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PERSPECTIVE

A beginner's guide to infrastructure-less networking concepts

Anna Förster[1] | Jens Dede[1] | Andreas Könsgen[1] | Koojana Kuladinithi[2] | Vishnupriya Kuppusamy[1] | Andreas Timm-Giel[2] | Asanga Udugama[1] | Andreas Willig[3]

[1]University of Bremen, Bremen, Germany

[2]Hamburg University of Technology, Hamburg, Germany

[3]University of Canterbury, Christchurch, New Zealand

Correspondence
Asanga Udugama, University of Bremen, Bremen, Germany.
Email: udugama@fb1.uni-bremen.de

Abstract

Infrastructure-less networks connect communication devices end-to-end by managing links and routes independent of fixed networking facilities, relying on dedicated protocols running on end-user devices. The large variety of infrastructure-less concepts and related aspects can be confusing both for beginning Ph.D. students as well as experienced researchers who wish to get an overview of neighbouring areas to their own research foci. Frequently discussed topics such as different types of sensor-, vehicular-, or opportunistic networks are covered. The authors describe different networking concepts by looking at aspects such as the main properties, common applications, and ongoing research. Furthermore, the concepts by common characteristics such as node mobility, network density, or power consumption are compared. The authors also discuss network performance evaluation by describing commonly used metrics, different evaluation techniques, and software tools for simulation-based evaluation. The references given in each section help obtain in-depth information about the presented topics and give hints about open research questions, which can be a starting point for own investigations.

KEYWORDS

body area networks, delay tolerant networks, mobile ad hoc networks, performance evaluation, vehicular ad hoc networks, wireless sensor networks

1 | INTRODUCTION

A large number of different wireless networking methods and technologies have been developed in recent years. One of the main areas of wireless networking includes networks that do not strongly rely on existing network facilities which can be broadly termed as infrastructure-less networks, as opposed to heavily infrastructure-dependent networks such as 5G or 6G. In the infrastructure-less world, terms such as Mobile Ad Hoc Network (MANET), Wireless Sensor Network (WSN), Internet of Things (IoT), Device-to-Device (D2D), Vehicular Network (VANET), Delay-Tolerant Network (DTN), Opportunistic Network (OppNet), and many variations of these have been extensively discussed in the literature. All of them have also been extensively studied in dedicated surveys. However, to the best of our knowledge, no introductory overview exists to compare their properties and discuss their similarities and differences.

This paper closes the gap by exploring the development of the aforementioned research areas and explaining differences and similarities. We have set ourselves the rather challenging goal of summarising, from a ten thousand-foot view, some of the defining characteristics and research topics of a wide range of similar yet different types of networks. The authors of this paper share the strong belief that if you consider yourself, for example, an expert in vehicular networks, you should also be knowledgeable in sensor networks, opportunistic networks and several others. Otherwise, as a community, we risk reinventing the wheel again and again while the solution to our problems might have been just another buzzword away.

We target this paper to newcomers in the area, such as beginning graduate students. However, also more experienced newcomers, such as industry experts or experienced researchers, will profit from reading it to understand the different terms and their main properties and research contributions. This is especially true for upcoming fields, such as flying ad hoc networks.

As it can be seen at the beginning of the introduction, which mentioned MANETs or VANETs, there is also the notion of "ad hoc network" which is closely related to the term "infrastructure-less network". They are often used synonymously. However, an ad hoc network has a special property that many other types of infrastructure-less networks do not share. Ad hoc networks establish end-to-end routes for forwarding messages, even though the nodes may be mobile and the network topology may change frequently. In contrast, other infrastructure-less network architectures, such as opportunistic networks, do not set up end-to-end routes but use other forwarding methods, as discussed in a later section. This paper is a broad overview of all types of infrastructure-less networks irrespective of their forwarding method.

There are some types of networks that resemble infrastructure-less networks from a wording point of view, for example, peer-to-peer networks or crowd computing. However, they are omitted here because they are not covered by the definition of an infrastructure-less network, as we define it in Section 3. We make no attempt to cover the *entire* field of wireless networking and communications [1], we do not consider the performance of the discussed types of networks, nor will we say that one is better than the other. We offer a high-level comparison of their goals, challenges, and assumptions and we do sketch the main research breakthroughs. It is those more "soft" differences, which we aim to highlight in this paper, giving the reader an idea of the pre-dominant types of assumptions being made for the different types of networks and the differences in emphasis of research being applied. It is unavoidable that such a discussion will be influenced by our own research interests, biases, and perceptions, which we have attempted to counter by having a range of contributing authors, working in different areas. In this regard, we also like to point out that the focus of topics in the paper results from the work area of the authors. Therefore, not all aspects of infrastructure-less networks are covered in the same level of detail. This is the reason why we are more detailed about, for example, the architecture of network designs while mentioning security and privacy only occasionally. Additionally, to allow readers to delve deeper into their areas of interest, we provide an extensive array of valuable references to accompany each concept under discussion.

We also like to clarify up-front that in the interest of conciseness and readability, we will leave out in many places (necessary) qualifications such as "from our point of view" or "this is what we perceive to be the mainstream in this field". So, for example, we will prefer a statement like "In wireless sensor networks (WSNs) nodes are mostly assumed to be static" instead of the much more accurate but much wordier "In our view most of the papers in sensor networking assume largely static networks; this does, however, not preclude the case where some or all nodes in the network are mobile, and in fact, there are several works where explicit (and clever) use is being made of mobile networks".

This guide is organised as follows. We start with a description of our goals and our approach in Section 2. Then, we define an infrastructure-less network, and identify relevant research fields in Section 3. In this same section, we put the different fields in relation to each other, and we discuss them individually in detail. Section 4 compares the infrastructure-less networking research areas among each other in terms of certain important network characteristics, such as delay and mobility support requirements. Section 5 looks into the evaluation metrics and methodologies often used for infrastructure-less networks. The tutorial is concluded in Section 6.

2 | GOALS AND METHODOLOGY

In this section, we first identify our goals and objectives and then discuss the approach we decided to follow to compile this guide. Our high-level objectives are:

- Provide the reader sufficient information to understand the most significant differences and similarities between different flavours of infrastructure-less networks.
- Enable the reader to transfer knowledge and experience from one field to another.

These objectives are based on our own experience with supervising students at the postgraduate level. Most of them focus on one particular aspect of infrastructure-less networks, for example, sensor networks, and find it very hard to connect to related fields, to find relevant literature and to transfer knowledge from one field to another. We believe this is mostly due to the amount of published literature, which makes it simply impossible to follow all fields and to read all publications. At the same time, a high-level overview and comparison between these closely related fields is largely missing. We aim to fill this gap with this paper.

Our objectives transform into more concrete goals to:

(1) Offer a high-level definition of infrastructure-less networks and identify current research fields therein
(2) Provide a concise and representative (but not exhaustive) description of each individual field
(3) Identify important network characteristics, which drive the differences in the research fields
(4) Compare research fields in terms of those network characteristics
(5) Discuss typical performance evaluation tools and metrics

The structure of this tutorial follows the above-identified goals closely. For the first goal, we first identified well-known infrastructure-less networks such as sensor networks, mobile ad hoc networks, vehicular networks, and so on. This first list is coming directly from the research fields of the involved authors. Then, we studied the recent literature to identify further types of infrastructure-less networks. In this way, we were able to identify some more fields: train-to-train networks (T2T) and ship-to-ship (S2S) networks. We also discuss shortly D2D networks, which can be defined as somewhere between ad hoc networks and infrastructure-borne networks.

In order to address the second goal, we decided to study some particular topics of each infrastructure-less type of network as follows:

- Definition and main properties: Give a high-level definition as it can be found in the corresponding literature and discuss important properties and assumptions.
- Targeted applications: Discuss the main driving applications of the field.
- History: Discuss where this type of network comes from and why it separated later.
- Most prominent research: Discuss the major contributions and achievements in the field.
- Open issues and research challenges: Discuss ongoing issues and challenges, not yet solved.
- Most relevant communication technologies: List the most widely applied wireless communication technologies for implementation.
- Most related other concepts: Compare to the most closely related fields.
- Summary and recommended readings: Summarise and provide recommendations for further general studies, like surveys and books.

The third and fourth goals are addressed in Section 4, where we identified the most important network or system characteristics, which drive the development and deployment of the discussed infrastructure-less networks. These include mobility, scale, density, connectivity, data traffic, and power restrictions. We compare each of the infrastructure-less networking fields in terms of each individual network characteristic. In Section 5 we identify the performance tools and metrics, most widely used in the infrastructure-less networking community, which also addresses our fifth and last goal.

3 | INFRASTRUCTURE-LESS NETWORKS: FLAVOURS AND CONCEPTS

In infrastructure-based networks, some stations play a special role. Depending on the technology, these are called base stations (2G/GSM networks), eNodeBs or gNodeBs (3G/4G/5G networks), gateways (LoRaWAN/SigFox), or access points (wireless local area network (WLAN) in some of its operating modes). In all of these technologies, these base stations are key facilitators for any communication: any node wishing to communicate must associate (and perhaps authenticate) itself with a base station before it can communicate with others, and subsequently, all communication is relayed through this base station, even if the initiating node and the final destination are direct neighbours. The base stations must be pre-deployed. They are interconnected with each other via a so-called backbone to facilitate communications over longer distances and to manage the mobility of nodes. A key property of such an infrastructure-based network is that end devices *critically depend* on the base stations, and removing the latter will leave the end devices unable to communicate.

In the broadest sense, in an infrastructure-less network, the critical reliance on infrastructure stations like base stations are completely removed or at least substantially weakened to allow end nodes to communicate with each other in a self-organised fashion, perhaps over multiple hops. The absence of infrastructure nodes means that end nodes need to have all the required capabilities to act as facilitators for the communications of other nodes, that is, they engage with routing, they need to collaborate with each other to allocate channel resources like frequency, code, or time, and they need to be able to carry out a wide range of management tasks involved with networking, for example, address assignment, fault management, and so forth. It is *not* required that a node carries out all these functions all the time, it is perfectly reasonable for a set of nodes to *elect* one of them as a leader node and have this leader deal with all the management tasks, but in an infrastructure-less network, each end node must have the capabilities to take over this role, if needed. Overall, infrastructure-less networks need to be *self-organising*. Furthermore, due to mobility and the instability of wireless channels, the network topology frequently changes, and consequently the network must *adapt* to this, for example, in its routing protocol or wireless resource allocation.

The research area of infrastructure-less networks includes many different concepts or flavours, some of them connected closely to each other, some even overlapping, and some with very unique properties. They have developed historically from each other. As a first step before we dive deeply into details, we depicted these "family ties" in Figure 1. This family tree is built upon some important properties of these concepts. In this family tree, we see, for for example, three of the most prominent representatives, mobile ad hoc networks (MANETs), WSNs, and delay-tolerant networks (DTNs) have all emerged from the main idea of ad hoc organization, but have a different goal behind them. For example, in WSNs, we are mostly concerned about energy efficiency, while in DTNs, we need to tolerate substantial delays, mostly for space communications. Many concepts emerged and specialised from WSNs, such as body sensor networks (BSNs), underwater (Wireless

Underwater Sensor Networks (WUWSNs)), or underground (Wireless Underground Sensor Networks (WUSNs)) sensor networks, each of them targeting a specific environment. Many also emerged from MANETs, such as vehicular networks (VANETs), which are faster and move on roads, flying networks (FANETs) to cater to drones, aeroplane-to-aeroplane networks (AANETs) to serve aeroplanes' special needs, and train-to-train (T2T) and ship-to-ship (S2S) networks to cater for further specialised applications. Opportunistic Networks (OppNets) have emerged from DTNs by bringing them to personal communication, mostly on smartphones. Device-to-device networks (D2D) are a special case of cellular networks, where the base station permits direct communication between devices for offloading traffic from the main network.

In this section, we will step through the individual concepts and discuss them. We will focus on their main properties, application scenarios, and achievements. The goal is not to exhaustively discuss all work performed (the sheer amount of available work simply does not allow this) but to offer an orientation to the reader to learn the differences and the unique properties of these concepts. Further, more in-depth readings are provided for each concept in the form of references.

3.1 | Delay-tolerant networks

3.1.1 | Definition and main properties

Delay-tolerant networks are designed to cope with intermittent connectivity along the path between the source and the destination of data messages [2], in contrast to legacy Internet communication which requires uninterrupted end-to-end connectivity. For this reason, intermediate nodes of DTN have large buffers which can keep a set of data packets called *bundles* for an extended period of time. The intermediate node acknowledges the reception to the sender on behalf of the destination; this functionality is also called *custody node.* There may be multiple custody nodes along the path. Custody nodes are, in many cases, mobile, for example, in space networks. A DTN, therefore, follows the *store-carry-and-forward* principle —the custody node physically carries stored information from one location to another and then forwards it once the next hop is reachable.

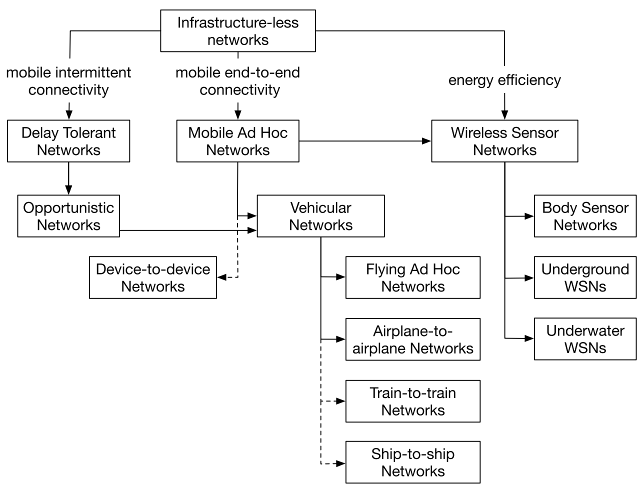

FIGURE 1 Infrastructure-less networks family tree.

3.1.2 | Application scenarios

Delay-tolerant networks were initially deployed for extraterrestrial networks such as satellites or deep-space vessels where due to large distances or occlusions, links are temporarily unavailable—see Figure 2, which also highlights the store-carry-and-forward principle mentioned before. In addition, properties of data generated by spacecraft have to be considered. On the one hand, there is operational data to control and monitor the spacecraft itself. These data are usually small by volume but must be transported with high priority and reliability in order to intervene in case of spacecraft malfunction. On the other hand, there are bulk data collected from scientific missions which need to be offloaded to Earth as efficiently as possible in order to save the scarce capacity of space links. With the growing amount of spacecraft in the Earth orbit and exploring deep space and the increased amount of instruments on board the spacecraft, the amount of data to be transported by the network has increased in the last decades.

3.1.3 | History

The ideas behind DTN had been around for many decades in the latter part of the 1900s. These ideas were mainly driven by the needs of the space programme of USA's National Aeronautics and Space Administration. A pioneer was Vint Cerf with his work on the *Interplanetary Internet* (IPN) in 2003 [3]. Those ideas were subsequently adapted for terrestrial networks by Kevin Fall [4]. The idea was to enable Internet Protocol (IP) based communications in use cases where connectivity was intermittent. The focus especially was on the ability of transport protocols, such as Transmission Control Protocol (TCP) to operate in use cases such as terrestrial mobile networks, exotic media networks, military and sensor networks where delays resulted in disruptions to communications. As a result of the ideas that were generated and the different solutions which were being proposed, subsequently, standardisation bodies were involved in developing common architectures and protocols, able to handle delay and disruption tolerance in

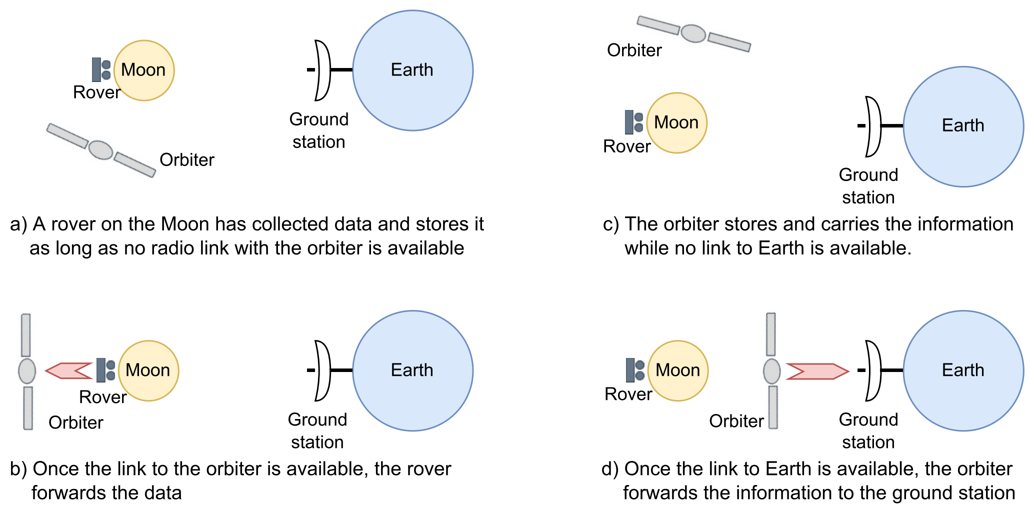

FIGURE 2 Delay-tolerant networks (DTNs) which were first introduced for space applications are only intermittently connected and mostly use the concept of store-carry-and-forward to deliver data.

networks. One such effort is the definition of the DTN architecture and the Bundle Protocol (BP) by the Internet Engineering Task Force in the form of Request for Comments [5–7].

