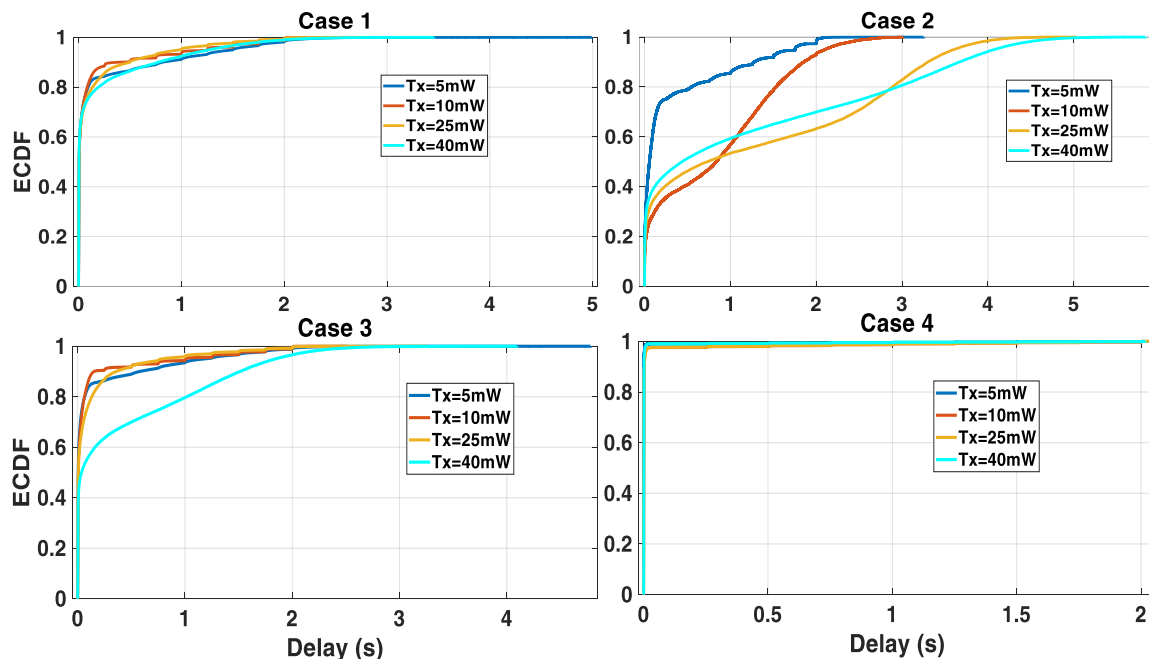


Figure 6.13: Packet end-to-end delay probability distribution for all simulation cases and different transmit power levels.

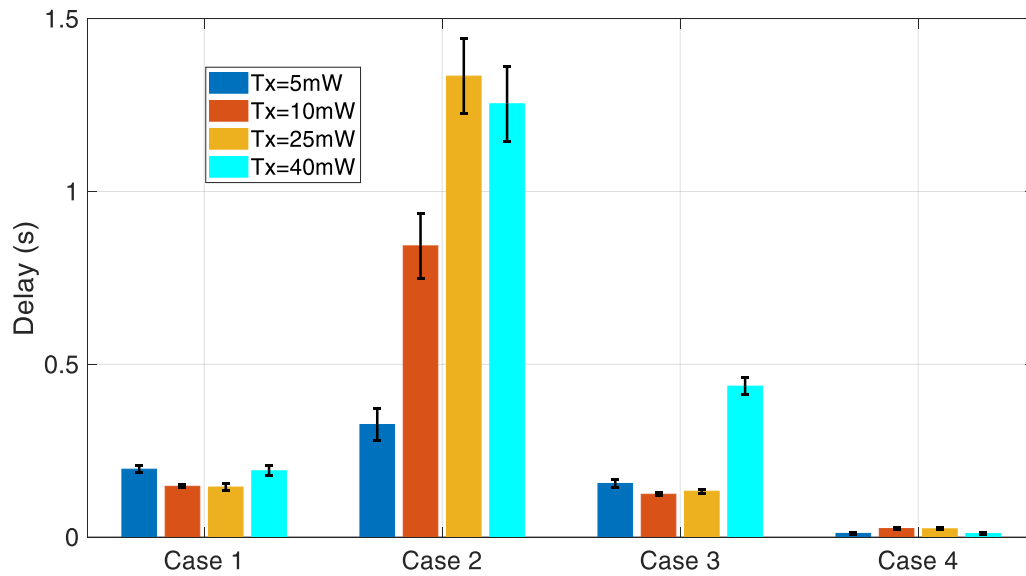


Figure 6.14: Average end-to-end delay for all simulation cases and different transmit power levels.

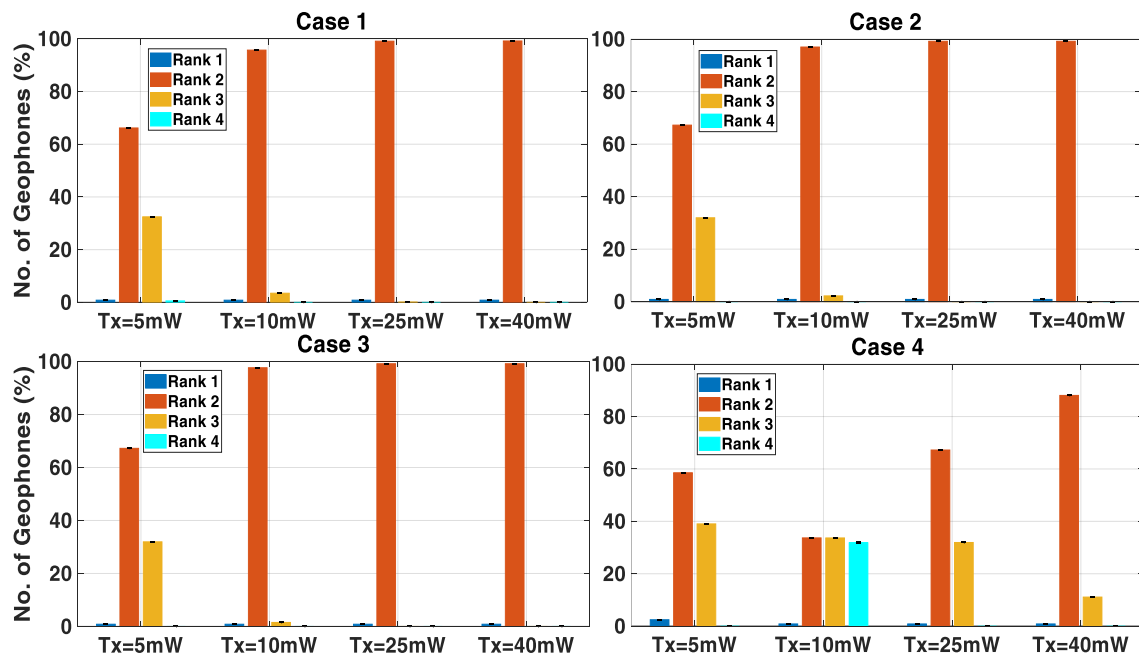


Figure 6.15: Rank distribution for all simulation cases and different transmit power levels.