3.1.4 | Research topics

Delay-tolerant networks were thought of as a solution to make existing networking protocols operate under intermittency. Since intermittency was disruptive for transport and network layers, research has focused on finding solutions at these layers. The transport layer was disrupted due to breaks in sessions. The network layer was disrupted due to nodes attaching to different networks at different times, thereby, breaking the hierarchical addressing required for routing.

Therefore, research that focussed on the transport layer problems introduced adaptation or shim layers below the transport layer, such as the BP [5, 8]. Solutions focusing on the routing layer identified different packet routing schemes that considered other factors compared to IP-based routing [9] provides a detailed survey of the routing protocols, including the metrics used in those protocols to determine how best to forward packets.

3.1.5 | Open issues and research challenges

Along with the continuing exploration of space, DTNs will rapidly grow in size and get a meshed structure so that manual routing, as it is performed nowadays, is no longer useful. Instead, the routing will become automated. In contrast to mobile networks on Earth, where user mobility is hard to predict, space vessels move on regular trajectories, which makes it possible to calculate future connectivity patterns. Routing algorithms make use of this fact for example, by deploying *contact-graph routing* where a connectivity pattern is assumed for a given time and then replaced by the next one when the topology of the network has changed.

The constraint of such routing schemes is that, even though they consider changing connectivity, they do not take load requirements into account. While this is tolerable nowadays, where each transmission in a space network is previously scheduled, it will become increasingly complex the more space vessels are actively collecting and exchanging data. This issue becomes particularly important with the introduction of swarms of small satellites, which need communication not only for the offloading of surveillance data but also for the positioning and coordination inside the swarm. In the farther future, one can also think about deep-space relay satellites that buffer data from distant vessels and forward them to Earth. Besides the variation of the traffic load, another reason for less predictable changes in the link quality between space vessels is interference by the environment, such as solar effects. For this reason, routing protocols relying on regular schedules have to be extended for example, by a machine learning component, in order to cope with these less predictable effects.

Furthermore, the IPN remains an important topic when manned space missions are connected to IP-based terrestrial networking services, in contrast to unmanned spacecraft communication for which various non-IP based protocols are provided by an international standardisation organization named Consultative Committee for Space Data Systems (CCSDS)[1]. The biggest challenge for such manned missions is that they can no longer directly communicate with Earth due to the long propagation time of the signals and link interruptions due to lack of transmission range or occlusions, for example, on a Mars habitat. As already mentioned, the transport layer with TCP as the standard protocol does not work

[1] www.ccsds.org.

efficiently in space communication. Transport protocols for space conditions have been specified by CCSDS, the challenge is the seamless integration into the terrestrial network. On the application layer, one could think about proxies for web access that buffer, for for example, content from the terrestrial Internet. Such proxies could learn about the popularity of content to load information proactively to make it immediately available when the users demand it. Live streams should respond to hints from lower layers about the available link capacity and may need to be buffered transparently on a proxy if no direct connection is available.

3.1.6 | Most relevant wireless technologies

Space-borne communication networks do not use off-the-shelf wireless technologies as they are known from terrestrial networks. Researchers, national space agencies and private operators develop specialised wireless transmission systems adapted to conditions in space, in particular the fact that signals are very weak at the receiver side due to the large distances to be covered. In order to foster interoperability between the different players working in this area, CCSDS has published recommendations for the design of interfaces used for space communication links.

3.1.7 | Most related other concepts

As shown in Figure 1, DTNs are the foundation for several types of terrestrial networks with intermittent connectivity. Opportunistic networks forward data between mobile user devices where the users' mobility pattern dictates the available connectivity. Mobile ad hoc networks (MANETs) focus on extending IP-based networks to operate with topologies rapidly changing over time, however expecting paths to be set up for end-to-end connectivity. OppNets combine the ideas of MANETs and DTNs by relaxing the requirement of having end-to-end connectivity between MANET users and, at the same time, removing the assumption of DTNs that contacts can be predicted or looked up.

3.1.8 | Summary and recommended readings

Delay-tolerant networks have been initially introduced for space applications that suffer from long propagation delays and intermittent connectivities. They were later applied to terrestrial applications such as opportunistic networks, vehicular networks, and others. One of the earliest publications about DTNs in space networks and the IPN is ref. [10], which can be used as an introduction to the topic. The publication [11] gives both a historic overview of space networks as well as an outlook into the future. In ref. [12], the communication technologies and architectures for the IPN and DTNs are summarised. The survey in ref. [13] provides an overview of routing methods in DTNs.

3.2 | Opportunistic networks

3.2.1 | Definition and main properties

Opportunistic Networks (OppNets) have developed from DTNs and have one important distinctive property: the mobility of the nodes is not known apriori. OppNets target mostly human-centred applications and devices, such as smartphones, where devices exchange data whenever they are in contact with each other. Participants can join and leave the network at any time, and there can exist isolated nodes or islands. This property comes from the assumption that OppNets do not use infrastructural communication technologies, but only localised ones such as WLAN or Bluetooth, which enable communication between two nodes whenever they are in the physical reach of each other. OppNets are largely technology-agnostic, they can work with any wireless local technology as long as it allows to dynamically discover and exchange data with physical neighbours. There is no strict differentiation between OppNets and DTNs in the literature [14]. However, for the sake of good structure and scientific rigour, we decided to split and discuss them separately, as their research activities and fine properties differ from each other.

3.2.2 | Application scenarios

OppNets target applications where infrastructure is either not existing at all, damaged or overloaded, and where sporadic communication is tolerable. Examples include disaster management applications [15], communication in remote regions [16], as well as communication in scenarios where larger groups of humans split up into smaller groups that act independently and only meet other groups sporadically, like, for for example, when tourists move around in a city in groups that make and break due to the interests they have [17, 18]. Other emerging application areas are vehicular communications [19, 20], agriculture [21], and smart city scenarios [22–24], where information exchange is localised and sporadic.

3.2.3 | History

To the best of our knowledge, one of the first publications to talk about intermittently connected user-held devices was the work of Vahdat and Becker from 2000 [25], who proposed a simple, but a very efficient Epidemic forwarding for partially connected ad hoc networks. Later on, a publication describing the Haggle networking architecture [26] was published in 2004, from which the EU-funded FP6-IST HAGGLE project [27] resulted, which elaborated and evaluated the architecture and proposed a forwarding mechanism called BUBBLE Rap [28] to disseminate data. The SCAMPI follow-up project [29] focused on services. Since then, different efforts have focused on improving and evaluating the performance of OppNets. These include new forwarding protocols [25, 30–32], new or improved caching mechanisms, use of upcoming link technologies [33, 34] and newer usage scenarios [35]. A recent development is the use of OppNets in the Internet of Things, where stationary or mobile nodes disseminate information using OppNets [36].

3.2.4 | Research topics

Most researchers assume that OppNets are always delay-tolerant, because the intermittent contacts and isolation of nodes often result in prolonged delivery times. This is true in most cases, especially when considering people-driven mobility and a relatively low percentage of people running OppNet services on their devices. This assumption has led to the deployment of the store-carry-and-forward principle which was already discussed in section 3.1. An example of how OppNets rely on this principle is shown in Figure 3 which also depicts the main challenge in data dissemination in OppNets. Node 6 is the node that finally delivers the data packet to destination node 7, but how can intermediate nodes predict this? The mobility is mostly human-driven, and predictions are hard to make, which has to be considered when designing forwarding protocols for OppNets.

MObility framework for CHaracteristics Analysis (MOCHA) [40] compares mobility traces in terms of their social, spatial, and temporal characteristics. Their results show that traces from similar environments (e.g., cities) and similar entities (e.g. vehicles) exhibit similar, but not identical properties. Most of the derived metrics have been described in ref. [41], including radius of gyration, travel distance or jump size, connectivity, centrality, betweenness, contact times and contact probabilities, etc. An example of their usage in forwarding protocols is Transmission Prediction Mechanism Exploiting Comprehensive node forwarding capability (TPMEC) [42], which selects the next hop of a message given the contact probability for the final destination (from historical encounters). Other protocols use variants of the centrality metric, for example, influencer [43] or efficient broadcast [37]. Many more are described in ref. [44].

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The most important existing implementations of OppNets are the Serval project [45], Forban [46], SOSChat [47] and FireChat [48]. All of these implementations employ Epidemic-like flooding. Also, the DTN standards described in Section 3.1 are relevant here and often used for various application scenarios, such as agriculture [21].

3.2.5 | Open issues and research challenges

There are many open research challenges in OppNets:

- Unavailability of dedicated communication technologies. Currently, OppNet implementations use Bluetooth or WLAN adaptations and tweaks. One disadvantage is that this hinders the normal operation of the user-carried devices, such as simultaneous usage of WLAN for browsing.

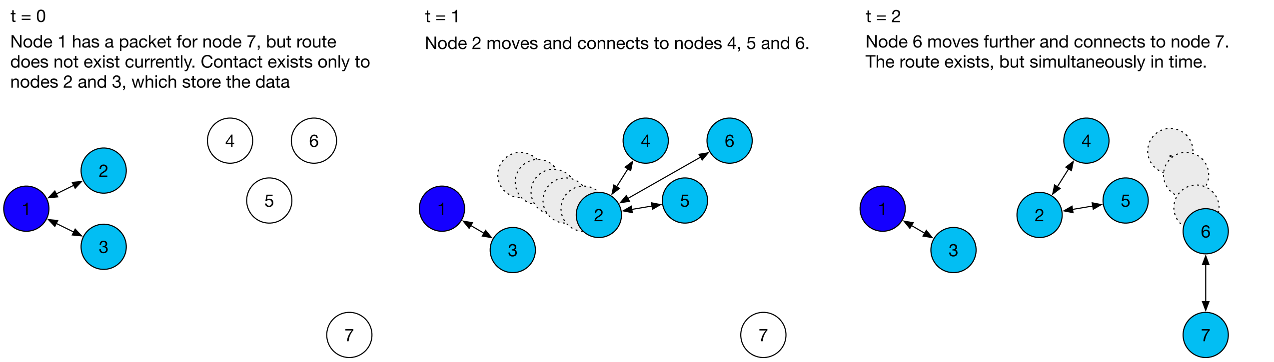

FIGURE 3 Opportunistic networks make use of occasional (unpredictable) connections and mostly use the concept of store-carry-and-forward to deliver data.

One solution to this is to duty-cycle [49] the WLAN connection to only serve OppNets from time to time. Conversely, this severely impacts the data dissemination protocols, which assume that neighbours are discovered quickly. Thus, real-world implementations perform always well below the predicted performance in simulation [50].
- Security and especially data privacy is very problematic with most of the proposed destination-oriented data dissemination protocols. Many of them require the nodes to exchange information about their contacts, their mobility, or their social preferences. Such information is highly sensitive and further prohibits real-world applications.
- Optimal broadcast (destination-less) data dissemination techniques are largely missing. Even if some protocols have been proposed [32, 37, 38], they still perform well below the possible optimum. Existing destination-less protocols require very high communication costs and cache sizes and do not scale with increasing traffic.
- Seamless handover between delay-tolerant and non-delay-tolerant applications and infrastructures has not been extensively studied yet. The open questions include how to differentiate between both types of traffic and how to connect delay-oriented infrastructures like WLAN with delay-tolerant ones.

The need is also great for controlled testbed environments and real deployments.

3.2.6 | Most relevant wireless technologies

Nodes in OppNets require direct wireless communication technologies to communicate among nodes. The most widely discussed wireless technologies [51] are IEEE 802.11 [52] in ad hoc [53] or WiFi Direct mode [54–56], Bluetooth [52, 57, 58], LoRaWAN [59], and the PHY [60] mode of LoRa. Sometimes also IEEE 802.15.4 is considered [61], but not available on end-user devices. An overview of all relevant technologies is provided in the Appendix.

3.2.7 | Most related other concepts

The foundations of OppNets evolved from the concepts of mobile ad hoc networking (MANET) and delay tolerant networking (DTN). MANETs focused on extending IP-based networks to operate in an ad hoc mode, expecting paths to be formed for end-to-end connectivity. OppNets combine both ideas by relaxing the requirement of having end-to-end connectivity between MANET users and, at the same time, removing the assumption of DTNs that contacts can be predicted or looked up. Wireless sensor networks and all their subconcepts are also related to OppNets. In fact, many routing protocols in WSNs are named “opportunistic” [62], referring to the hop-by-hop discovery and data dissemination in WSNs. In the WSN case the “opportunistic” approach (e.g. opportunistic forwarding) is often more targeted towards exploiting link fluctuations/fading, and not so much to counter the mobility of nodes. Especially in highly unstable environments such as underwater WSNs [63], opportunistic protocols are used.

Last but not least, vehicular networks are opportunistic-based too, even if the mobility of vehicles is slightly more predictable than that of humans alone [19, 20]. However, VANETs can be also more challenging than OppNets in general in terms of speed, as vehicles can travel at very high speeds.

3.2.8 | Summary and recommended readings

OppNets focus on enabling data delivery in environments where connectivity is intermittent. They use the store-carry-and-forward methodology to deliver destination-less or destination-oriented data and exploit mobility as a means of disseminating data by using encounters with other devices to exchange cached data. There are several surveys that provide insights into the different aspects of OppNets. A good overview of the research achievements in OppNets is provided in ref. [35]. The surveys in refs. [44, 64, 65] provide a concise summary of the different architectural elements, the application scenarios, and some of the forwarding protocols used in OppNets, and cover also performance evaluation topics.

3.3 | Mobile ad hoc networks

3.3.1 | Definition and main properties of MANETs

A MANET is an ad hoc, multihop wireless network in which the nodes can possibly be mobile [66, 67]. A MANET is often only set up temporarily and for a limited purpose. Mobile Ad Hoc Network nodes are usually assumed to be human-centred devices like laptops, tablets and the like, and these devices run applications of interest to humans, for example, web browsers, video- and audioconferencing tools, chat software, tools for collaborative editing, etc. A typical MANET scenario is depicted in Figure 4.

Accordingly, MANET research and MANET protocols are designed to support well IP-based protocols (IP, TCP, UDP, SCTP, multicast protocols, etc.) and IP-based applications (e.g. video conferencing and collaborative editing), and the resulting user traffic characteristics (packet sizes and packet inter-arrival time distributions) are similar to user traffic characteristics in wired networks.

There exist some typical assumptions about MANETs. As opposed to WSNs (Section 3.7), MANET nodes have quite limited or no interaction with the physical environment, as they mainly serve human-interest applications. Mobile Ad Hoc Network nodes can be mobile but are commonly assumed to move at relatively low speeds, for example, pedestrian speeds. The mobility patterns are often assumed to be completely

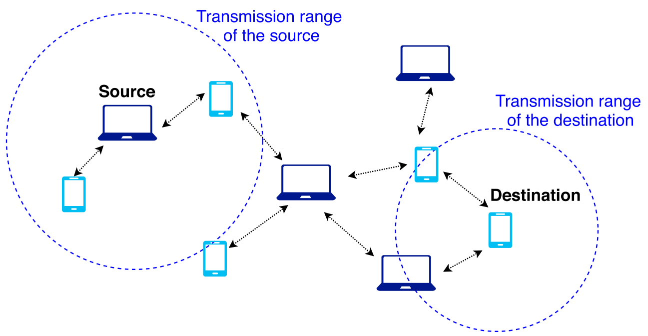

FIGURE 4 A typical mobile ad hoc network (MANET).

random (like for example in the random waypoint model [68, 69]) and not strongly bound by additional constraints—unlike vehicular networks (VANETs, Section 3.4), where nodes are constrained to move along streets. A single MANET is considered to be connected to most if not all of the time, that is, any node in the network has a route to any other node. Network partitioning is usually considered a rare exception and treated as such. MANETs are often assumed to be multi-hop wireless networks, with low to moderate network diameters. MANETs can operate in isolation, for example, as a temporary network set up for an ad hoc working group to support collaborative work on a document. However, there can also be one or more nodes with access to the general Internet, which then serve as gateways. All nodes except for the gateways have the same set of capabilities, even though the member nodes can temporarily elect some particular member to take on special roles, for example, related to resource management.

3.3.2 | Targeted applications

Important use cases include temporary local networks and extensions to existing networks, for for example, an ad hoc working group sharing files or doing collaborative editing during a meeting, where the participants communicate directly with each other. This can also include the sharing of resources like printers, file servers, etc, perhaps facilitated by service discovery protocols [70, 71] that allow nodes to offer and advertise services to others, and nodes needing services to specify their requirements and find service providers. Another use case is the extension of wired networks for Internet access and the establishment of a multi-hop connection between wireless terminals and an Internet Gateway (IGW). Here, most communication is between the wireless terminals and the gateway, and rarely between wireless terminals (except for routing/forwarding or other network management purposes). These use cases clearly show that MANETs were always considered as a means of extending the reach of traditional networks. Establishing paths include delays and overheads due to the signalling involved, varying based on the specific signalling protocol used. But once the paths are established, the applications simply employ traditional communication protocols (IP, TCP, UDP, etc.), expecting similar end-to-end delays and overheads.

However, it is fair to say that there is no real "killer application" for MANETs and neither has there been any strong commercial interest and research emphasis has shifted somewhat towards vehicular and flying ad hoc networks (VANETs and FANETs), and WSNs. Nevertheless, the research activities of the MANET community have laid important foundations for these newer fields and MANETs can be regarded as their "ancestor".

3.3.3 | History

Research efforts in infrastructure-less networking already started with the DARPA packet radio project, initiated in 1973 (see [72, 73]). The introduction and commercialisation of wireless local area technologies like the IEEE 802.11 standard then led to a vast increase in research activities. The first version of IEEE 802.11 was published in 1997, building on earlier commercial systems like WaveLAN (introduced in 1988) and ArLAN. Research in MANET routing protocols gained traction in the early to the mid-1990s, when Destination-Sequenced Distance-vector routing, one of the first routing protocols for MANETs was published in 1994 [74]. Later on, many more protocols emerged and were adopted as Internet standards.

3.3.4 | Research topics

The area that has received perhaps the most attention is multi-hop routing protocols. In recognition of node mobility, and in response to the observation that in many scenarios it is simply not necessary for a node to have a route to an arbitrary other node available immediately, the class of *reactive* routing protocols have gained prominence in the MANET area. Examples of this class are the Dynamic Source Routing [75] and Ad-hoc On-Demand Distance Vector routing protocols [76].

Reactive routing protocols differ from their (pro-active) counterparts on the Internet. In pro-active routing, the routing protocols are active all the time to gather information about the topology and to calculate forwarding tables for all possible destinations, independently of whether there is any actual data transfer ongoing. In reactive routing protocols, routes are only discovered and the routing state is only created when an actual need arises, that is, if some source node wants to send a packet to a destination node. Note, however, that not all MANET routing protocols are reactive ones, for for example, Optimized Link State Routing [77] is a pro-active routing protocol.

There are further classes of MANET routing protocols, for example, geographic routing protocols [78] like the greedy-perimeter stateless routing protocol [79], where routing is only based on geographic positions. In particular, a forwarder node will have to make a routing decision knowing only the geographic position of the destination and of its immediate neighbours.

An important and foundational stream of research has been concerned with the provision of quality-of-service (QoS) guarantees over multihop wireless networks, including transmission scheduling schemes [80, 81], admission control or QoS-aware routing [82, 83]. Another prominent line of research has been the behaviour and performance of TCP over wireless networks [84], in particular multihop wireless networks [85–87]. A key difficulty is related to TCP's congestion control algorithm [88] which in several TCP versions have a tendency to interpret packet losses as a sign of congestion, triggering TCP to reduce the sending rate. In wireless networks, however, packet losses can also be induced by the wireless channel.

Besides the construction of protocols and systems for MANETs, the emergence of wireless multihop networks has triggered a significant amount of theoretical research, which comes broadly under the notion of network information theory [89] and which includes important results on the capacity of mobile multi-hop networks [90, 91] or the application of novel coding techniques like network coding to wireless multihop networks [92].

3.3.5 | Open issues and research challenges

Broadly, the research mainstream has moved away from general MANETs towards more specialised types of wireless multihop networks, including vehicular networks (Section 3.4), flying ad hoc networks (Section 3.5), sensor networks (Section 3.7), and opportunistic networks (Section 3.2).

3.3.6 | Most relevant wireless technologies

The field of MANETs grew more or less in parallel with the emergence of commercially available WLAN technologies, and in this class the IEEE802.11 standard family [93] (also referred to as WiFi) gained practically complete dominance already in the second half of the 1990s. Hence, naturally, the bulk of research work was built on WLAN. Some of the WLAN (and more general WLAN) characteristics most relevant for MANET research are: (i) ranges of up to a few hundred of metres; (ii) data rates of tens or even hundreds of Mbit/s; and (iii) availability of decentralised medium access control protocols. An overview of all relevant technologies is provided in the Appendix.

3.3.7 | Most related other concepts

The most related other concepts are vehicular and flying ad hoc networks (VANETs, FANETs) and the different types of WSNs. VANETs consider a special case of MANETs with vehicles as devices and the resulting vehicular mobility on road networks. FANETs are often seen as a specialisation of VANETs, where devices are flying drones moving without the restrictions of a road network. In the case of WSNs, the main difference is the extreme resource limitation within sensor nodes and the need for energy efficiency. At the same time, mobility is usually not considered a lot in WSNs and applications do not centre on humans but on interactions with our physical environment.

3.3.8 | Summary and recommended readings

The research activities in the field of mobile ad hoc networks have been foundational for several other fields of ad hoc networks, in particular, they have led to a deeper understanding of the challenges in routing, QoS provisioning, end-to-end transport, and several other issues in multi-hop mobile wireless networks. Surveys of routing protocols can be found in [94, 95]. There also exist good books summarising the research on MANETs [66, 67].

3.4 | Vehicular ad hoc networks

3.4.1 | Definition and main properties

Vehicular Ad Hoc Networks (VANETs) are an important component of intelligent transportation systems (ITS), which aim to improve transportation of humans and goods to be safer, more environmentally friendly and more resource-efficient [96]. An ITS system architecture (an example is shown in Figure 5) involves several stakeholders and devices, including vehicles (also autonomous ones), road-side units (RSU), possibly satellites and stationary computing elements like (the cloud) servers. An essential part of an ITS is the communication between vehicles (V2V—vehicle-to-vehicle communications) and between vehicles and RSU or other fixed infrastructure (V2I—vehicle to infrastructure). In the ITS architecture adopted in the United States,[2] the V2X part of an ITS relies on ad hoc networking techniques.

There are some key properties distinguishing vehicular ad hoc networks [97, 98] from general ad hoc networks. First, a primary purpose of vehicular networks is to support a wide range of road safety applications (e.g. collision avoidance, intersection collision warnings, lane change assistance, emergency vehicle warnings, etc.), and many of these applications require vehicles to frequently broadcast their own position, speed, and heading to their immediate neighbourhood. A fairly typical assumption is that these messages are sent every 100 ms [99]. In addition to these time- and reliability-critical applications, they also need to support general IP traffic to support applications in the area of entertainment or traffic resp. vehicle fleet management. Secondly, the mobility assumptions in VANETs are substantially different from those in general MANETs. In VANETs, the nodes move at vehicular speeds ranging from 40 to 60 km/h in urban environments and often exceeding 100 km/h on motorways. Hence, vehicular nodes move much faster, leading to a

[2]See https://local.iteris.com/arc-it/.

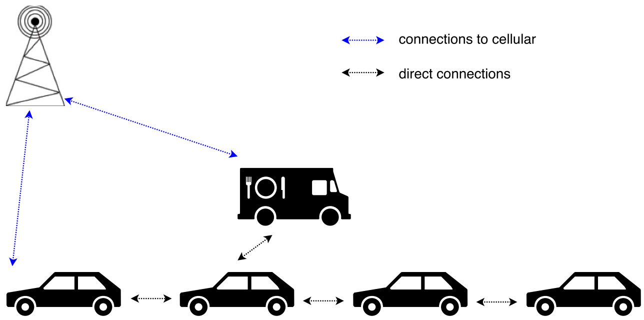

FIGURE 5 Typical Vehicular Network (VANET) scenario.

much more volatile topology and only relatively short connectivity periods. At the same time, the movements of vehicles are much more predictable (since they usually follow streets) and can be strongly correlated (e.g. all cars on a one-way road will move in the same direction). Third, in VANETs there is a strong need to include geographical concepts, for example, one needs communication primitives allowing to disseminate information to all or only some of the nodes within a given geographical region. This has not received much attention in the MANET space. A further related point is that in VANETs many information items are only of local relevance and only need to be disseminated in some geographical neighbourhood of a transmitter. Information is also often only valuable for a limited amount of time, like for example, information about ephemeral events like congestion.

3.4.2 | Targeted applications

The main application areas for vehicular networking are described in [99], together with important requirements. Of particular importance are applications related to road safety, for for example, collision warnings, warnings about overtaking vehicles, merging assistance, stationery vehicle warnings, and others. The goal of traffic efficiency and management applications are to improve the traffic flow and efficiency, for for example, reducing fuel consumption through platooning [100], disseminating map updates to vehicles, and others. Furthermore, there are infotainment applications.

3.4.3 | History

Research and development of ITS in general and vehicular networks in particular already started in the 1990s. A key development was the Dedicated Short-Range Communications (DSRC) technology in the United States [101, 102], which combined the IEEE 802.11p protocol and the WAVE resp. IEEE 1609.x standards suite [103–105], the latter specifying operation on multiple frequency channels, security aspects, networking services and message formats for vehicular applications (the WAVE Short Message Protocol). These developments were supported by the allocation of a frequency band in the 5.8–5.9 GHz range dedicated to vehicular communications. In the last few years, there has been substantial interest in augmenting or even replacing the DSRC services with cellular technologies like LTE or 5G, also often denoted as C-V2X ("cellular vehicle-to-x") [106, 107].

3.4.4 | Research topics

An important research area in VANETs are MAC protocols [108, 109]. These are challenging to design because VANETs are faced with a fast-changing topology and have to provide reliable and periodic local broadcasts of safety messages to neighbouring vehicles. To address reliability and periodic transmissions, distributed TDMA-like MAC protocols have received some attention [110–112]. The majority of the work, however, has focused on the properties of IEEE 802.11p, as it is a part of the DSRC protocol stack. A key problem in IEEE 802.11p is that safety messages are transmitted as local broadcasts, and the sender does not get any feedback about the transmission outcome. Hence, the transmitter will not know if its messages have experienced collisions, in particular, hidden-terminal collisions and the reliability of IEEE 802.11p for safety applications has received significant attention, for example, in [113–115].

Another important research area in VANETs is routing [116, 117]. Due to the high relative speeds, the network is quite volatile and established routes become stale quite quickly, posing serious problems for classical MANET-type routing protocols. Furthermore, VANETs often have to deal with intermittent connectivity between nodes, for example, when a platoon of cars on a motorway becomes separated temporarily. These issues have motivated researchers to design specifically tailored VANET routing protocols, some of which extend classical MANET routing schemes [118], while others use geographical routing and forwarding [119].

A third important research area for VANETs is protocols for information dissemination, which can deal with the problems posed by intermittent connectivity [120–123]. These protocols often incorporate store-carry-and-forward techniques, which implies that VANETs also operate the same way that opportunistic networks do. Information dissemination protocols also need to be cognizant of the fact that information is often only of value for a limited time or within a limited region. This research area overlaps largely with opportunistic networks, detailed in Section 3.2.

3.4.5 | Open issues and research challenges

VANETs pose substantial challenges in the areas of security, trust, and privacy [124]. In traditional centralised approaches to security (e.g. in enterprises) users and nodes are usually authenticated against a centralised database and the devices themselves are tightly managed. In ITS it would be impractical or even impossible to establish a centralised database for authentication, and the devices/vehicles are generally unmanaged and can be compromised. It is therefore in general hard for a receiver of a vehicular message to authenticate or trust the sender. Instead, it appears more promising to establish trust in the contents of a message, for example, by comparing it against messages from other senders related to the same event.

3.4.6 | Most relevant wireless technologies

The preferred technologies for VANETs and ITS have varied between regions. Until quite recently, both the US and Europe have converged on a technology known under the designation IEEE802.11p, which started out as an amendment to/a variant of WLAN and has since been integrated into the WLAN standard [93, 125]. It shares many characteristics of other WLAN variants, but has a modified physical layer (to increase range and make it more robust to mobility) and includes MAC layer modifications that remove the need for authentication/association and increase interoperability with the IEEE1609.4 WAVE multi-channel extension. Recently, there has been substantial interest in C-V2X, see above. An overview of all relevant technologies is provided in the Appendix.

3.4.7 | Most related other concepts

VANETs have commonalities with general MANETs but use different assumptions about traffic load (in particular the added safety-critical traffic) and mobility features (higher speeds and better predictability). Due to their mobility properties VANETs also have a higher propensity to be only intermittently connected, which explains why opportunistic networking techniques have also often been considered in the context of VANETs [122, 126, 127].

3.4.8 | Summary and recommended readings

Vehicular ad hoc networks, while sharing some commonalities with MANETs have unique characteristics which make them a class of their own. These characteristics include much higher node speeds, more constrained node trajectories, and more volatile topologies, which result in a higher potential for intermittent connectivity. The potential societal and commercial benefits of VANETs are well understood and have motivated government agencies and car manufacturers to enter this area [128]. For further studies, these papers give a good overview of VANETs [129–132].

3.5 | Flying ad hoc networks

3.5.1 | Definition and main properties

A FANET is made up of several drones, formally called unmanned aerial vehicles (UAV), possibly of different types. A drone is a remotely or autonomously piloted aerial vehicle that carries an application-dependent payload, for example, cameras, LIDARs, or other sensors. There are two main classes of drones: fixed-wing and rotary-blade drones (the latter are also often referred to as copters). Fixed-wing drones are similar to aeroplanes, they have fixed wings with a predetermined aerofoil generating lift, and a propulsion system moving the drone forward [133]. In rotary-wing drones, lift and movement are generated through rotating rotor blades. Fixed-wing UAVs can achieve much higher speeds, much longer mission times, and can carry more payload, but copters have better maneuverability, for for example, they can perform vertical take-off and landing or can hover over a fixed position. Some designs of rotary UAVs are discussed in [134, 135]. Many UAV applications can benefit from deploying multiple UAVs, operating individually and only interacting to avoid collisions, or forming a FANET to enable deeper collaboration. Such applications include object detection (several UAVs searching for an object and sharing information about their observations so far [136]), or object inspection (several UAVs take observations of the same object, e.g., from different angles/positions, or using different sensors). It is fair to say that civil applications of collaborative swarms are still rare. General advantages of using several UAVs instead of a single one include increased dependability through redundancy, and the ability to operate "in parallel" to gain significant speedups.