6.3.4 Discussions

The results obtained in the previous section prove that, when operating in the 5 GHz band (case 4), the main challenges and requirements outlined in Chapter 1 can be addressed based on the proposed WSDA network architecture, technology and protocol. These requirements outlined includes:

- i). Scalability and Reliability: Results obtained show that the architecture is scalable to large number of nodes when operating in the 5 GHz band. With 1200 geophones actively recording per sweep, up to 96% PDR can be achieved reliably in the network as can be seen in case 4 of Figure 6.9. Moreover, the PDR can be improved further by simply increasing or doubling the minimum contention window value to decrease collision probability and consequently packet drop probability.
- ii). Latency: As can be seen in Figure 6.13, 90% of the packets successfully received at the CCU have an end-to-end delay of less than 1.2s, with the worst case extending up to 2s maximum. This will enable a form of real-time data delivery considering the requirement that data should be delivered before the vibroseis truck moves to the next shot point, thereby increasing the overall survey productivity.
- iii). Self-configuration and management: With the adoption of RPL protocol, the network auto configure itself into subnetworks in the form of DODAGs as depicted in Figure 3.1. This enable geophones within each subnetwork to group themselves hierarchically into parent and leaf nodes. However, for the configuration in case 4 with transmit power of 25 mW, geophones can have a maximum rank of 3, with very few having rank of 4. This means geophones can reach the gateway in either 1, 2, or 3 hops maximum. With 40 mW transmit power, geophones can reach the gateway in either 1 or 2 hops only.
- iv). Interference minimization: With the deployment of subnetworks based on the frequency re-use concept where no two adjacent subnetworks use the same frequency, interference can be kept at the barest minimum. The interference is further reduced in case 4 when operating in the 5 GHz band which has more available non-overlapping channels, thereby enabling high re-use distances, thus minimizing both CCI and ACI interference.

As mentioned earlier, interference from external devices is not expected in this case as the survey is mostly carried out in remote areas. In addition, techniques such as channel bonding or dynamic frequency selection can be utilized to further reduce interference and optimize the network performance.

With regards to the effect of transmit power level on interference, transmit power generally influence interference in both the 2.4 GHz and 5 GHz bands. In the 2.4 GHz band, higher transmit power will result in better communication coverage, but at the expense of increased CCI and more signal leakage into adjacent channels, leading to increased ACI. This will consequently result in decreased network performance. Similarly, in the 5 GHz band high transmit power will result in increased ACI. Therefore, based on the specific environment and requirements, keeping the transmit power at an optimal level to balance communication coverage and interference considerations is the key to reducing the effect of transmit power on interference in both bands. Based on the results obtained, 10 mW is optimal in the 2.4 GHz band and 25 mW or 40 mW in 5 GHz band. The evaluation presented in this section has been published by the author of this thesis in [168].

In the following section, an evaluation of geophone energy consumption as well as the overall network life-time is presented.

6.4 Energy Consumption

Energy efficiency is an important factor to consider in seismic data acquisition process. This is because the seismic sweep or acquisition process (which includes shooting phase, data recording phase, and data transfer phase) repeats continually for several days or weeks, hence geophones need to stay operational for as long as possible to avoid frequent replacement or recharge of batteries [34]. Thus, in this section the energy consumption of geophones based on the proposed WSDA architecture as well as the overall network life-time is investigated.

In WGNs, energy consumption can occur in three different units of the geophone. This include the sensing, processing, and communication units. Thus,

the total energy consumed by a geophone is the sum of energy consumed in each of the individual units. However, different factors such as sensing type, hardware type and configuration etc., contribute to the amount of energy consumed in each of the units as discussed in the following sections.

Sensing Energy Consumption

The energy consumed by a node due to sensing depends on the hardware or use case (e.g., passive or active sensing). Like in seismic data acquisition, passive sensing which is event driven consumes less energy compared to active sensing in which the node is continuously sensing. Power consumption during sensing may arise from either signal sampling, signal conditioning, or analog-to-digital conversion. However, several literature suggest that energy consumed due to sensing only represents a negligible percentage of the total power consumption in a node [169] [170] .

Processing Energy Consumption

The energy consumed due to processing largely depends on the hardware used. Most of the power consumed during processing comes from switching energy (e.g., switching from sleep to active mode), or energy consumed while no computation is carried out (leakage energy)[169]. For example, depending on the resolution settings and data rate the LIS2DH12 MEMS accelerometer processor [171] has an energy consumption value of about 10 to 60 μA in active mode.

Radio Energy Consumption

The geophone radio unit is responsible for transmitting (Tx) and receiving (Rx) packets in the network. Some factors that influence energy consumption in the radio unit includes transmit power level, different modes of radio operation (transmit, receive, idle, and sleep modes), data rate, communication technology and protocols, environmental factors etc. In this thesis however, the focus is mainly on the energy consumed during the different modes of radio operations.

However, the amount of power consumed during these different modes of radio operation largely depends on the device hardware type and power rating. Furthermore, the RPL protocol adopted in the proposed architecture has “energy” as one of the objective functions used in DODAG formation as discussed in Section 5.2.4.

Caveat: It is important to mention that the state-of-the-art ESP32 microcontroller unit (MCU) device is considered as the reference device in all evaluations and discussion in this thesis. This is because ESP32 is a system on a chip MCU with integrated WLAN module designed specifically for low power operations. Table 6.2 gives the power consumption values for different modes of radio operations of the ESP32 MCU.