A typical FANET Architecture is shown in Figure 6. A ground station is usually operated by a human user, it can range from a simple remote control for small UAVs to much larger stations which include also payload control. The ground station transmits control commands for manipulating the UAV flight paths, and possibly also control commands for the payloads (e.g., starting/stopping sensors) through the uplink channel. In the opposite direction, the downlink channel is used for acknowledgements of control commands, frequent status information from the UAVs (e.g., position, speed, heading—*telemetry*), and transmitting sensor data or payload information. The information exchanged among UAVs often includes position/speed/heading and mission-specific information, for example, about task allocation, coordination of movements in swarms or formations. The communications technology used among UAVs can generally differ from the one used for ground communications. Within the UAV swarm, there is often one or a few designated members which maintain the ground link and which act as a gateway for the other UAVs, hence, a multihop ad hoc network needs to be established among the UAVs. Alternatively, each UAV can have a separate link to the ground station, and inter-UAV communication is going through the ground station. In another alternative

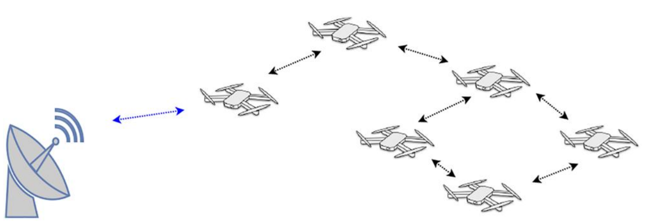

FIGURE 6 Typical flying ad hoc network (FANET) architecture.

network architecture, UAVs could be grouped into clusters with an ad hoc intra-cluster communication, and inter-cluster communications being facilitated by the ground station.

3.5.2 | Targeted applications

A FANET broadly needs to support three different kinds of data, with different requirements.

Telemetry data
A UAV periodically reports the status of onboard sensors (IMU and GPS information) and its own state (speed and direction).

Coordination data
Data required to coordinate the UAVs, for example, frequent information about the position, speed, heading for collision avoidance, data for collaborative flight path computation, routing and network information.

Sensor data
Onboard sensors data (e.g. camera) is being reported to the ground station.

In the last few years, drones or UAVs have found applications in a wide range of areas focusing on the above requirements, for environmental monitoring [137], surveillance and inspection of infrastructure [138], search and rescue [134, 136], logistics and delivery services, telecommunications and public safety communications [139–143], as well as to collect data from ground sensors, and in forestry and precision agriculture [144, 145].

3.5.3 | History

FANETs are a relatively young area of active research. The earliest known work related to the use of UAVs for commercial purposes was in agriculture [146], in 2002. The work was related to developing an unmanned helicopter to map the area covered by crops.

3.5.4 | Research topics

There are several primary areas on which research has focussed. The first of these is the designs (or the types) of UAVs. The work in refs. [135, 137, 147–149] provides research done on the designs of the different drone types. A second large area concerns applications of UAVs (see the references given above), which often integrate techniques from artificial intelligence (e.g., computer vision) and optimization to determine tasks for individual UAVs, compute flight paths, and so on. In particular, (cooperative) path planning is a rich area of research, see for example, [150–153]. And of course, classical topics like routing have also received significant attention [154].

3.5.5 | Open issues and research challenges

The research issues in FANET design overlap substantially with important research issues in VANETs. In both cases, the mobility characteristics of high node speeds and frequent topology changes make the design of routing or medium access control protocols a challenge. In the case of MAC protocols, the research emphasis is largely the same between FANETs and VANETs, whereas in the case of routing protocols the different properties of FANETs (three-dimensional node deployments, reduced predictability of node trajectories) require unique solutions. Note that FANETs also naturally have some overlap with AANETs, though the latter tend to operate at higher speeds and have a substantially lower network density than FANETs.

Aside from these more classical research areas shared between VANETs and FANETs, there are some issues specific to FANETs. A more foundational issue is to gain a more detailed understanding of the link characteristics in aerial networks so that suitable channel models can be created. A second key area is the design of coordination and collaboration protocols allowing UAVs to perform joint task allocation and path planning. Furthermore, many applications will also require high-quality video to be streamed from selected FANET nodes to a human on the ground, and this traffic needs to properly co-exist with real-time traffic for coordination and control.

A quite important issue for individual UAVs and FANETs is airspace management [155], which in the broadest sense focuses on avoiding collisions between aerial vehicles, in particular between UAVs and manned vehicles. However, this problem is out of scope for this paper.

3.5.6 | Most relevant wireless technologies

For air-to-air communications between drones, most publications assume WLAN (or its 802.11p variant) [93], particularly when higher data rates are required between drones (e.g. for transmission of video streams). Cellular D2D is also used to enable reliable communication among UAVs [156]. For lower data rate requirements and when energy is an issue, a low-power local or personal area networking technology like IEEE 802.15 [157] has been considered. An overview of all relevant technologies is provided in the Appendix.

3.5.7 | Most related other concepts

FANETs have many similarities with VANETs, for example,: (i) the relatively high speeds of the involved vehicles (fixed-wing UAVs can reach speeds of up to 100 m/s); (ii) the need to frequently exchange information about the position, speed and direction with neighbours to avoid physical collisions; and (iii) the fact that energy considerations do not play a major role in the design of network protocols—in both cases the energy consumption of a UAV is dominated by the energy required to keep it in the air. However, there are important differences in the mobility properties: in VANETs, the stations move in two dimensions and are often constrained to roads; in FANETs, the stations move in three dimensions and are much less constrained. Furthermore, VANETs are made up of independent nodes under different ownership, whereas to date FANETs are mission-specific and the nodes cooperate under a common authority.

3.5.8 | Summary and recommended readings

FANETs are a young and emerging area, and one can expect substantial change over the next few years as commercial applications and the regulatory landscape evolves, for example, allowing for a larger degree of autonomous and beyond visual line-of-sight operations. In terms of network properties FANETs are perhaps closest to VANETs and AANETs, but with some important differences, including different mobility properties or the fact that as of today FANETs are made up of cooperating stations under the same ownership. A number of surveys have appeared recently, including [135, 149].

3.6 | Air-to-air networks

3.6.1 | Definition and main properties

Ad hoc networks consisting of multiple aircraft used to extend the connectivity over continents and oceanic regions are referred to as Aircraft-to-Aircraft Networks (AANET) or Aeronautical Ad Hoc Networks. AANETs enable air-to-air communication to exchange information among Aircraft over multiple hops. Generally, the use of wireless communication in aviation applications is categorised as follows (additionally, refer to Figure 7):

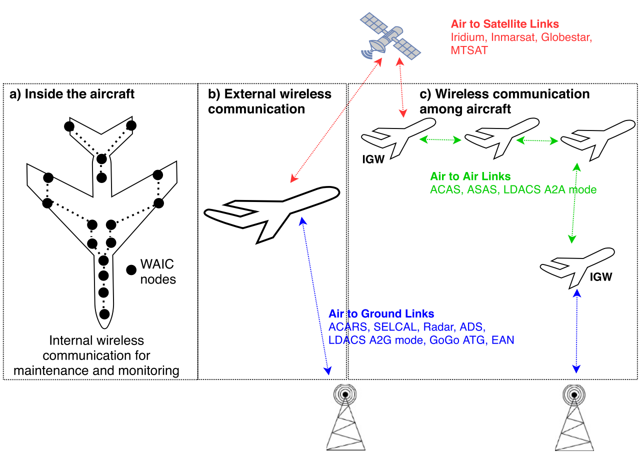

FIGURE 7 Categories of wireless communication used in aviation—(a) inside the aircraft, (b) external wireless communication, and (c) communication between aircraft.

Inside the aircraft

Modern aircraft use different communication technologies and a large number of sensors and actuators, for the purpose of improving the operations, providing more comfort for passengers, and simplifying the maintenance procedure.

However, the current means of communication used for maintenance purposes, for example, monitoring the air quality inside the cabin, is still based on wired technologies. In 2015, the frequency band of 4200–4400 MHz was allocated for on-board wireless communication. The current standard that is being discussed to replace on-board wired communication is called "Wireless Avionic Intra Communication (WAIC)" [158]. The WAIC standard considers a TDMA scheme in combination with channel hopping and ARQ to compensate for packet losses caused by interference. The WAIC-based avionic applications can be considered as a specific category under WSNs (refer to (a) of Figure 7).

External wireless communication

When an aircraft is in the air, either a satellite link or a cellular link is used for communication. This requires to enable communication with the control centres, ground staff and also to let passengers access the Internet, for example, GoGo@2Ku system is capable of supporting at least 70 Mbit/s per aircraft [159] (refer to (b) of Figure 7).

Communication between aircraft

Though satellite links provide global coverage, they are expensive and have higher delays. Unfortunately, cellular coverage is limited to the land area. Considerations of these hindrances and avionic requirements like reducing the congestion of air space during peak times, direct communications among aircraft for supporting formation flights to reduce fuel consumption, have inspired both academic and industrial communities to develop the AANET concept. AANETs extend the coverage range over oceanic and remote airspace where no connectivity to the base station and satellite exists. AANETs also reduce the communication cost and delay in communications compared to the traditional avionic wireless communication achieved with satellite links.

The different kinds of existing as well as upcoming communication technologies used in avionic applications are shown in Figure 7. Additional details about these technologies are given in ref. [160]. Here we focus only on the third category, which is concerned with the *communication between aircraft*, referred to as AANETs.

3.6.2 | Targeted applications

There are mainly 3 types of applications that require connectivity over air.

Air Traffic Control (ATC) provides all communications between the cockpit crew and the air traffic controllers and the computation of aircraft position using DMEs (Distance Measuring Equipment). This should be very safe and reliable. The current system is based on radar-based technologies.

Airline Operational Communications exchange business-related information between the crew and the airline operations centre on the ground, for example, related to catering.

Aeronautical Passenger Communication dedicated for entertainment applications.

3.6.3 | History

AANETs are still a relatively young research area with the earliest works appearing in 2005–2006. Their focus was the extension of Internet connectivity over other aircraft using ad hoc networks to reach the aircraft that has better Internet connectivity [161]. The idea to have ad hoc networks in the air mainly came about with the introduction of Internet connectivity inside aircraft for the use of passengers using mechanisms such as Connexion by Boeing [162].

3.6.4 | Research topics

Most application scenarios considered in AANETs serve ATC needs. Some research focuses on reliable communication to share flight recorder information among aircraft [163] in proximity from time to time and to exchange control information for fuel-saving purposes. For example, the sharing of the expected waiting time for landing via the propagation of Traffic Collision Avoidance System messages helps an aircraft to smoothly reduce the speed even before reaching the airport's coverage area. This helps to reduce fuel consumption by avoiding drastically reducing the speed. *Formation flight* is an upcoming avionic application to let multiple aircraft fly together similar to the formation flying of birds. This helps to save fuel and thus carbon dioxide emissions. Aircraft flying over the North Atlantic air space are extensively studied for AANET research as they create stable communication links due to less movement and stable velocities [164–166]. An aircraft closer to the ground or having a satellite link acts as an IGW of the AANET.

3.6.5 | Open issues and research challenges

Like in MANETs, several ad hoc routing protocols have been proposed and evaluated for AANETs. The main research challenges of AANETs are on mobility, security, reliability, and interference. One key research area is to discover an aircraft, which serves as an IGW which has either a satellite or a ground-based cellular connection. A popular routing scheme used in AANETs is geographic-based forwarding [160]. Further, the upcoming communication technologies used in AANETs such as L-band Digital Aeronautical Communications System (LDACS) [167] are being evaluated to integrate secondary data without interfering with the existing system like DMEs. In contrast to MANET mobility models with unpredictable node trajectories, AANET mobility mainly depends on pre-planned flight routes. Therefore mobility patterns are mainly analysed based on existing flight data records [164]. In summary, the relative position of the aircraft is more or less stable in an AANET, while the connection to an IGW is constantly changing. Energy efficiency is not an issue in AANETs and thus also resource intensive optimization and machine learning algorithms are considered to enhance the reliability of communications [168, 169] and to find the optimum IGWs.

3.6.6 | Most relevant technologies

L-band Digital Aeronautical Communications System Air-to-Air (A2A) mode enables IPv6-based air-to-ground communication ensuring interference-free coexistence of LDACS in parallel with other aeronautical systems in the same frequency band (960–1164 MHz). L-band Digital Aeronautical Communications System supports bidirectional links to multiple aircraft under its control. User data transmissions over LDACS are scheduled by the ground station, while control data uses statically allocated recurring resources. The current specification documents do not include scheduling. The LDACS data link layer uses ARQ to provide reliable data transmission. L-band Digital Aeronautical Communications System specifications are not yet standardized [167, 170]. Some of the LDACS A2A most relevant characteristics for AANET research are: (i) ranges of up to 370 km; (ii) data rates of 315 to 1428 kbit/s (ground-air) and 294 to 1390 kbit/s (air-ground); (iii) 512 planes per cell; and (iv) 34–968 bytes payload. An overview of all relevant technologies is provided in the Appendix.

3.6.7 | Most related other concepts

As in MANETs, AANETs are also formed in dynamic topologies with self-organised routing. But compared to MANETs, aircraft forming AANETs travel along predefined trajectories rather than having random changes in direction or speed. Furthermore, while power consumption is amongst the more important issues in MANETs, this is not the case for AANETs. The characteristics of radio propagation follow mostly the Line of Sight pattern for AANETs. Both, acceptable delays and throughput to satisfy passengers' needs in the aircraft and additionally, reliable links are the main requirements for AANETs [160] while MANETs are mostly focused on energy-aware routing and maximising the network lifetime.

3.6.8 | Summary and recommended readings

AANETs provide an extension of the Internet connectivity over other aircraft using ad hoc networks to reach an aircraft that has better Internet connectivity and also enhancing information sharing among aircraft. In contrast to MANET applications, aircraft manufacturers and telecom operators are very keen on realizing AANETs. The main challenge is to certify technologies used in AANETs before real deployments. We recommend the survey in ref. [160] to know more about the current research progress, recent experimental results and future research directions, and possible scenarios for AANETs.

3.7 | Wireless sensor networks

3.7.1 | Definition and main properties

Wireless sensor networks consist of (wirelessly) interconnected sensors [171–173], which can measure a range of different environmental variables, for example, temperature, or light intensity. Individual sensors are housed in a sensor node platform, which integrates the actual sensors, a general-purpose processor or microcontroller, memory, transceiver, energy supply, and possibly some additional circuitry. Sensor node platforms tend to be small embedded platforms with rather limited resources in terms of computational power and memory, and are often deployed in large numbers. A very early paper in the field coined the (still) visionary notion of "smart dust" [174]. While the popular node platforms have evolved over time (for example memory is now in the orders of tens to hundreds of megabytes whereas in the beginning, memory was in the order of tens to hundreds of kilobytes), the "small platform" assumption still holds, relatively speaking [175]. Furthermore, most sensor nodes are assumed to be battery-driven and thus energy efficiency becomes crucial and has been one of the main drivers for research. We briefly summarise some of the "typical" assumptions being made in much of the mainstream sensor networking research:

- A large fraction of nodes is battery-driven and needs to conserve energy, for example, through frequent sleeping. Network designers and researchers often aim for network lifetimes in the order of months or even years. Nodes are severely limited in terms of resources like memory and/or computational capability, due to cost reasons and for reasons of energy expenditure. This limits the amount of processing that nodes can do.
- A common communication pattern is convergecast, where the sensor nodes report their data to one or a few special *sink nodes*, which are responsible for collecting the data and its further forwarding. There is usually also communication from the sink to all sensors, for example, to change the configuration of the sensor network or disseminate code updates.
- The network can be large, sometimes dense, and may have a network diameter of several hops so that routing is required. Most of the nodes are static, but sinks can be mobile [176].
- Packets mostly contain sensor data and tend to be rather small. Sensor data can be generated periodically or in an event-driven fashion, and the network may have to carry a substantial fraction of periodic data packets.

3.7.2 | Targeted applications

Sensor networks have been designed for many applications, for example, in environmental monitoring [177], monitoring of built infrastructure [178, 179], distributed industrial and process control [180–182], or agriculture [183, 184]. Most of these applications share one property: the network is isolated from the rest of the world, the sensors are geographically close to each other and some environmental properties are monitored. In some rare cases, also actuators are involved, for example, for irrigation applications [185].

3.7.3 | History

The field of sensor networks came into being when advances in hardware miniaturisation and low-power circuitry for processors and transceivers made possible the construction of the earliest sensor node platforms [174, 186]. A key point in the development of sensor networks was the publication of the IEEE 802.15.4 standard for the physical and medium access control layers in 2003 [187] and the market availability of compliant transceivers (e.g. [188]). Slightly later, the first version of the complementary ZigBee standard was developed [189], which builds on IEEE 802.15.4.

The Internet of Things (IoT) [190] concept has emerged in the last decade from the field of WSNs. The main difference is the connection of individual devices to the outside world, and the strong focus on IP protocols, in particular IPv6 in 6LoWPAN. In WSNs, we usually assume that individual nodes are connected to each other and to a sink and only the sink is connected to the outside world. Thus, in some way, a WSN is a stand-alone network, visible only as a whole from the outside. In the IoT, it is assumed that each IoT node is connected to the outside world and has its own IP address. Furthermore, IoT communication architectures are usually infrastructure-based. Hence, research in WSNs is largely focused on (wireless) networking, while IoT research focuses on integration with cloud and edge computing, data analysis, and applications.

3.7.4 | Research topics

As already discussed, a key driver for WSNs has been energy efficiency. The energy budget available to a sensor node is ultimately spent on hardware operations, and it is well-known that the single most effective method to save hardware energy expenditure is to simply *not use* the hardware and put it into a *sleep mode* as often as possible. This observation has led to the concept of *duty cycling*, where the node alternatively wakes up to perform sensing, analysis and communication, and then returns back to sleep. However, a sleeping node cannot communicate with other nodes. This restriction changes the network topology (and thus impacts routing) and requires additional levels of coordination between neighboured nodes wishing to exchange data for collaborative data processing, as they need to agree on a common schedule where both nodes are awake and can exchange data.

We briefly describe some of the main areas of activity in the field of sensor networks:

Physical layer design
Design of energy-efficient coding and modulation schemes, power control algorithms, and rate- and power adaptation schemes [191]. Compressive sensing schemes [192, 193] help to reduce the number of samples of a physical signal that need to be taken (and transmitted!) to achieve satisfactory reconstruction, whereas compression, source coding, and distributed source coding schemes [194, 195] optimise the encoding of the physical data to reduce the number of bits needed to encode a sample or a sequence of samples.

MAC layer
Design of MAC protocols for WSNs, particularly the design of energy-efficient MACs and the support of reliability, timeliness, and throughput [196]. One of the main objectives is to enable duty cycling without time synchronization and thus synchronous transmissions with sleep-enabled nodes.

Routing and topology control
There is a huge body of work on routing for sensor networks [197], building on the area of MANET routing, but additionally considering the constraints of WSNs, in particular energy-efficient routing. Routing is, together with MAC, perhaps the area that has received the most attention. The area of topology control [198] is concerned with thinning out the network topology (by deliberately removing nodes or links) to simplify routing. Clustering algorithms [199] are a prime example of topology control algorithms, since they can significantly simplify routing by forcing simple cluster members to route packets to their cluster heads, and the network of cluster heads being much smaller than the overall network.

Transport and reliable end-to-end delivery
The energy-efficient and reliable transfer of data end-to-end, say from a sensor node to a sink node, has also received some attention [200]. Efforts have not so much focused on TCP, as TCP often is not a natural fit for sensor networks. Some issues with TCP include its inefficiency when the role of a transmitter is rotated over time, or its difficult integration with data-centric networking principles allowing routers/forwarders to actually modify payload data.

Localization and time synchronization
The goal of localization is to provide nodes with information about their geographical position relative to some reference frame [201]. Position information can play a substantial role in applications (as it enables to relate sampled information to its location) and in protocols (e.g. geographical routing). Time synchronization is important when sampled data and observed events need to be anchored in time, for example, to infer which of two events has occurred earlier [202]. Particularly localization has attracted a significant amount of interest and still does.

Data-centric networking
An important design strand in sensor networks which set them truly apart from other types of wireless mobile networks is the inclusion of data-centric networking [203, 204]. Roughly speaking, in data-centric networking application data plays a role in protocol decisions. A simple example is congestion control, where a congested router does not just throw away the most recent packet but the packet which is least important to the application (e.g. which contents can be predicted best).

Intermittent computing
The concept of energy efficiency has naturally led to leveraging energy harvesting techniques directly in the field, like solar panels. However, a new problem arises: the power is not always available and the firmware/software needs to cater for interruptions and unpredictability. Such nodes are called *transiently powered* and new operating systems have been developed to support them, like MementOS, CleanCut, or HarvOS [205].

3.7.5 | Open issues and research challenges

Open challenges are still security and trust in sensor networks, as well as deployment and maintenance. The trust domain is shared with IoT and focuses on how to trust the data arriving from the sensors [206]. This is a major issue and spans problems like security attacks and data manipulation to data ageing, hardware ageing, and software bugs. Deployment and maintenance are also major problems when installing WSNs and IoT applications, as the devices are usually out of reach, have very limited resources for self-assessment and self-control, and rely on notoriously unreliable wireless communication in the wild. Solution ideas include containerisation for sensor nodes [207], but the research area is not very well developed currently. Furthermore, especially with the rise of IoT, time and mission-critical applications start gaining more importance. These include the so-called Industry 4.0 [208], space applications, and predictive maintenance [209]. Reliability and resilience [210] become more and more important.

3.7.6 | Most relevant wireless technologies

While the early phases of sensor network research have used custom-designed low-power radio technologies, from 2003 onwards the IEEE 802.15.4 low-power wireless PAN standard [157] has played a dominant role, not the least due to early commercial availability and its role serving as a foundation for the ZigBee protocol stack and providing the physical layer for a number of industrial WSN technologies like WirelessHART or ISA100.11a [211, 212]. The 15.4 standard aims to achieve high energy efficiency, it offers relatively low ranges in the order of tens to hundreds of metres (depending on transmit power, frequency band and antennas), low to moderate data rates of up to 250 kbit/s, and a hybrid medium access control protocol combining both scheduled transmissions and random access.

More recently, technologies like LoRA/LoRAWAN [213, 214] have established themselves as wireless "low-power wide area networks", they are optimized for the sporadic transmission of small data packets over large ranges of up to 10 km, predominantly using sub-GHz frequency bands. However, ad hoc WSNs can only leverage the LoRa physical layer, as LoRaWAN is infrastructure-based. An overview of all relevant technologies is provided in the Appendix.

3.7.7 | Most related other concepts

Body sensor networks can be regarded as a particular sub-class of WSNs. Body sensor networks tend to be relatively small, both in terms of the number of nodes (at most a few tens of sensors per person) and in terms of network diameter—BSNs are usually single- or at most two-hop networks. In underwater sensor networks, nodes are either fixed (e. g. buoys) or mobile, such as tethered or autonomous underwater vehicles (AUV). A key challenge is that radio frequencies are strongly attenuated so that traditional wireless communication does not work [215]. In underground sensor networks sensors are installed under the ground, which changes the communication properties and protocols used.

3.7.8 | Summary and recommended readings

Wireless sensor networks, or more recently the "Internet of Things", is a field that has reached a mature stage, as there is now a well-accepted set of technologies and design approaches for sensor networks. Much of the attention in this field has shifted to the integration of sensor networks into IP-based networks, and their usage in broader application scenarios like for example, Smart Cities [216].

For further reading, the books [171–173] are recommended which give comprehensive introductions about WSNs.

3.8 | Wireless body sensor networks

3.8.1 | Definition and main properties

Wireless BSNs—often also called Wireless Body Area Networks (BANs) or Wireless PANs in IEEE standards—are a special class of WSNs, in which sensors are attached to or implanted in the body of a human or an animal to measure vital signals for further analysis by medical or health professionals or for well-being purposes [217, 218]. Of course, several design concerns for WSNs, like for example, the importance of energy efficiency, also apply to BSNs. However, there are some characteristic properties of BSNs that make them substantially different from "normal" WSNs:

Network size and architecture
Typically, the number of sensors that are deployed on or inside a human body is limited to a few or a few dozen at most. These sensors often report to a coordinator or sink node, which is also attached to the body. The sink node can collect and pre-process the data and transfer it to a server for further processing. The sink node could be a separate node or could be integrated with a mobile phone or smartwatch. Body sensor networks usually adopt a star topology where each sensor is one or at most two hops away from the sink. Most of the traffic will be from sink to sensors or from sensors to sink.

Overlapping networks
A common feature in the application of BSNs is that several distinct networks may have to share the same space, for example, when multiple persons are close together. The sharing patterns depend on the movements of people and can usually not be planned in advance. It is imperative that the networks remain separate and that there is no risk of sensor data belonging to one person being mistaken for the sensor data of another person. Furthermore, there can be co-technology interference coming from other BSNs operating nearby. This is often referred to as *co-existence.*

Intra-network mobility
Body sensor networks can have substantial intra-network mobility with resulting fast changes in the network topology. For example, when one sensor is attached to the wrist and the other to the chest, then the relative position of these two sensors changes quickly when the person walks or runs. And depending on the orientation and precise placement of these sensors, a line-of-sight may periodically disappear and re-appear.

Network mobility
In addition to intra-network mobility, a BSN itself moves as a whole when the person wearing it moves. This can become important when the BSN uses a wireless technology operating in an unlicensed frequency band that is shared with other technologies. For example, the BSN may be based on the IEEE 802.15.4 standard [157] operating in the 2.4 GHz ISM band, which is also shared with IEEE 802.11 WLAN networks.

When a BSN moves into an urban environment with many WLAN access points in range, it experiences a dynamically changing "interference landscape".

3.8.2 | Targeted applications

Body sensor networks are used in a range of applications in the general fields of medical and healthcare, well-being and sports [217, 219, 220]. Applications in the medical and healthcare fields include ambient-assisted living and patient monitoring, measuring blood sugar or cardiovascular parameters including electrocardiograms, pacemaker diagnostics, rehabilitation support after strokes or accidents, and others. Non-medical applications include the monitoring of heart rate for fitness training, detection and tracking of movements during sports practice, and entertainment.

3.8.3 | History

Body sensor networks are instances of PANs, a class of networks meant to interconnect personal or wearable computing devices with transmission ranges in the order of centimetres to a few metres [221]. The Bluetooth technology, arguably one of the first PAN technologies, was standardized in 1998 by the Bluetooth Special Interest Group, the physical and MAC layer evolved into the IEEE 802.15.1 standard. In the year 2003, the first version of the IEEE 802.15.4 standard appeared, which was designated as a low-rate wireless PAN technology, and which had addressed energy-efficiency as a key design goal—this made IEEE 802.15.4 popular in the realm of WSNs, and there has also been a body of work considering its usage for BSNs [222–224]. In 2007, the IEEE has established a task group for creating a dedicated body sensor networking standard under the designation IEEE 802.15.6, the first version of which was published in 2012 [225]. One distinctive feature of IEEE 802.15.6 is the inclusion (amongst others) of a human-body communications physical layer, which allows implanted devices to communicate with on-body devices using radio signals in the 5–50 MHz range.

3.8.4 | Research topics

A number of key research questions are related to the intra-network mobility patterns resulting from the different poses that humans can adopt, including running, walking, lying, or sitting. Particularly when the human carrier runs or walks, the qualities of communication links can change periodically and quite drastically, and hence the overall network topology will also change quickly. This has substantial impact on routing protocols [226–228], but also on other aspects, like for example, the choice of a suitable transmit power. One interesting approach is to *learn* the current channel quality and choose the transmit power accordingly [229]. More generally, activities such as routing or resource allocation, which critically depend on the state of communication links, can be supported by methods for *pose estimation* or *motion recognition*, that allow to infer the current pose of the human carrier and predict the link qualities accordingly. Activity detection and pose estimation in BSNs are for example, discussed in [230, 231], whereas [232] uses regularities in motion patterns for data compression of motion information.

Any research that aims to exploit the channel properties found in BSNs need a good understanding of these channels, and hence channel modelling becomes an important issue. Besides the impact of periodicity induced by movements like running or walking, it is particularly non-standard channels involving implanted sensors and the propagation of signals through tissues that have received intense interest, see for example, [233, 234].

Another interesting research issue is interference management, which considers both *external interference* (i.e. interference generated by other technologies operating in the same frequency band as the BSN), and *internal interference*, which addresses the case where several BSNs using the same technology and channel resources have to operate in close vicinity to each other. Some research has for example, considered the issue of WLAN interference on IEEE 802.15.4-compliant body sensors networks when both operate in the 2.4 GHz ISM band, addressing it by considering a combination of transmit power and frequency adaptation, shown by simulation and experimental studies [235, 236] as well as analytical optimization [237]. The case of internal interference has for example, been addressed in refs. [224, 238, 239].

Recognising that the BSNs themselves have only limited capabilities for medical signal processing and that much of the generated data needs to be inspected by professionals, the integration of BSNs with fixed network infrastructure has recently gained significant interest. This concerns in particular the integration of BSNs with cloud-, edge- or fog computing systems, see for example, [240–242].

3.8.5 | Open issues and research challenges

Body sensor networks process sensitive information about a person's health status. In case they are connected with cloud services, privacy becomes an issue that needs investigation. For implantable sensors, the aim is to reduce the sizes as far as possible which poses challenges for the energy supply and the wireless communication interface.

3.8.6 | Most relevant wireless technologies

Aside from the Bluetooth and IEEE 802.15.4 technologies popular for general sensor networks and widely used also for BSNs, there has also been some work assuming the IEEE 802.15.6 wireless BAN standard mentioned above [225]. Furthermore, also short-range technologies such as RFID, EnOcean, ANT, and NFC have been considered. An overview of all relevant technologies is provided in the Appendix.

3.8.7 | Most related other concepts

Body sensor networks are a special case of WSNs. They are optimised to be small and light so that they can be conveniently worn or implanted into the body. A long battery life is however only critical for implanted sensors.

3.8.8 | Summary and recommended readings

Body sensor networks share many traits with WSNs but require tailored solutions to deal with the very specific mobility patterns, perform interference and resource management, and deal with the special kind of propagation channels that is involved when sensors are implanted. Multiple surveys were published about BSNs [217, 219, 229, 243] which are recommended for further reading.

3.9 | Wireless underground sensor networks

3.9.1 | Definition and main properties

In contrast to traditional sensor networks, WUSNs are deployed below the surface, that is, they are buried in the soil. This is their main property and the main difference from all other concepts discussed in this paper. The unique underground environment not only creates a very challenging wireless channel, but also influences other system aspects, including deployment and maintenance, and the lack of solar power for energy harvesting. Additionally, sensor nodes are even more exposed to humidity, as they are in direct contact with the soil. However, their topologies usually remain stable over extended periods of time, not counting hardware failures or special applications where nodes are supposed to move with the soil (e.g. to monitor landslides). Furthermore, WUSN nodes are less vulnerable to theft, as they are well concealed below the ground. Sometimes WUSNs are also called Internet of Underground Things [244].

3.9.2 | Targeted applications

The most prominent application for WUSNs is agricultural soil monitoring [245, 246], where nodes are buried in the field to monitor the soil temperature and moisture. Other prominent applications are structural monitoring for dams [247], underground mining monitoring [248], or landslide monitoring [249]. All these applications have in common that most of the sensor nodes are buried below the ground, while some few are aboveground and serve as gateways to the outer world. This is depicted in Figure 8, which represents a typical WUSN deployment.

3.9.3 | History

Wireless Underground Sensor Networks have emerged from traditional sensor networks. Around the mid of the 2000s, researchers used off-the-shelf sensor nodes and attached coaxial cables to extend the antennas above the ground, while the sensors attached to the node were underground [249]. Probably the first work to consider burying the nodes completely was GlacsWeb [250], a glacier monitoring application, where the sensor probes were in the ice or even in the sediment and the gateway was on the surface. Early works were all based on commodity sensor nodes communicating in the 433–434 MHz frequency range. Later on, researchers tried to use the 2.4 GHz ISM bands, but with little success [248], since higher frequencies do not penetrate the ground well enough to reach a gateway above the ground. The new LoRa communication technology has given rise to many more deployments, because of the improved communication range and the growing number of available devices and gateways [251, 252].