Table 6.2: Radio Power consumption (PC) for the ESP32 MCU [172]

Mode	PC (mA)	PC (Watts) @3.3V
Idle	15	0.0495
Sleep	0.8	0.00264
Receive	100	0.33
Transmit	180	0.594

6.4.1 Simulation Setup

To reduce the complexity of the simulation, only one subnetwork is considered in the simulation unlike in Section 6.3 where ten subnetworks (corresponding to the number of geophones that are actively recording due to shot generated from a 3 truck fleet). Besides, all geophones in the network are homogeneous in nature having same functionality and same data traffic generated. Thus, results from one subnetwork will be the same as from the other subnetworks. Furthermore, as the seismic sweep is a repeated process throughout the entire planned duration of the survey, energy consumed per sweep is an important metric to look at in this investigation. According to [38], up to 145 sweeps/hour frequency can be achieved in a typical 2 fleet flip-flop seismic data acquisition. Thus, the simulation is carried out for 1000 sweeps¹, 3500 sweeps (approximately representing 24 hours continuous SDA operation), and 10500

¹1000 sweep cycles corresponds to ~5 h of simulation time, 3500 sweeps to ~21 h of simulation time, and 10500 sweeps to ~63 h of simulation time

Table 6.3: Simulation Parameters

Parameter	Value
Subnetwork	1 (120 nodes)
Traffic type	UDP
Packet size	1500 B
Send interval	250 ms
Battery capacity	38.48 W h(138.528 kJ)
Shot period	16 s
Recording period	5 s
Number of shots	1000, 3500, & 10500
Technology	IEEE802.11ac
Frequency band	5 GHz
Bandwidth	20 MHz
Data rate	65 Mbit s ⁻¹
Transmit power	25 mW
Simulation time	300 s
Energy consumption model	"StateBasedEpEnergyConsumer"
Physical environment	Flat ground
Propagation model	Two-ray ground reflection

sweeps (approximately representing 3 days continuous operation). Based on the results obtained, linear regression technique is used to extrapolate in order to determine the number of sweeps or the time it takes before the first geophone runs out of battery. It is important to mention that an initial battery capacity value of 38.48 W h (138.53 kJ) obtained from “**Smart Solo**” (a typical state-of-the-art geophone device) data sheet [173] is used as reference geophone battery in this evaluation. Table 6.3 gives a summary of the simulation parameters used in the energy consumption evaluation. Simulations are carried out for 10 runs and results evaluated with 95% confidence level for different RPL OF metrics (Hop count, Energy, and ETX).

6.4.2 Results

Figure 6.16 shows probability distribution of the energy consumed by geophones over different number of shots or sweep, evaluated for the three RPL objective functions. For 1000 shots, the energy consumed by geophones in the network is bimodally distributed between 0.83 to 0.98% for all RPL objective functions.

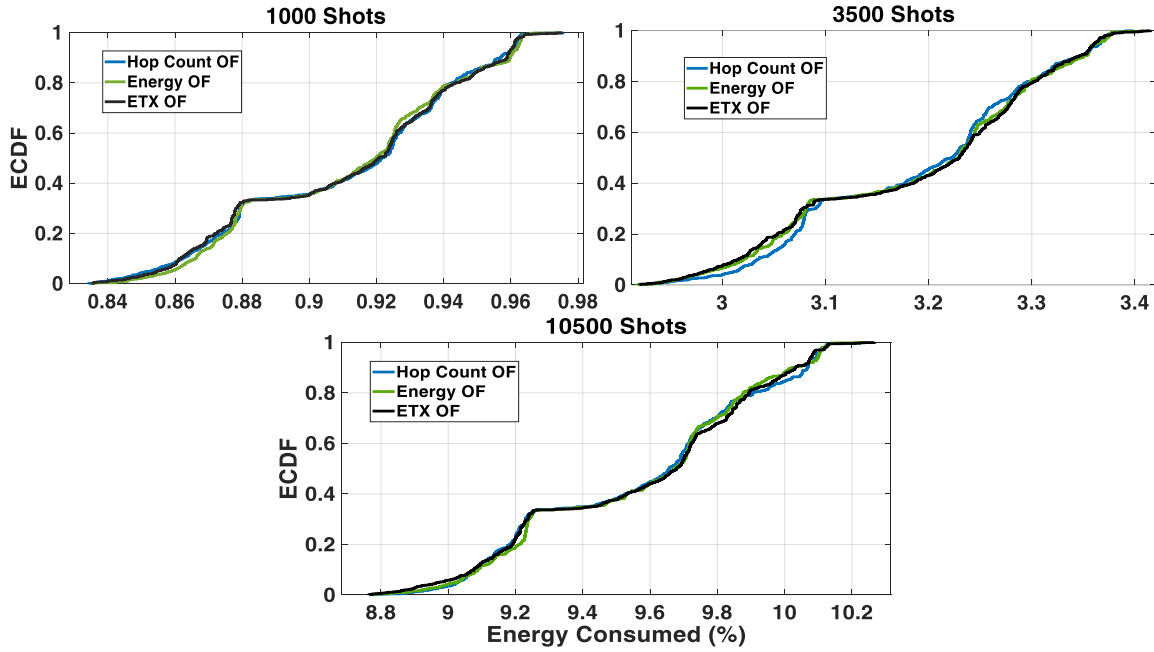


Figure 6.16: CDF of percentage energy consumed in geophones for different number of sweeps and different RPL objective functions

This distribution can be seen more clearly in the density plot shown in Figure 6.17, with two distinct peaks or modes, indicating two possible set of geophones energy consumption values. An explanation to this is that the peak to the left represents the energy consumed by leaf geophones while the peak to the right represents the parent geophones. Due to the constant forwarding of packets from children geophones, the energy consumed by parent nodes is slightly more than that of child geophones as can be seen from Figure 6.17.

Similar explanation applies in the case of 3500 and 10500 shots. As expected, the energy consumed is higher than that of 1000 shots, also bimodally distributed between 2.92% and 3.42% for 3500 shots and 8.6% and 10.3% for 10500 shots, indicating the two sets of geophone energy consumption values i.e., child and parent geophones.

Furthermore, it can be noticed that the energy consumed for the three different RPL OF is almost the same for all number of shots, even though in ideal case the “energy” OF should show better performance. This is because of the homogeneous and static nature of the network, thus no frequent topology changes is expected after initial deployment of geophones. Hence, geophones tend to maintain there initial parents irrespective of the OF type configured because of the less frequent control messages transmission in accordance with

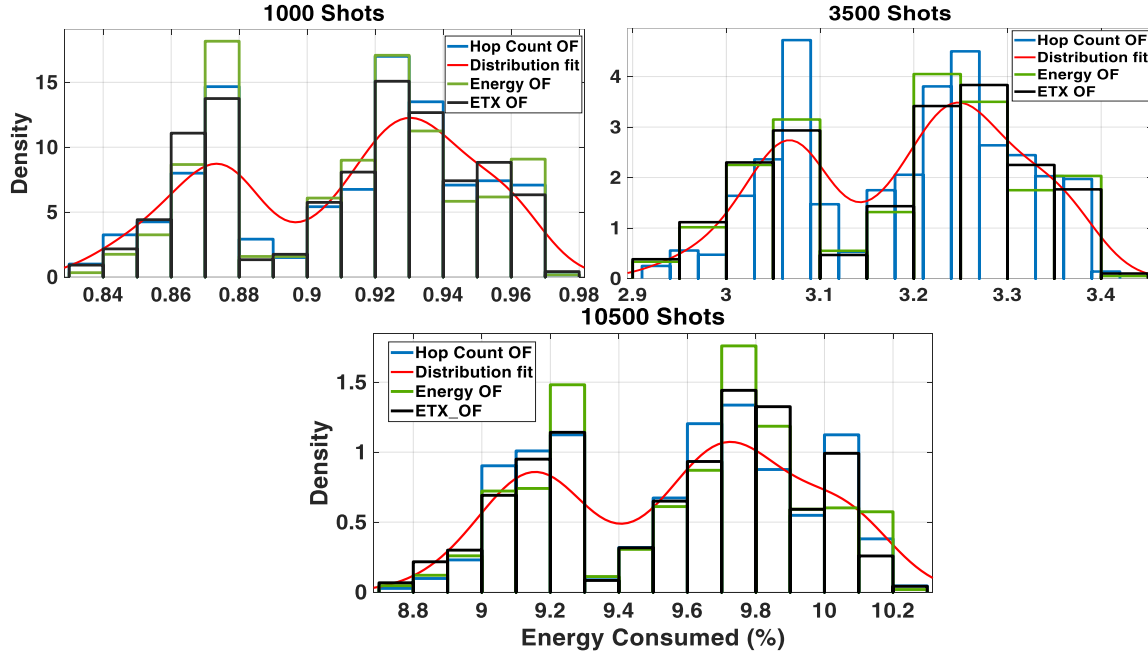


Figure 6.17: PDF of percentage energy consumed in geophones for different number of sweeps and different RPL objective functions

the RPL trickle algorithm, thereby resulting in geophones maintaining their initial parents. However, it can be noticed that for longer sweep periods, the “energy” RPL OF takes into effect, showing slightly lower energy consumed as compared to the other OFs.

Based on these results, an estimation of the network life-time is carried out by extrapolating the results obtained using linear regression technique to find the number of shots until 100% of the energy is consumed in a geophone. In other words, the expected time until the first geophone dies in the network as a result of battery drain. Table 6.4 shows the estimated network life-time for both child and parent geophones.

Table 6.4: Network life-time estimation, showing the number of sweeps till 100% of energy is consumed

	No. of shots	Time (Days)
Leaf geophones	114,171	33
Parent geophones	107,619	31

These results show that geophones can last for as long as a month of continuous seismic data acquisition operations based on our proposed architecture and protocols. However, it is important to mention that two parameters largely

determine the energy consumption results; (i) Battery capacity of geophones, higher battery capacity will result in longer network life-time and (ii) the hardware specifications of geophones, especially the radio unit (Tx, Rx, idle modes of operation).

Based on this, it is imperial to have a tool that analytically estimates the energy consumption of geophones, which utilizes the hardware specifications as inputs, which is discussed in Section 6.5. This will be very useful especially in the planning stage of the seismic data acquisition process to determine which hardware to buy or use based on predefined survey specifications (e.g., duration of survey) coupled with information from device data sheet.

6.5 Energy Consumption Modeling for WSDA

Results obtained in Section 6.4 show that energy consumed in WSDA largely depends on the hardware and the capacity of the battery used. This motivates the development of a model that estimates the energy consumed in geophones based on packet transmission (Tx) and reception (Rx) in our proposed network architecture. The model is an extension of the IEEE 802.11 DCF model presented in Chapter 4, mainly utilized in determining the duration of packet transmission and reception, which is consequently employed to compute the energy consumed for each Tx or Rx based on the hardware radio power consumption specifications.

The model utilizes the device radio hardware specifications as input. Two main packet Tx and Rx phases are considered:

Network setup or initialization phase: this phase involves transmission and reception of RPL control packets for topology or DODAG formation.

Data transmission phase: this phase involves transmission of seismic data packets during the sweep cycle over the 5 s geophone recording period.

In addition to the assumptions outlined for the DCF model in Chapter 4, the model has the following assumptions:

- i). Single subnetwork is considered.

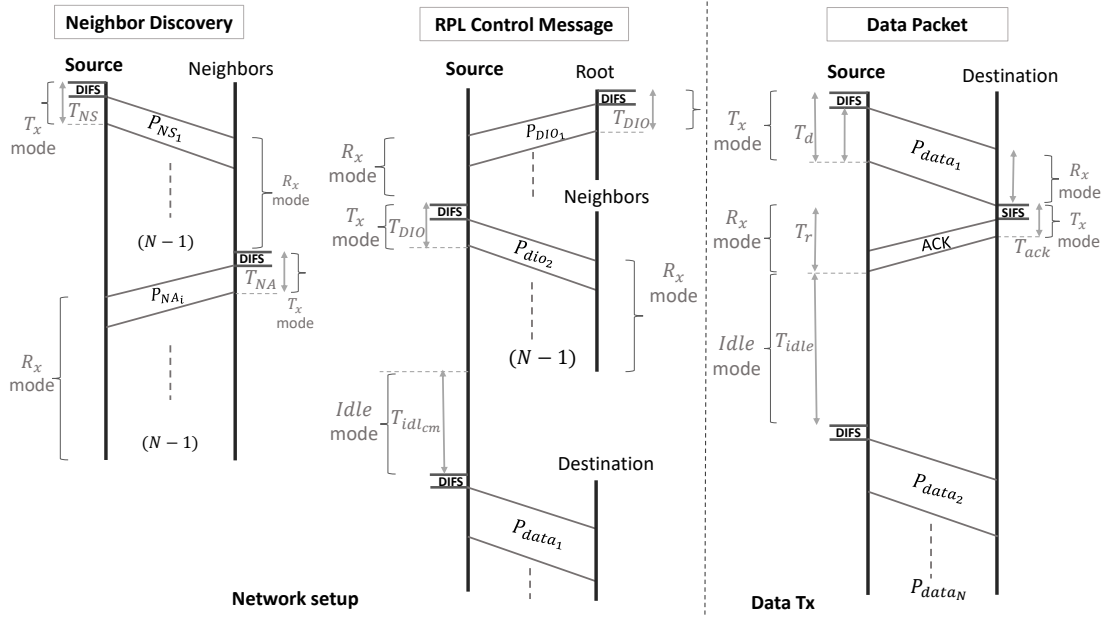


Figure 6.18: Illustration of the energy consumption model depicting the two main packet transmission and reception phases in the proposed WSDA network architecture.