3.9.4 | Research topics

A significant amount of communication technology feasibility studies have been conducted to identify which communication technologies are suited for the underground scenario. MicaZ sensor nodes operating at 2.4 GHz have been tested in ref. [253], while mica2 nodes at 433 MHz have been more successfully applied in ref. [254]. The newer LoRa standard has also been shown to work well at its lower frequencies (434 MHz) [248, 252]. Further research has been conducted with custom sensor nodes at 433 MHz in ref. [255] and in ref. [256]. In general, underground communication performance is strongly impacted by the volumetric water content of the soil [257]. Broadly, the lower the frequency, the better the communication performance.

Channel modelling has been mostly considering soil moisture, as it is the main determinant of communication performance underground, as shown in the studies above. In ref. [258], researchers have investigated the impact of environmental conditions (rainfall, soil porosity and vegetation root zone) on soil moisture, which affects underground communication performance and consequently also places constraints on node deployments (e.g. distance constraints). Several underground path loss models have been proposed. They can be classified into UG2UG (underground to underground), UG2AG/AG2UG (underground to aboveground and vice versa) and general models. One of the main problems is to estimate precisely the complex dielectric constant of the soil. Different approaches have been developed, but most of the resulting models [259, 260] require a soil sample analysis in a laboratory, which is not practical for real deployments, where the soil properties differ over small distances. Simpler and more practical models have been proposed for UG2AG/AG2UG communications, where the additional refraction by the soil has been taken into account, for example, in ref. [261]. A more general approach for both UG2UG and UG2AG/AG2UG has been proposed in ref. [262], which relies only on wavelength, clay portion, and soil moisture. Furthermore, it performs in situ measurements and is thus more practical for real deployments.

3.9.5 | Open issues and research challenges

Energy harvesting is still a significant challenge. Currently, most of the research focuses either on wireless power transfer approaches from external sources on the ground or extending the sensor node lifetime via energy harvesting from sources like vibration or temperature differences [263]. However, wireless power transfer requires a dedicated above-ground infrastructure, which is expensive and makes the deployment vulnerable to sabotage and damage. On the other hand, power harvesting from vibration is suitable only if there are vibration sources in the field, like regular agricultural activities. In this case, sufficient energy can be harvested to send out some data to the agricultural machines [264]. However, this scenario is not suitable for more passive monitoring or some agricultural

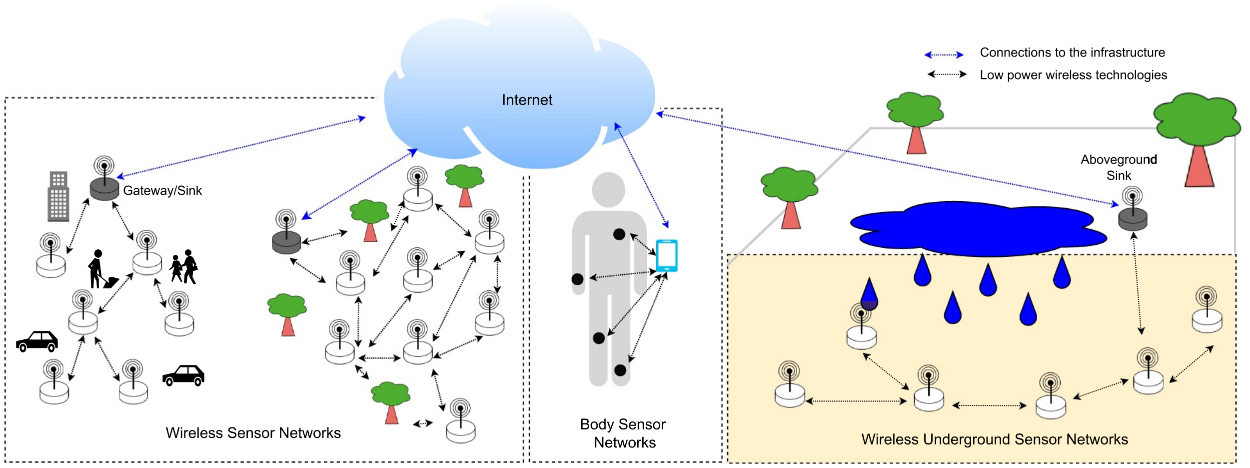

FIGURE 8 Types of wireless sensor networks (WSNs).

crops. Thus, a solution for an autonomous underground energy source is still largely missing.

Routing and MAC protocols for UG2UG topologies have not been considered a lot in the literature. Mostly standard protocols are used, such as LoRaWAN. Some researchers have applied opportunistic [21] or probabilistic approaches [265]. However, the underground environment poses some new challenges but also has some advantages as compared to the aboveground environment. For example, soil moisture largely dictates the path loss and thus the communication quality [266]. This can lead to complete link outages where no communication whatsoever is possible. The real problem with these events is their duration, which can span several hours to a few months, depending on the weather conditions (e.g. monsoons or rain periods). On the positive side, besides rain, the underground environment is much more stable than the aboveground. Temperature is largely stable, passing animals, people and vehicles have little to no impact, and soil changes are very slow. These properties need to be taken into account in future research in the area of routing and MAC protocols in order to significantly extend the lifetime of WUSN deployments.

Simulation and testbed environments are also largely missing. Typical WSN simulators are not adapted (yet) to the needs of WUSNs, especially in terms of channel models available and soil moisture models. One promising candidate is Castalia-WUSN for OMNeT++,[3] but its development is sporadic. Data measurements and traces are also rare, one good example being [267] or the Thoreau deployment [268].

3.9.6 | Most relevant wireless technologies

In the first implementations of WUSNs, researchers turned mostly to WSN-like standards, such as 802.15.4 [157, 253]. Later on, lower frequencies were adopted [254] and the new LoRa standard [248, 252] was embraced. An overview of all relevant technologies is provided in the Appendix.

[3]https://github.com/ComNets-Bremen/Castalia-WUSN.

3.9.7 | Most related other concepts

Clearly, WUSNs have a family relationship with traditional WSNs. To wit, there exist many deployments and concepts combining underground sensors with aboveground sensor nodes for wireless communications, for example, for potato monitoring [21]. The similarities and differences to underwater sensor networks are discussed in Section 3.10.

3.9.8 | Summary and recommended readings

Wireless underground sensor networks are a very interesting alternative to traditional sensor networks or current IoT deployments since they offer the chance to use a concealed and safe environment. They enable some novel applications such as decision agriculture or landslide monitoring. However, experience with real deployments is still very limited with wireless communications over larger distances and energy harvesting being the two most challenging issues.

There are not many surveys dedicated to WUSNs, and some of them are outdated. One recent but short overview of challenges and application scenarios is provided in [269]. A very good and detailed book about wireless communications in the soil is [244]. It also provides some information about deployments and applications.

3.10 | Wireless underwater sensor networks

3.10.1 | Definition and main properties

Wireless Underwater Sensor Networks—sometimes also referred to as UWSNs—are sensor units included into AUV floating or moving inside the water, sometimes supplemented by buoys on the surface. Especially in seawater environments, the sensors have to tackle harsh environmental conditions for communication. Not only the damping of the radio signal is challenging, but also the delay for acoustic, that is, sound-based communication requires special hardware and settings [270].

3.10.2 | Targeted applications

Wireless Underwater Sensor Networks are used in general for environmental monitoring or aquaculture applications like fish farms, reef monitoring, monitoring offshore installations etc. [270–272]. They are also deployed in disaster warnings, such as tsunamis, by seismic monitoring [273] or can augment navigation to avoid dangerous underwater obstacles [274].

3.10.3 | History

The predecessor of transmitting messages underwater in a digital way were signalling systems for submarines which were already discussed since the beginning of the 20th century.[4] Underwater digital communication has been developed since the early 1970s [275] and was in the beginning focused on point-to-point communication with research taking place on the physical layer. Attempts of underwater networking have been discussed since the beginning of the new millennium [276]. Even in recent publications, the main focus is on dealing with the challenges coming from the communication channel, that is, high transmission delays or high signal damping depending on the used technology [270].

3.10.4 | Research topics

The communication in this harsh environment is also the main research challenge in this area [277]. Microwave links only work across small distances due to the high conductivity of water [278, 279]. The most important alternative, acoustic communication, is subject to high interference and only provides a small data rate [280, 281]. Also, the propagation speed is smaller than light or radio waves by several orders of magnitude which results in higher propagation delays. As an alternative, optical communication like laser communication can achieve data rates up to Gbit/s over distances of tens of metres, even though the optical channel suffers from light absorption in the water and scattering by particles [282]. Magnetic induction [283] provides low propagation delay and well-predictable channel characteristics. The low production cost of magnetic induction-based nodes allows for communication for example, to be deployed for large-scale applications.

Therefore, the main research focus is on the physical technologies as well as on special protocols capable of dealing with the special conditions as listed below.

Physical transmission

Trends and challenges in the physical aspects of acoustic communication are summarised in ref. [284]. Further research challenges are keeping the devices in a fixed position in the presence of currents, and power efficiency due to lack of solar charging [285]. Furthermore, nodes can act as range extenders that pick up the signal of a neighbour and retransmit it [283]. Research challenges are multidirectional antennas, arranging multiple antennas in an array, and the properties of the underwater channel.

Localization

Inside the water, localization systems such as GPS do not work because the radio signals from satellites cannot penetrate the water. Therefore, dedicated underwater localization systems have been developed [286–288]. Many of them are based on anchor nodes with well-known positions which send out acoustic signals. By comparing the time of arrival, the location can then be determined.

Medium access

As mentioned before, the signal propagation speed in acoustic channels is low compared to radio channels and also dependent on environmental factors such as temperature. This property requires an adaptation both of contention-based as well as contention-free medium access protocols [273]. Further challenges are service guarantees, for example, minimum throughput of a connection, node mobility, coping with high propagation delay and cross-layer design for example, between the MAC layer and the physical transmission.

Routing

Most publications about WUWSN routing assume acoustic communication. Wireless Underwater Sensor Network routing protocols tackle unreliable links by making use of omnidirectional propagation which is deployed in a WUWSN-specific way by allowing it to fall back to a spare neighbour node if the current one fails [289]. The selection of neighbours is also investigated in optical networks where an energy-efficient routing algorithm is described [290] which balances the energy consumption amongst the nodes. Research challenges in WUWSN routing protocols are scalability, selection of forwarding nodes, mobility support [289], support of multiple network interfaces [291], and avoiding dead-ends [292].

Architecture

There are three important design goals for the architecture of WUWSNs: Clustering means grouping a number of nodes into smaller sets of nearby located neighbours, basically in order to reduce the energy consumption. Coverage of a sensor network requires that the sensors' detection ranges should cover the geographic area of the network without gaps so that any event inside that area is detected. Maximising connectivity relies on proper control of the network so that there is a path between every two nodes of the network as often as possible, or in order words, the network forms a single connected graph [293].

Hybrid networks

Hybrid approaches jointly use different types of bearer technologies or routing methods. On the physical layer, similarities between the optical and acoustic channel statistics are identified in order to predict each channel based on knowledge of

[4] archive.macleans.ca/article/1906/8/1/submarine-signalling-on-the-ocean.

the other one [294]. On the network layer, a multimodal routing protocol optimises the efficient and fair use of links across different physical bearer technologies with low and high speeds [291].

3.10.5 | Open issues and research challenges

The communication channel in WUWSNs mostly depends on environmental effects such as the turbidity of the water which affects both optical and acoustical links. Therefore it is desirable to identify regular patterns, for example, dependent on the time of the day in order to predict the communication conditions. Another aspect of communication is the extension from pure sensor networks to robotic networks that deploy both sensors as well as actuators. With the increasing demand for underwater surveillance and offshore installations, an "Internet of Underwater Things" will develop with a rapidly increasing number of nodes, so the question of network scalability arises—a routing protocol that works well with tens of nodes might not scale well to hundreds or thousands of nodes. Since underwater nodes may have to sustain for long times without service, energy-efficiency of protocols as well as energy harvesting is crucial.

Most relevant wireless technologies

Because of the special conditions for underwater communication, off-the-shelf wireless bearer technologies as they are known from other communication applications are not suitable. The most widely used technology are underwater acoustic modems, both proprietary solutions and developments by the scientific community became available over time [295, 296]. There are also software-defined modems that provide maximum flexibility [297].

Most related other concepts

Wireless Underwater Sensor Networks are similar to WUSNs in the sense that they have to face a harsh environment, difficult communication conditions, and restricted energy supply. Also similar to WUSNs, they have to perform unattended operations over an extended period of time which may be several months. In contrast to WUSNs, underwater networks may have to cope with mobility if nodes are installed on vehicles such as underwater robots. The speeds are however lower than in vehicular networks.

Summary and recommended readings

In the past years, careful monitoring of the oceans and offshore facilities has gained increasing interest. Wireless Underwater Sensor Networks are one way to perform long-term observations in this difficult environment. Special research challenges are posed by quickly changing communication channels, narrowband links, and high interference.

In order to get an introduction to the topic of underwater networks, the publication [276] is recommended which gives an overview of the design of underwater networks. Additionally, [272] offers a more general overview of the whole research area listing the basics as well as a survey of existing research projects. The articles [63, 298] discuss practical issues when setting up a WUWSN in a real environment.

3.11 | Other ad hoc concepts

Apart from the concepts presented above, there are some further ones, which deviate in one way or another from the ad hoc concept or are too application-specific. We discuss those shortly next.

3.11.1 | Device-to-device mode

Device-to-Device (D2D) communication refers to a special mode of 4G (also referred to as LTE) and 5G (also referred to as New Radio) where two end User Equipment, for example, mobile phones, can directly communicate with each other without relaying the data via the base station (called eNB). Device-to-device communication aims to extend cell coverage, possibly provide services without base station infrastructure, use cellular resources efficiently, and reduce the burden on the base station. The latter is also referred to as cellular off-loading.

Some of the targeted applications are proximity-based services, push-to-talk public safety, V2X, and X2X applications [299]. Here, X2X can be any kind of scenario, a car communicating with a traffic light, or a phone communicating with a smart poster advertising a concert. The current killer D2D application for most of the cellular operators is V2X, which is planned to be deployed in Europe as the *5G D2D mode*.

Cellular D2D communication has been discussed in 3GPP since release 12 in 2012 in parallel to the work done by the research community. The 3GPP standards are governed mostly by cellular operators focusing on business-oriented applications. Two main types of D2D are *Type 1: Inband D2D*, which uses licenced spectrum, and *Type 2: Outband D2D*, which uses unlicensed spectrum. In *Type 1: Inband D2D*, the sharing of the licenced spectrum can be done in two ways. In the *underlay* approach, the primary cellular users and D2D users share the same spectrum, while in the *overlay* approach, a dedicated spectrum is assigned to the D2D users, making sure that the primary cellular users do not interfere with the D2D users.

Compared to the two types discussed by the research community (*inband* and *outband*), 3GPP standardisation has focused on *four sub modes* to serve specific applications. 3GPP release 14 [300] has introduced an *outband* solution, called *LTE V2X*, which uses spectrum originally allocated for the IEEE 802.11p vehicular standard [125]. The latest releases 16 (2019) and 17 (2021) of 3GPP propose an *inband* solution, based on the *5G D2D mode, also known as new radio*, specifically for V2X autonomous driving.

Early research papers focused on *Type 2: Outband D2D*, to solve co-channel interference among D2D users and other wireless users like WLAN and Bluetooth [301, 302].

With the introduction of four sub-modes that consider both types of *inband* and *outband* communication, most of the research focused on addressing the optimal use of the cellular spectrum and the resource allocation mechanisms. The resource allocation challenges are on how the eNB assigns exact resources (time- and frequency resources) to D2D users or how the eNB delegates resource allocation to some end devices [303, 304]. The latter case represents how a platooning leader negotiates the range of resources from the eNB to allocate for the platooning. The resource allocation is also done to prioritise the dissemination of emergency messages [305].

Train-to-train

Train-to-train networks focus on two main applications. Firstly, the communication between different trains and the infrastructure (CBTC, *Communication-based train control*) is nowadays done with several components and unreliable communication channels. Focussing on wireless communication technologies aims at more reliable and simplified infrastructure. This will lead to increased reliability and safety. Additionally, the number of trains on a single track can also be increased. Here, the communication range is several hundreds of metres up to kilometers. Wireless local area network and 5G are planned to be used for communication [306, 307].

Secondly, the communication between the individual carriages of one train can also be replaced by wireless communication links. Here, the advantages are easier coupling and decoupling of trains and the radio communication is less susceptible to outdoor influence like dirt and rain. The required communication range in this application is a couple of metres. Here, IEEE 802.11.ad is a commonly used standard. It offers high data rates over short distances [308].