- ii). All nodes are within the communication range of the gateway and can hear the transmission of each other.
- iii). In the network setup phase, only DIO packet transmission and reception are considered for upward routes construction.

Figure 6.18 illustrates the energy consumption model depicting the two packet transmission phases considered i.e., the network setup and data transmission phase.

Network setup phase

In this phase, two packet Tx and Rx are considered; *Neighbor Discovery (ND)* and *RPL control messages* packets. The ND comprises of two packet types (Neighbor Solicitation (NS) and Neighbor Advertisement (NA) packets). As shown in Figure 6.18, in the ND process, the source node or gateway transmits a NS packet in broadcast mode for the duration T_{NS} . This transmission is heard by all its $(N-1)$ neighbors also for T_{NS} duration, where N is the number of nodes in the network. During this period, all the $(N-1)$ neighbors switch to receive mode and power is dissipated. Each of the neighbor nodes will then reply with a NA packets also in broadcast mode and is received by

all the $(N - 1)$ neighbors for the duration T_{NA} . The time T_{NS} and T_{NA} are computed based on the IEEE 802.11 DCF model discussed in Chapter 4.

Similarly, for the RPL control packet, the root node or gateway broadcast DIO message to initiate DODAG formation in the network. This transmission is then heard and received by all the $(N - 1)$ neighbors. Following the reception of the DIO by a geophone, it then further transmits its own DIO packet to all its $(N - 1)$ neighbors in broadcast mode, allowing them to become candidates for children geophones. This transmission is also heard and received by all the neighbors during which they switch to receive mode of operation and power is dissipated. The idle time from the figure comes from the simulation setup where 10s duration is set for network initialization before geophones start generating data packets. During this period, the geophone switch to idle mode of operation and power is dissipated.

Data transmission phase

In this phase, data packet generation follows the proposed traffic model discussed in Section 3.3 over the 5s geophone recording period duration. Once the first packet is generated, the geophone switch to transmit mode of operation and transmits the packet to its intended destination in unicast mode, for the duration T_d which includes all packet retransmissions and the backoff duration according to the DCF model in Chapter 4. The destination node is in receive mode during this duration. Once the transmission is complete, the destination node replies with an acknowledgment (ACK) packet after SIFS duration. During this period, the destination node and the source node are in transmit and receive mode of operation respectively, and power is dissipated accordingly. After the ACK packet is received, the geophone switch to idle mode of operation according to the proposed traffic model until the next packet is generated at the next send interval time. The process repeats until the last packet is transmitted.

Therefore, the total energy consumed (EC) can be computed as the sum of the energy consumed due to packet transmission and reception in all the two phases as expressed in Equation(6.8).

$$EC = EC_{ND} + EC_{RPL} + EC_{data} \quad (Joules) \quad (6.8)$$

where EC_{ND} is the energy consumed as a result of neighbor discovery packets Tx and Rx, EC_{RPL} is the energy consumed due to RPL control messages /DODAG formation, EC_{data} is the energy consumed due to data packet Tx. Each of the terms in Equation(6.8) can be expressed further as follows. For EC_{ND} ,

$$EC_{ND} = P_t T_{NS} + (N - 1)P_r T_{NS} + P_t T_{NA} + (N - 1)P_r T_{NA} \quad (6.9)$$

where N is the number of geophones in the subnetwork, P_t is the power consumed by the hardware in transmit mode of operation, P_r is the power consumed by the hardware in receive mode of operation, T_{NS} is the time it takes to transmit the neighbor solicitation (NS) packets, T_{NA} is the time it takes to transmit the neighbor advertisement (NA) packets.

The energy consumed due to RPL control messages transmission and reception is expressed as in Equation(6.10).

$$EC_{RPL} = T_{DIO} \left[P_r + P_t + (N - 1) \left[P_t + P_r \right] \right] + P_{idle} T_{idle_{cm}} \quad (6.10)$$

where N is the number of geophones in the subnetwork, P_{idle} is the power consumed by the hardware in idle mode of operation, $T_{idle_{cm}}$ is the time spent by the geophone in idle mode before generating the first data packet, T_{DIO} is the time it takes to transmit the DODAG information object (DIO) packet. The energy consumed due to data packet transmission is expressed as in Equation(6.11).

$$EC_{data} = K \left[P_t T_d + P_r T_{ACK} + P_{idle} T_{idle} \right] \quad (6.11)$$

where K is the number of packets sent over 5s geophone recording period, T_{idle} is the time spent by the geophone in idle mode of operation, T_{ACK} is the time taken to receive ACK packet by the reference geophone, T_d is the time taken

Table 6.5: Energy consumption analytical and simulation model parameters

Parameter	Value
Subnetwork size	120 geophones
Packet Payload	1500 B
Send interval	250 ms
Bit rate	65 Mbit s ⁻¹
CW_{min}	32
No. of shots	1
Transmit power	100 mW
Energy consumption model	StateBasedEpEnergyConsumer
Tx power consumption	0.594 W
Rx power consumption	0.33 W
Idle power consumption	49.5 mW

to transmit data packet which includes retransmission, backoff, and average CW value [153].

$$T_d = \frac{1}{1 - P_D} \sum_{i=0}^m P_{suc}^{(i)} \left[T_s + iT_c + \sum_{j=0}^i \overline{W}_j \tilde{\theta} \right] \quad (6.12)$$

where P_D is the probability that a packet is dropped after m tries given by P_f^{m+1} , P_{suc} is the probability that the transmission is successful, T_s is the average time the channel is sensed busy due to a successful transmission, T_c is the average time the channel is sensed busy by each station during a collision, $\overline{W}_j$ is the average backoff counter value at any given transmission stage $j \in i$ expressed as $W_j - 1/2$, $\tilde{\theta}$ is the total duration a node spends during the backoff process before decrementing its counter.

Model Validation

In this section, a comparison between the energy consumption analytical model and simulation results is presented. The simulation is carried out for 10 runs and results are evaluated with 95% confidence level. The parameters used for both the simulation and analytical model are outlined in Table 6.5. The radio unit power consumption values are obtained from the ESP32 MCU data sheet [172]. OMNeT++ discrete event simulator is used to validate the model.