Also, the combination of both applications is currently evaluated. Here, the objective is the automatic coupling and decoupling of trains and individual carriages while driving on the track [309]. This would further increase the efficiency on the track as several trains with similar destinations are combined into one without the need for stopping and manual coupling.

Ship-to-ship

Direct communication between ships is developed since the 90s as the *Automatic Identification System* (AIS). The standard is maintained by the International Telecommunication Union[5]. Most commercial vessels are equipped with AIS transceivers and transmit their voyage data like position, speed, course, destination port, etc. regularly using maritime VHF frequencies. The main objective of AIS is collision avoidance, sharing journey information, and general monitoring by the vessel traffic service. Although AIS is a widely used service for exchanging basic information between ships, it does not offer sufficient bandwidth for increasing communication requirements. In some cases, expensive satellite communication is used. Especially the communication between vessels in the vicinity, like during towing or berthing, requires high-speed and low-latency communication technologies. Several approaches are currently being explored.

The *VHF Data Exchange System* (VDES) maintained by the *International Association of Lighthouse Authorities* can be seen as an extension of AIS. It uses AIS as the underlying communication technology but can also use more efficient modulation schemes for higher data rates [310]. Due to the used frequency band, VDES offers only limited bandwidth. Triton (*TRI-Media Telematic Oceanographic Network*) is a project which offers high-speed ship-to-ship and ship-to-shore communication technology. The basic idea is to migrate the concept of VANETs to ships [311]. It is based on WiMAX with some adaptations which make it incompatible with existing systems. Therefore, it is only used in a few limited scenarios. The objective of *netBaltic* is to offer high bandwidth, non-satellite communication between ships. For that, it focuses on existing technologies like standard IP and Ethernet connections which simplifies the integration. The communication is adapted according to the distance to shore and the area: Near shore, the infrastructure is used. To extend the shore communication range, mesh communication is used. For communication outside the range, delay tolerant direct communication is used [312]. *e-navigation* is a general communication concept by the *International Maritime Organization*. It focuses more on the communication flows and optimization than on the technical details themselves.[6] An overview of the existing technologies for ship-to-ship communication and the related concepts is given in ref. [313].

3.12 | Summary

In this section, we have presented various infrastructure-less networking concepts and their distinguishing properties. Now we give a comparative overview of them in terms of the networking layers they mainly focus on. Table 1 summarises the research efforts of the community as presented in the previous subsections, organised by network layer and infrastructure-less concepts. In infrastructure-less networks, a modified OSI stack is usually used, as shown in the table. The table also includes cross-cutting concerns like privacy and security. The table is not intended to be exhaustive and is purely subjective. Due to the substantial amount of publications in infrastructure-less networks in general, even a cell marked with "minus" might represent quite a lot and important work. Thus, this table should be understood as an orientation help to understand where most of the research and publications have been focused and not to say that one or another layer is less relevant.

The network protocols and research approaches discussed in this survey mainly cover the medium access control, network (routing/forwarding), and transport layer, as seen in the table. The application-specific layers are not touched widely —to forward messages, application-specific details are usually

[5] https://www.itu.int/rec/R-REC-M.1371/.

[6] https://www.imo.org/en/OurWork/Safety/Pages/eNavigation.aspx.

irrelevant. An exception could be if data messages are subject to QoS, for example, the application requires a maximum end-to-end delay. However, application requirements are considered when designing and evaluating solutions at the lower layers. At the same time, there are some infrastructure-less concepts where the application has been the focus, for example, VANETs, WSNs, and BSNs. Here, novel applications were developed, and the lower layers of the stack were adapted.

The MAC and physical layers are usually considered when designing and evaluating protocols at the other layers, but have seen real research focus only on the area of WSNs and its subtopics like BSNs, WUWSNs, and WUSNs. Another concept that deals a lot with the MAC and physical layers is D2D, where spectrum access and allocation play the most prominent role. The link layer (retransmission and error control, neighbour management) is an important issue with infrastructure-less concepts because links change significantly due to mobility and/or interference.

Security and privacy also play a significant role across all networking layers. They are usually considered at all layers. However, for some of the presented concepts, security plays a more important role than privacy and vice versa. Moreover, for WUWSNs and WUSNs, privacy does not play a significant role, as data is considered human-independent.

Most research efforts have been dedicated to the transport, network, and link layers across all concepts shown. However, while all three layers and their challenges and problems have been considered widely, most publications and works follow a cross-layer design where a single protocol spans two or three layers.

4 | QUALITATIVE COMPARISON OF NETWORK CHARACTERISTICS

In the previous sections, we have described individual concepts. There is a myriad of relevant, important, and interesting applications for infrastructure-less networks. In fact, they are too many to be described and discussed here in detail. Instead, we will focus on their main properties, putting limitations and requirements on the networking stack they use. In this section, we will focus especially on their mobility, connectivity, traffic, delay, scale, density, and energy consumption. These requirements follow also the generalised family tree, presented earlier in Figure 1.

All figures in this section visualise our own view of the comparison of different concepts, highlighting their similarities and differences in terms of network and system properties.

4.1 | Mobility

Mobility of nodes (speed and direction) has an impact on connectivity with nodes moving away and to each other, and this has an impact on topology and its rate of change. An important property of mobility is predictability, which allows nodes to efficiently allocate resources in advance, to hand over, or to wait for particular neighbours to communicate with.

In Figure 9, we visualise the assumptions researchers make in the different infrastructure-less networking concepts we discuss in this paper. We consider mobility of nodes and predictability of mobility as independent, orthogonal properties. These properties emerge from the application scenario and from the used devices. The x-axis presents the typical speed of

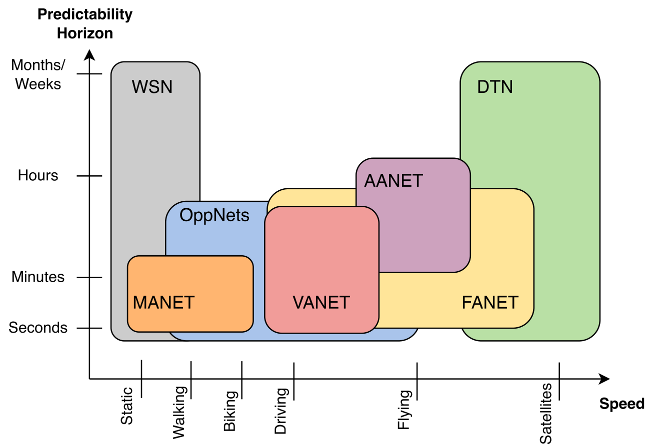

FIGURE 9 Qualitative comparison of "typical" assumptions about node speeds and predictability horizons.

TABLE 1 Main research foci of the different infrastructure-less concepts across the networking stack.

	MANET	OppNet/DTN	VANET	AANET	FANET	WSN	BSN	WUWSN	WUSN
Application	o	o	+	o	o	+	+	o	o
Transport/Congestion control	o	o	o	–	–	+	o	–	–
Routing/Forwarding	+	+	+	+	+	+	+	+	+
Link	+	+	+	+	+	+	+	+	+
MAC	o	o	o	o	o	+	+	+	+
PHY	–	–	o	+	–	+	+	+	+
Security	o	o	+	+	+	o	+	+	o
Privacy	o	o	o	o	o	o	+	–	–

Note: Legend: – → limited, o → moderate, + → extensive.

the nodes, from static to very high speeds to the right. The *y*-axis presents the predictability horizon, with low predictability being at the bottom and better and longer predictability being at the top. For example, it is typically easy to predict the position of a mobile node in the next few seconds, given its current speed and direction. However, its long-term position cannot be predicted as easily.

In **WSNs** nodes are usually assumed to be static, or they move with relatively low speeds (like data mules in agricultural scenarios). The position of static nodes is trivially predictable, while the mobile nodes in WSNs can be well predictable (e.g. a tractor passing every day to gather the data over a field) to being quite unpredictable (WSNs for animal monitoring). The sub-types of WSNs, like BSNs or WUSNs, typically share the same mobility properties as for traditional WSNs.

In **MANETs** mobility is typically considered, but application scenarios are targeted towards pedestrians or office workers in an indoor environment. Thus, at most biking speeds are considered and the predictability is relatively good, in the sense that nodes stay close to each other and move a little around, like in an office building.

In **VANETs** the node speeds are substantially higher, they are often assumed to be in the range between 40 and 60 km/h in urban scenarios and in the order of 80 and100 km/h or higher in rural scenarios or on motorways. Furthermore, since vehicles usually stick to streets, their movements can often be predicted over timespans of minutes or even hours in rural or highway scenarios, and tens of seconds to minutes in urban scenarios. Importantly, these observations can actually be exploited in the construction and configuration of VANET protocols.

Mobility in **FANETs** depends on the type of drones. Fixed-wing drones can achieve maximum speeds similar to an aeroplane but also need to maintain a minimum speed to sustain the lift. Hence, their trajectories are predictable over short time horizons, and, depending on their mission, even over longer ones. Rotary-wing drones usually have lower speeds, and have the ability to hover and to make quick changes in direction. Furthermore, it holds for all types of drones that (at least as of 2022) their movements are not constrained to roads.

Delay-tolerant networks typically enable communications between satellites or between satellites and ground stations. The speeds are very high, but the predictability is almost perfect, as satellite orbits are pre-calculated. However, DTNs and OppNets are often used as synonyms in the literature and one has to be aware of which type a specific application targets.

A key feature in opportunistic networking is the usage of store-carry-and-forward communications, which builds on node mobility. **OppNets** approaches have been used in conjunction with pedestrian nodes, but have also found their way into vehicular/VANET scenarios and FANET scenarios. The very notion "opportunistic" suggests that the considered predictability horizon tends to be in the order of seconds or minutes, and not higher (otherwise one could, similar to DTNs, actually apply scheduling methods to plan communications well in advance instead of opportunistically or greedily picking the option that seems best right now). At the same time, human mobility is usually coarsely predictable over the course of days too, for example, when a person goes to work or to school. This is a property often leveraged in OppNets with the so-called history-based data dissemination protocols. However, the predictability in these horizons is low.

By definition, **AANETs** are run between aeroplanes which move at high speeds. Furthermore, usually, the path of commercial flights is very well known and from the path and the flight schedule the trajectory of an aeroplane can be predicted. Since flights only last for hours, it does not make sense to evaluate the predictability for the next weeks or months.

In summary, most infrastructure-less networking concepts need to cope with mobility, even if the concrete assumptions for speed and predictability differ. The borders between the individual concepts are vague and many exceptions can be found in the literature.

4.2 | Connectivity

Mobility can turn a network that is normally fully connected into a network with only intermittent connectivity, networks can frequently get partitioned and re-connected, or they can even spend all of their lifetime in a state where the overall "network" indeed only consists of a number of connected clusters, with occasional "rendezvous" between clusters. An example of the latter is clusters of cars on a highway, with relatively small distances between nodes/vehicles within the same cluster, but larger distances between clusters. Depending on the amount of time that a network spends in a partitioned state, normal packet forwarding can become severely affected.

In Figure 10, we distinguish in the *y*-axis between "full connectivity" and "intermittent connectivity". By full connectivity, we mean that the network and the protocols make an assumption that the network is normally fully connected and that end-to-end paths do exist as a rule. It is treated as an error or exception should an end-to-end path not exist, and packets that cannot be forwarded further are dropped. For example, this is the main assumption in Internet connectivity. In

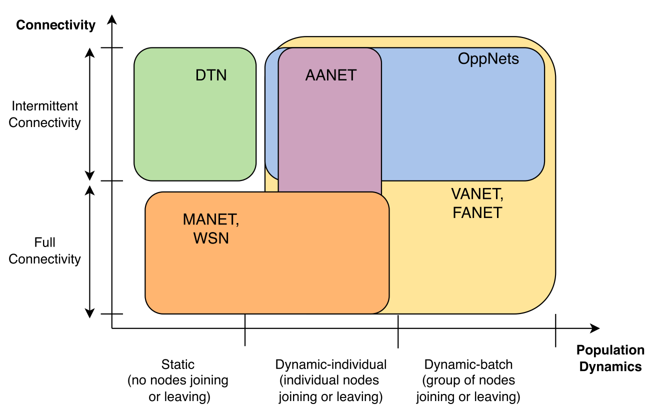

FIGURE 10 Qualitative comparison of "typical" assumptions about network connectivity and dynamics of nodes.

intermittently connected networks, the non-existence of an end-to-end path occurs frequently, and the network protocols are actually prepared to deal with this, for example, by adopting the store-carry-and-forward strategy. On the x-axis of this figure, we aim to catch the typical assumptions on the dynamics of the node population. In "static" settings the arrival or departure of nodes is not explicitly considered. In "transient-individual" scenarios the node population is dynamic and changes with the arrival and departure of nodes, but nodes arrive or depart individually. In "transient-batch" scenarios it is also possible that nodes arrive or depart in larger groups or batches.

In **MANETs** and **WSNs** the protocols typically assume full connectivity and in tendency either assume static node populations or individual arrivals or departures of nodes (group arrivals appear to be rarely considered). In **FANETs** and **VANETs**, the protocols account for individual nodes and clusters of nodes leaving and joining the network and they mainly cater for nodes with high mobility. Hence, the connectivity can vary from intermittent to a fully connected network.

In **DTNs**, particularly of the "Interplanetary Internet" type, changes in the node population are usually not considered, and the connectivity is intermittent—after all, the store-carry-and-forward paradigm has featured prominently in DTNs, and DTNs emerged historically before opportunistic networks. **OppNet** protocols are well prepared to deal with intermittent connectivity (which is a main motivation for opportunistic networks in the first place). Of course, also fully connected networks are served well, but naturally, the protocols will not be optimal in such scenarios. It is also fairly common to assume a dynamic node population in OppNets, there usually being no restrictions to individual departures or arrivals.

AANETs can be both intermittently or fully connected. The first case is valid when the aircraft flying over the land or during landing or take off as individual aircraft come into contact with others in their range for a short time. The latter case is valid for aircraft flying over the ocean, for example, East and West-bound flights over the North-Atlantic corridor (flights between Europe and the USA). A group of aircraft following the same path has full connectivity among neighbouring aircraft for about 4–6 h. Only individual nodes move in and out of the network formation and group arrivals and exits are not considered.

In summary, the connectivity of the above networks is to some extent influenced by the mobility of individual nodes and most of these networks operate well in intermittent connectivity with increasing network performance in times of full connectivity.

4.3 | Scale and density

The scale and density of networks can vary significantly. Scale refers to the varying size of the network in terms of the number of nodes served, without considering the area where they are deployed. Some networks are typically quite small in scale, for for example, most BSNs consist of only a few sensor nodes. Others, like vehicular applications, may have to cope with node numbers in the order of hundreds to thousands of vehicles.

The density of the network considers also the area where the nodes are deployed, which then impacts the number of single-hop neighbours a node has. For example, space probes have a very low density, while vehicular networks can have very high densities. In Figure 11, we have represented density as the typical number of neighbours (y-axis) and the scale as network size (x-axis).

MANETs are characterised by mobile nodes which connect dynamically, with network sizes ranging from tens to hundreds of nodes, and node densities usually not exceeding a few (tens of) neighbours. **FANETs** being typically mission-oriented, are deployed with network sizes of tens to hundreds of nodes. Node densities typically do not exceed more than tens of neighbours.

AANETs are formed for communication between aircraft over the air at altitudes of 10–13 km. The scale of AANETs depends on the number of aircraft in the communication range of each other and the aircraft flying in the same direction for the time the network is formed. AANETs are dense over areas close to airports (or more generally populated areas), and sparse in unpopulated areas such as flying over the oceans. Hence, network sizes of AANETs are in the order of tens of nodes while the neighbour size can be just up to a few nodes.