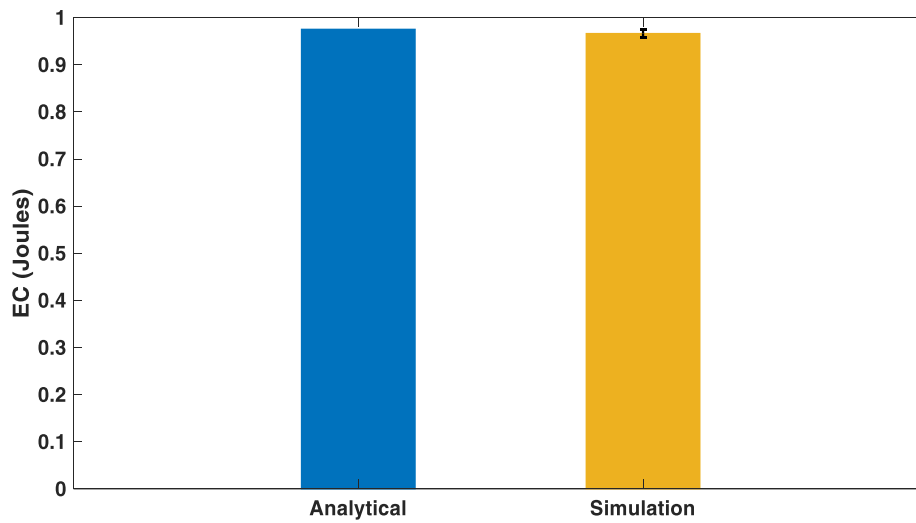


Figure 6.19: Energy consumption analytical vs simulation results

Figure 6.19 shows the comparison between analytical and simulation energy consumption results. The analytical result closely follows the simulation, both with energy consumed value around 0.97 J. In addition, a further analysis of the analytical result is carried out to investigate the energy consumed in the different packet transmission and reception phases as shown in Figure 6.20. Most of the energy is consumed in the network set up phase when transmitting the RPL control messages (around 0.5 J). However, it is expected that this value will significantly reduce in the subsequent shots due to the RPL trickle timer algorithm. With this algorithm, it is expected that the frequency of transmitting RPL control messages after the network initialization phase will significantly decrease, especially considering the fact that the network is static, no topology changes is expected after initial deployment, thereby reducing the energy consumption.

Another noteworthy component is the energy consumed in the seismic data transmission phase, which is around 0.24 J. This component can be used to estimate the network life-time based on the expected number of sweeps planned in a particular survey, computed as the energy consumed per node per shot or sweep. The energy consumption evaluation and modeling presented in Section 6.4 and 6.5 respectively has been published by the author of this thesis in [174].

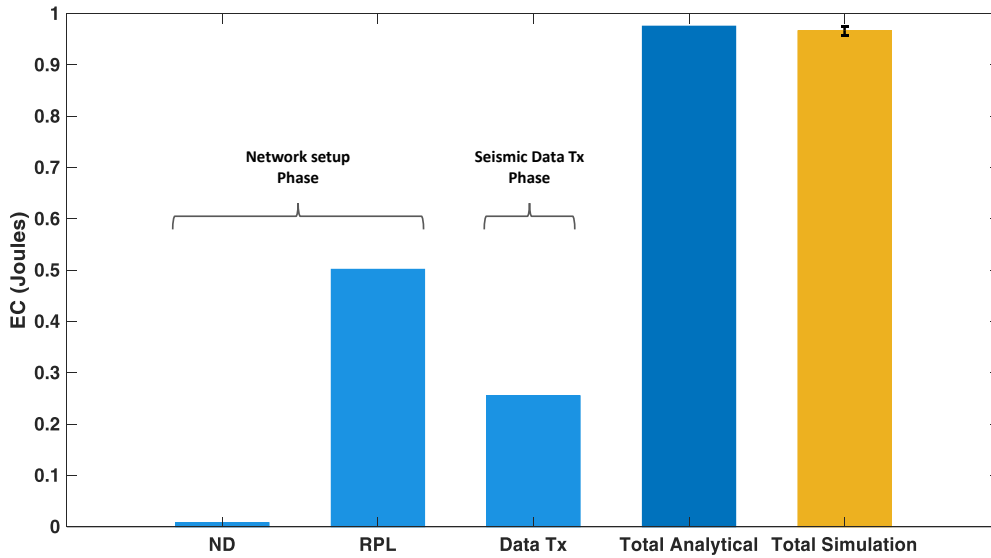


Figure 6.20: Comparison between analytical and simulation energy consumption results, depicting the different energy consumption components that make up the analytical results

6.6 Conclusion

In this chapter, a proof of concept to the third research question outlined in this thesis is presented. Results obtained proved the hypothesis that “careful networking planning, appropriate choice of wireless technologies and protocol will ensure scalability in large-scale WSDA networks”. Furthermore, the results show that the proposed architecture effectively address the challenges and requirements outlined in Chapter 1 such as scalability, reliability, latency, self configuration and management, simplicity and cost effectiveness etc. In addition, it is shown that WSDA network life-time largely depends on the battery capacity as well as the hardware specification of the geophones employed. On the basis of this, an analytical model that estimated the energy consumed in geophones is presented and validated using simulations in OMNeT++ simulator.

7 Conclusion

Large-scale seismic data acquisition networks for onshore oil and gas exploration arising from the growing demand for better subsurface imaging and enhanced resolution of seismic data collected is the fundamental reason for increased survey cost in conventional cable-based seismic data acquisition networks. Thus, exploration companies as well as researchers put more emphasis towards research and development of cost effective wireless-based seismic data acquisition solutions, with the aim of maintaining the same QoS or at least close to that provided in cable-based surveys.

Following a comprehensive review on the state-of-the art SDA methods, equipment and devices, network architecture, technologies, and protocols, an outline of the challenges and requirements for WSDA is presented in this thesis. Based on this, a network architecture for WSDA is proposed with the aim of addressing the challenges outlined. The architecture involves dividing the survey area into subnetworks with each subnetwork having a gateway that serves as a relay node to the CCU. Due to its ubiquitous and license-free advantages, IEEE 802.11 based technology (IEEE 802.11n/ac) in ad hoc mode of operation is adopted as the enabling wireless technology, with RPL as the background routing protocol. As a direct means of addressing interference in the architecture proposed, subnetworks are deployed based on the frequency reuse concept, in such away that no two adjacent subnetworks use the same frequency channel. Some major bottlenecks or research challenges associated with the proposed network architecture include the CSMA/CA based MAC of the IEEE 802.11 technologies as well as the enabling routing protocol. Three major scenarios (scenarios 1, 2, and 3) are defined in this thesis with the aim of evaluating and validating the proposed network architecture in terms of the research questions outlined through both analytical and simulation methods.

For the MAC evaluation, an analytical model is developed that estimate the expected network performance in terms of the default IEEE 802.11 DCF

medium access scheme using scenario 1. The model serves as a tool to undertake parameter studies to observe how parameters like seismic data packet size, data rate, default contention window value, network size etc., affect the network performance especially in terms of scalability, latency, and reliability. This is useful especially in the survey planning stage when mapping out optimal number of geophone deployment in a subnetwork that will ensure acceptable performance in terms of collisions, retransmissions, latency, and packet drop.

The proposed model is an extension of the classical Bianchi model that accounts for unsaturated traffic conditions based on the proposed RPA model, backoff counter decrementing probability, packet drop probability, and the duration a node spends during the backoff procedure before decrementing its counter. The model is validated using simulation for different data rates and varying network size. The results indicate that scalability is better addressed with higher data rate. With lower data rates, some of the assumptions made in the model like binary queue, and unsaturated traffic do not hold for larger network size as it tend to approach saturation traffic case. Generally, saturated traffic condition needs to be avoided in any case as it does not provide the required QoS for WSDA networks. To increase overall reliability in WSDA networks, it is shown from the model that perfect synchronization of geophones should be avoided. In addition, an evaluation of the proposed RPA traffic model is presented with the view of addressing the near real-time SDA, and investigating for an optimal packet size (which represents seismic data sample size) to be transmitted. Results show that a packet size that is large enough but not exceeding the Maximum Transmission Unit (MTU) is optimal in terms of providing the required throughput while keeping packet retransmissions at the barest minimum.

Based on the review of routing protocols in literature compared to the routing selection criteria defined for WSDA, RPL is adopted as the enabling routing protocol in this thesis for the proposed network architecture. The evaluation of RPL performance in simulation benchmarked against other prominent ad hoc routing protocols confirms its choice as the suitable candidate for large scale WSDA, especially in terms of scalability and network self-organization and maintenance. Furthermore, RPL topology is perfectly homologous to the logical topology of the proposed architecture where subnetworks represent

RPL DODAGs, gateways representing DODAG root nodes, and geophones as leaf nodes.

Following the conclusions derived from the performance evaluations with regards to the research challenges outlined for the proposed WSDA network architecture, a proof of concept to the main research questions outlined in this thesis is presented. The proposed architecture is validated using simulation with respect to the global network described in scenario 3. Results obtained show that all challenges outlined for WSDA networks can be addressed using the proposed models in this thesis.

With regards to scalability and reliability, results show that the proposed WSDA network architecture with IEEE 802.11 multi-hop ad hoc based technology employing RPL routing is scalable to large number of geophones in the network when operating in the 5 GHz band. This is due to reduced communication coverage arising from increased path loss at higher frequencies, thereby resulting in reduced CCI from within a subnetwork as compared to the 2.4 GHz. Furthermore, a PDR of up to 96% can be achieved reliably in the network, which can be improved further by increasing the minimum contention window value, which in turn reduces the collision probability of packets in the network.

In terms of latency, up to 90% of packets in the network are successfully received at the CCU with an end-to-end latency of less than 1.2 s, with the remaining packets extending up to a maximum of 2 s latency. This proves that near real-time acquisitions is achieved, which subsequently improves the overall survey productivity. In addition, the adoption of RPL addresses the network self configuration and management requirement as geophones self-configure into subnetworks in the form of RPL DODAG, enabling them to hierarchically organize themselves into parent and leaf geophones. It is important to note that irrespective of the RPL OF configured in the network (i.e., Hop count, ETX, Energy OF), the network performance is almost the same because no topology changes are expected due to its static nature.

In terms of interference minimization, it is observed that careful network planning can significantly minimize interference in WSDA. This is seen with the deployment of subnetworks based on the frequency reuse concept where no two adjacent subnetworks use the same frequency channel. However, with

IEEE 802.11 based technology employed, more number of non-overlapping channels results in lower interference effect in the network, and subsequently the better the overall network performance.

Generally, the device transmit power influences interference in both the 2.4 GHz and 5 GHz bands with respect to the proposed architecture. In the 2.4 GHz band, higher transmit power will result in larger communication coverage, but at the expense of increased CCI within a subnetwork and more signal leakage into adjacent channels which results in increased ACI. Similarly, in the 5 GHz band high transmit power will result in increased CCI. Thus, depending on the specific survey environment and requirements, keeping the transmit power at an optimal level to provide balance between network coverage and interference is key to reducing the effect of transmit power on interference in both bands. Based on the results obtained, 10 mW is optimal in the 2.4 GHz band and 25 mW in 5 GHz band.

Network life time is another crucial issue to consider in WSDA. Depending on the survey area and requirement, seismic data acquisition process can last for several days or weeks. Thus, geophones are expected to run for as long as possible to maximize time before replacement or recharging of geophone batteries is required. Based on the evaluation carried out in this thesis, it is shown that WSDA network life-time largely depends on the battery capacity as well as the hardware specification of the geophones employed. Based on the assumptions of geophone battery and hardware specifications defined for the evaluation in this thesis, geophones can run for more than 30 days at 24 hours operating time before requiring battery replacement or recharge. This is inline with typical requirements or specifications of most geophone devices.

In view of this, an analytical model that estimates the energy consumed in geophones is presented and validated using simulation. The model can be used as a tool for determining the expected network life time based on the specifications from a device datasheet. This is useful especially at the survey planning stage when determining which type of geophone device to use based on a predefined survey specifications. The model is an extension of the proposed IEEE 802.11 DCF model presented, employed to determine the duration of a packet transmission and reception, which is then utilized to

compute the energy consumed for each Tx or Rx based on the hardware radio power consumption specifications.

Generally, it is proven that careful network planning, appropriate choice of technologies and protocols will address challenges attributed to WSDA like scalability, reliability, latency, energy consumption, self-configuration and management. In this thesis it is shown that utilizing off-the-shelf license-free IEEE 802.11 technologies with CSMA/CA based MAC is viable for large scale deployment of geophones in WSDA networks. In addition, it is shown that a proactive, hierarchical based routing protocols (RPL) is a suitable option to use when enabling routing for WSDA networks. Besides the advantage of self-organization and management, utilizing routing also extends coverage as well as scalability in the network.

All codes used for the analytical modeling in this thesis are published in [175].

7.1 Future Work

Future work will be directed towards employing data compression at the geophone level to allow more data to be transferred within the specified bandwidth, especially when a low data rate wireless technology is employed. This will also result in reduced latency as smaller data sizes will lead to faster data transfers. In addition, contrary to uncompressed data, less energy will be required when transmitting compressed data. However, this might not necessarily be true especially considering the computational resources requirements during data compression and decompression, consequently leading to increased energy consumption and processing time, and potentially degrading the geophones performance.

7.2 Other Areas of Application

Apart from the main application area in which this thesis was centered around i.e., oil and gas exploration, the contributions in this thesis can be applied in various other fields or application areas which includes:

Environmental Monitoring: to monitor environmental phenomena like volcanic activities, landslides, glaciers etc., and analyze potential risks, after which management and mitigation strategies can be proposed.

Mining: to determine mineral resources located beneath the earth subsurface as well as monitor and improve the safety of mining operations. In addition, it can also be applied in field of geotechnics to analyze subsoil issues like subsurface voids and slope stability.

Earthquake Monitoring and Early Warning Systems: can be applied in earthquake vulnerable regions to monitor seismic activities, measure their magnitude and intensity, and provide early warnings to minimize the effect of potential risks.

Environmental and Ecological Research: to monitor environmental and ecological factors like habitat dynamics, animal behaviors, migration patterns etc., to investigate important areas like animal movements, terrestrial wildlife and other related ecological and environmental study.

Agriculture: to investigate subsoil composition and structure as well as monitor the health and stress levels of crops from collected seismic data. This will enable farmers to make effective decisions in selecting suitable crops, irrigation, fertilization, precision farming etc., to improve overall crops productivity and sustainability.

Archaeological Study: to investigate and identify certain historical structures and remains by analyzing seismic reflections to discover hidden or buried artifacts, subsurface features, and allow for visualization and reconstruction of archaeological sites.

Hydrological Studies: to provide important insights on underground water reservoir characterization, flow pattern and characteristics, impact of artificial activities on ground water etc. by monitoring ground water dynamics and fluctuations. It can also be used in flood risk assessment.

Civil Engineering: to monitor the health and integrity of structures such as buildings, dams, bridges, tunnels etc., and locate potential damage and weakness to allow for early maintenance and repairs.

Acronyms

ACI Adjacent Channel Interference

ADC Analog-to-Digital Converter

AODV Ad-hoc On-demand Distance Vector

BPSK Binary Phase-Shift Keying

CCU Central Control Unit

CDF Cumulative Distribution Function

CDMA Code Division Multiple Access

CCI Co-Channel Interference

CEPT European Conference of Postal and Telecommunications Administrations

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

DAG Directed Acyclic Graph

DAO Destination Advertisement Object

DIFS DCF Inter-frame Space

DIS DODAG Information Solicitation

DCF Distributed Coordination Function

DFFS Dynamic Frequency Selection

DIO DODAG Information Object

DODAG Destination Oriented Directed Acyclic Graph

DREAM Distance Routing Effect Algorithm for Mobility

DSDV Destination-Sequenced Distance Vector

DSR Dynamic Source Routing

DSSS Direct sequence Spread Spectrum

DTT Digital Terrestrial Television

EC Energy Consumption

E-TORA Energy-Aware Routing Protocol Based on TORA

ECBR-MWSN Enhanced Cluster-Based Routing Protocol for Mobile Wireless Sensor Networks

ECC Electronic Communications Committee

ECDF Empirical Cumulative Distribution Function

E2ED End-to-End Delay

ETSI European Telecommunications Standards Institute

ETX Expected Number of Transmission

FDMA Frequency Division Multiple Access

FHSS Frequency Hopping Spread Spectrum

FSPL Free-Space Path Loss

GDB Geolocation Database

GDD Geolocation Database Dependent

GDSTR Greedy Distributed Spanning Tree Routing

GEAR Geographic and Energy Aware Routing

GEM Graph Embedding for Routing

GPSR Greedy Perimeter Stateless Routing

IBSS Independent Basic Service Set

ICDF Inverse Cumulative Distribution Function

IEEE Institute of Electrical and Electronics Engineers

IGF Implicit Geographic Forwarding

IoT Internet-of-Things

ISI Inter-symbol Interference

ISM Industrial, Scientific and Medical

KPIs Key Performance Indicators

LEACH Low-energy Adaptive Clustering Hierarchy

LEACH-ME LEACH-Mobile-Enhanced

LLNs	Low Power and Lossy Networks
4G LTE	Long-term evolution
MAC	Medium Access Control
MBC	Mobility-Based Clustering
MCS	Modulation and Coding Schemes
MERR	Minimum Energy Relay Routing
MIMO	Multiple Input Multiple Output
MIEEPB	Mobile Sink Improved Energy-Efficient PEGASIS-Based
MSRP	Mobile Sink-Based Routing Protocol
MU-MIMO	Multi-User MIMO
MP2P	Multi-Point-to-Point
MPR	Multi-Point Relays
MTU	Maximum Transmission Unit
NA	Neighbor Advertisement
ND	Neighbor Discovery
NS	Neighbor Solicitation
OF	Objective Function
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OGF	On-demand Geographic Forwarding
OLSR	Optimized Link State Routing
P2P	Point-to-Point
P2MP	Point-to-Multi-Point
PDR	Packet Delivery Ratio
PD_{RLR}	Packet Dropped Retry Limit Reached
PER	Packet Error Rate
PHY	Physical Layer
PLCP	Physical Layer Convergence Procedure

PSME Program Making And Special Events
QAM Quadrature Amplitude Modulation
QPSK Quadrature Phase-Shift Keying
RPL Routing Protocol for Low-Power and Lossy Networks
ROAM Routing On-Demand Acyclic Multipath
SDA Seismic Data Acquisition
SELAR Scalable Energy-efficient Location Aided Routing
SIFS Short Interframe Space
SINR Signal-to-Interference Plus Noise Ratio
SNR Signal-to-Noise Ratio
TBRPF Topology-Based Reverse Path Forwarding
TDMA Time Division Multiple Access
TORA Temporarily Ordered Routing Algorithm
TVWS TV White Spaces
UAV Unmanned Ariel Vehicle
UHF Ultra High Frequency
VHF Very High Frequency
WG Wireless Gateway
WGN Wireless Geophone Network
WLAN Wireless Local Area Network
WRP Wireless Routing Protocol
WSD White Space Devices
WSDA Wireless Seismic Data Acquisition
WSDAN Wireless Seismic Data Acquisition Network
WSM White Space Maps
WSN Wireless Sensor Network
RLSS Registered Location Secure Server
RPA Recording Period Acquisition

RPL IPv6 Routing Protocol for Low-Power and Lossy Networks

RR Rumor Routing

RTR Retransmission Ratio

QC Quality Control

QoS Quality of Service

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