Delay-tolerant networks—The primary applications of DTN research are space communications, satellite and interplanetary networks and they do not involve dynamically changing network sizes. The network size of DTNs can be up to 15 nodes in maximum while smaller network sizes are more common. Delay-tolerant networks are extremely sparse networks. **OppNets** and **VANETs** are characterised by highly mobile devices in urban scenarios and hence, the scale of the network can be easily expanded to thousands of nodes. However, in some extreme scenarios (traffic jams for VANETs or concerts in OppNets), the number of nodes in the network may grow even larger. Often OppNets and VANETs experience a range of quickly changing densities, ranging from no

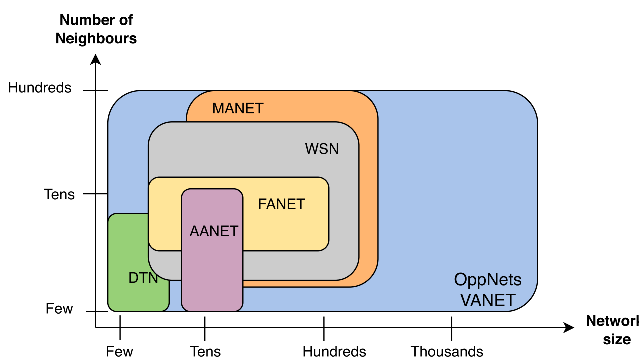

FIGURE 11 Density and network size for different infrastructure-less networks.

neighbours at all (in isolated areas) to hundreds of neighbours (in a city centre).

Wireless sensor networks are often deployed with a relatively high density, which allows for more aggressive duty cycling (i.e. a higher fraction of nodes sleeping) without breaking network connectivity. The scale of the WSNs is mainly limited by the cost of the devices and the transmission range of the devices involved. Typical WSN deployments are in the order of several tens of nodes, however some IoT applications involve deployments scaling up to orders of several hundred to thousands.

In summary, the scale and density of the discussed infrastructure-less networks mainly are characterised by the type of network requirements and leading to low network sizes and densities in DTNs and AANETs and comparatively higher network sizes in others mentioned. The application requirements do not necessarily limit the network size and density, however, the availability of neighbours and mobility dictate the size and density of these networks.

4.4 | Traffic characteristics

The different types of ad hoc and opportunistic network applications discussed in this paper generate traffic which can be characterised by the following properties:

4.4.1 | Intensity

The amount of data that has to be transported per time unit, averaged over a longer period of time, which means fluctuations of the traffic demand are not considered.

4.4.2 | Pattern

Traffic may not be constant over time, some applications generate variable traffic. For example, web traffic occurs in bursts whenever a web page is downloaded whereas a voice connection usually has a constant bit rate. Sensor data may generate periodic messages whenever measurement data is sent.

4.4.3 | Maximum delay required

Maximum amount of time between the sending of a data packet and receiving it. Differently from simply measuring the delay of a packet, the required delay is a property of the application, which says after how much time the data packet becomes unusable.

4.4.4 | Communication mode

Most traffic for example, in the Internet is transported from one originating to one destination node (unicast), where the two nodes are arbitrary. A special case of this is convergecast where the traffic is still one-to-one, but the destination node is identical for all data packets. Other options are multicast, broadcast, geocast, and anycast.

Individual characteristics of different network types are summarised in the paragraphs below. Figure 12 gives a graphical overview of the delay requirement and traffic intensity occurring in different networks. We focus mostly on these two aforementioned metrics, as they pose the most significant challenges for network design, while the traffic pattern and the communication mode can be tackled more easily.

MANETs may carry all types of traffic typical for the Internet, e.g. streaming, video conferencing, web traffic, etc. Some are tightly delay-constrained and have high intensity (video conferencing), others can tolerate some level of delay and have bursty traffic (web page access).

VANETs forward sporadic or periodic information between vehicles and roadside infrastructure in proximity. Typical messages can be grouped into safety messages—alerts such as a suddenly braking car—or traffic management messages, e.g. a traffic jam on nearby roads. While safety messages are tightly delay-constrained, traffic information tolerates a slower delivery, but is also delay-constrained. The intensity of messages can be very low to high and depends mostly on the number of involved vehicles and on the importance of the messages. The preferred way of delivering messages is broadcast for emergency messages and geocast for traffic information.

FANETs are used to offload surveillance data collected by drones to the ground and also to control the drones themselves. Surveillance data may be a video stream that generates approximately periodic real-time traffic whereas the download of photos is a file transfer generating traffic that adapts to the free capacity on the link. Sensor readings generate small periodic messages. Mission control/telemetry messages exchanged between the drones, or between a drone and the ground, are messages as well which may be periodic (e.g. regular position

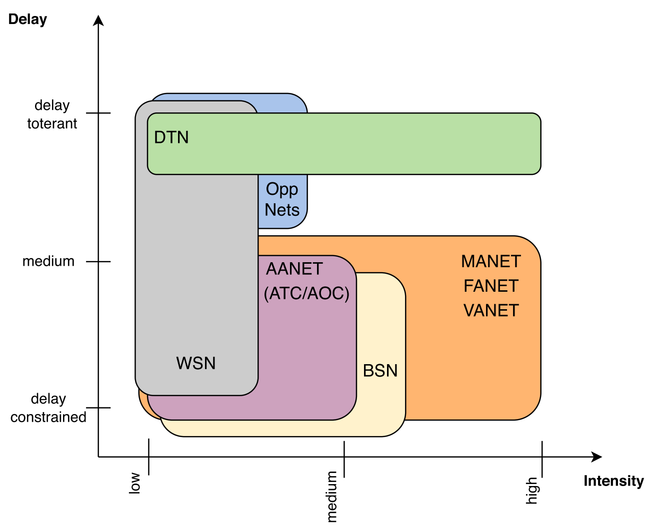

FIGURE 12 Delay requirements versus traffic intensity.

update) or occasional (collision warning). The control/telemetry messages have to be transferred in real-time with a minimum possible delay in the order of milliseconds. Real-time video or sensor data meant for human supervision is less critical, but should still be delivered with a constrained delay. Non-real-time data can be buffered and transmitted when free capacities are available.

OppNets are used to forward relatively small personal messages across users, with relatively low intensity. Messages can only be forwarded when two devices meet, therefore such networks are only useful for messages which are not delay-critical. The meeting duration between devices may be short and the bearer technologies for the message transmission such as Bluetooth Low Energy do not provide fast rates. Therefore, messages should have a low data volume such as text messages or a small picture, e.g. to indicate the time and location of an event in the city centre.

Delay-tolerant networks are widely used in space communication to exchange files, images, pre-recorded videos, etc. Technically, transferring such content is based on file downloads using elastic traffic which fills the remaining space of a communication link as mentioned earlier. For the special case of interplanetary communication, link speeds are limited due to the weak signals resulting from extremely large distances, which means the download of a single file may take a long time. Furthermore, the link delay is high and a real-time control or monitoring of a distant space vessel is not possible.

AANETs are used to send small delay-constrained messages between aircraft. The delay budget is a couple of seconds for ATC and several minutes for Airline Operational Communications. AANETs can also be used to offload flight recorder information, which is delay-critical in case of an emergency. Aeroplane-to-aeroplane network traffic intensity is in general low or medium, like in the L-band Digital Aeronautical Communication System used for ATC. However, in the special case of flight recorder offloading which is not depicted in Figure 12 for overview reasons, the data should be sent as quickly as possible which may result in a high intensity. Like in VANETs, the preferable option to deliver data in AANETs is geocast.

Wireless sensor networks collect measurement values periodically such as the ambient temperature, or they report sporadic events, for example, a car passing by. Their traffic, therefore, consists of periodic or sporadic short messages typical for machine-type communication. In some cases, these messages are delay-constrained/delay-critical, for example, in the case of safety monitoring. In other cases, they may not be delay-constrained, for example, in case of long-term environmental monitoring for research purposes, and only occasionally picked up by a human operator. Sensor networks often use convergecast for the delivery of data packets. Similar considerations as described before also apply to **WUWSNs** and **WUSNs** which are not included in Figure 12 for clarity. **Body sensor networks** are similar to WSNs by producing short messages, however the frequency of measurement, for example, pulse or blood oxygen level is typically higher than in sensor networks. Moreover, most BSN applications are very delay-constrained, as they mainly serve safety and health purposes.

In summary, the traffic characteristics for different infrastructure-less applications can be very diverse, from very low intensities like sensor networks in agriculture to very high intensities like space applications or VANETs. The delay tolerance is also very different: sometimes it is dictated by the application itself, like in safety-related vehicular applications, and sometimes it is imposed by the system architecture, as is the case for DTNs or OppNets. In case a high delay cannot be avoided, the applications need to handle it appropriately.

4.5 | Power restrictions and requirements

The emphasis on power requirements and restrictions varies greatly over the different types of infrastructure-less networks. When the emphasis is strong, the focus is mainly on two aspects: Finding the best energy source and optimising energy consumption.

The source of energy dictates the amount of available energy and thus the time the device can operate. Instead of increasing the amount of energy available, the consumed energy can also be reduced which leads us to the second aspect. The optimization is usually done on a systems level, taking both hardware and software into account. The objective is to reduce the energy consumption of the device to a minimum while reducing the functionality of the overall system only minimally. On the hardware level, the most common steps are a careful selection of individual components and power supply parts like voltage regulators. The software optimization usually tries to reduce the required energy by keeping everything to the lowest power mode possible. Duty cycling, for example, enables the radio only for short periods when data has to be transmitted. Also, the CPU frequency can be reduced if no complex operations are required. The challenge is to find a trade-off between lifetime, delay, and coordination overhead caused by sleeping nodes and network throughput. This results in a wide range of protocols and solutions for different applications. [314] gives an overview of the available energy-saving concepts in the area of WSNs, where it has been most prominent.

However, the energy constraints of the different infrastructure-less networks presented in this paper emerge mostly from the available power, which emerges in turn from the deployment environment. The main options are to have wall power (stationary and uninterrupted access to power) or to run on batteries. Depending on the size and the expected lifetime of the used devices, the batteries can be very large or very small, like for BSNs. A third option is to use energy harvesting techniques, such as solar power. This option is commonly combined with a battery, which is recharged on the spot. However, sometimes it is also used alone, for example, for passive RFID or EnOcean devices.

Figure 13 provides an overview of the importance of energy efficiency for the different concepts.

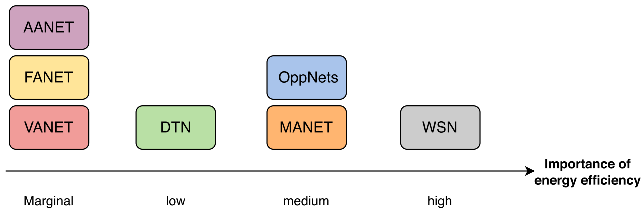

FIGURE 13 Importance of energy efficiency for the different infrastructure-less concepts.

For FANETs, **AANETs**, and **VANETs**, there are no real energy constraints from the communication point of view as the energy required can be obtained from the carrying vehicle. The energy required for the movement is usually significantly higher compared to the energy for the communication [315]. Here, energy-efficient path planning has a higher importance than energy-efficient network protocol operation.

For **DTNs**, the energy usage highly depends on the platform and thus the type of satellite. The radio can be disabled for certain periods of time if it is not required. If and how often it is disabled depends on the satellite type and the communication requirements. In general, there has not been much research on energy efficiency for interplanetary communications.

In **OppNets** and **MANETs** energy is not the main research focus. Although the devices usually operate on battery power, most applications assume that sufficient energy is available: The devices are usually recharged regularly and do not operate for a longer period of time without user interaction. However, communication has a significant impact on the lifetime of the involved devices and has been considered also in research.

For **WSNs** and its related siblings (**BSNs**, **WUWSNs**, **WUSNs**), the energy source is usually a battery and is limited due to the price, capacity, or size. Also, the availability of a primary energy source like sunlight plays a role. Energy optimization is one of the main research foci. For example, *Radio Duty Cycling* protocols were invented to reduce energy consumption drastically. The exact set of parameters and thus the optimization goals vary within this family and depend on the application. The nodes of BSNs could be recharged every couple of days. Wireless Underground Sensor Networks on the other hand can require a lifetime of several years. The concept of intermittent computing has been also developed to cater to the special needs of WSN applications (see Section 3.7).

In summary, the importance of energy efficiency and the used power sources are very diverse for the different infrastructure-less concepts. While this has been the main research focus for some of them, like all types of sensor networks, it has been only marginally or not at all considered for others, like AANETs. The availability and amount of power are dictated directly by the carrying devices—the smaller and more mobile the devices, the less power is available.

5 | EVALUATION TOOLS AND METRICS

This section gives a short overview of typical evaluation metrics and tools for infrastructure-less networks. Most of them are similar or identical to evaluating infrastructure-borne networks, but there are also some important differences.

5.1 | Evaluation metrics

There are several important and interesting aspects to consider when evaluating infrastructure-less networks. The usual network performance metrics can be used for all of them, for example, delivery delay, delivery rate or loss rate, throughput, and network overhead. When evaluating routing/forwarding protocols, metrics like route length, link/route lifetime, and route discovery time are important. For battery-powered devices, power consumption and node/network lifetime become critical. For memory-restricted devices, cache usage and cache drop rates are relevant. For on-body or in-body devices, thermal dissipation is health-critical. Table 2 provides an overview of all infrastructure-less concepts discussed in this survey and their typical performance metrics.

The underlying components used for computing and the interpretation of these metrics sometimes vary from one evaluation to another. An example is *Network Overhead*. Sometimes it refers to the total number of bytes exchanged (data bytes and overhead bytes together) in a network, while at other times only the overhead bytes required to deliver the data are considered. Yet another version is to compute the factor between the data bytes and all bytes sent. Therefore, each of the metrics described in the following (and listed in Table 2) needs to be specified in a given context.

5.1.1 | Delay (time)

The delivery delay measures how fast a message can be delivered to a single intended recipient or a group of recipients, either over a single link or end-to-end. For example, in case of emergency messages, it is always critical to know how quickly the data is delivered. The delay is typically measured for each packet (hop-by-hop or end-to-end), which can be summarised using average, confidence intervals or CDFs (Cumulative distribution functions).

5.1.2 | Delivery rate/loss rate (%)

The delivery rate or reception ratio provides a metric of how many packets were delivered successfully. There are several reasons for losing packets, for example, due to buffer drop in a congestion state, TTL expiry, transmission errors on links, crashing forwarders, cache drops, and so on. Delivery rate is

TABLE 2 Relevant performance metrics for all infrastructure-less concepts discussed.

Metric	MANET	VANET	FANET	AANET	DTN	OppNets	WSN	WUWSN	WUGSN	WSAN	BSN
Delay (time)	+	+	+	+	+	+	+	+	+	+	+
Delivery rate/loss rate (%)	+	+	+	+	+	+	+	+	+	+	+
Network overhead (%)	+	+	+	+	+	+	+	+	+	+	+
Throughput (data/time)	+			+				+			
Network capacity (throughput/space)	+										
Route length (hops)	+			+	+	+	+				
Route/link lifetime (time)	+			+				+			
Route discovery time (time)	+			+							
Duty cycle (%)							+	+	+	+	+
Node/network lifetime (time)							+	+	+	+	+
Energy consumption (joule)						+	+	+	+	+	+
Cache occupancy (%)					+	+					
Cache drop rate (%)					+	+					

typically computed by counting how many packets were expected to be delivered and how many were actually delivered, for each node in the network.

5.1.3 | Network overhead (%)

The term overhead in general refers to the additional activities needed to achieve an intended objective. It comes in many shapes and forms, for example, in routing protocols it could measure the number of routing control packets required to establish a route; in MAC and link-layer protocols it could refer to the additional packet header fields required for control purposes, to extra MAC control packets, to redundant bits in error-correcting codes, or retransmission packets, etc. Usually, it is computed by summing up all packets (bytes) in the network and dividing them by the bytes of the data payload (the actual data). However, sometimes also only the total number of bytes is reported, without dividing it by the payload.

5.1.4 | Throughput (data/time)

The throughput refers to the rate at which a node receives or sends out packets. It can be considered hop-by-hop or end-to-end. It should not be confused with the link speed or data rate for example, of a wireless bearer technology (e.g., WLAN, Bluetooth) which is also measured as data/time, but specifies how many bits per time are physically transmitted over the wireless medium. The maximum hop-to-hop throughput is determined by the performance of the bearer technology which connects two stations under ideal transmission conditions and can be reduced by interference or congestion on the radio channel. When measuring the end-to-end throughput, the overhead of higher-layer protocols (e.g. routing, transport, application) needs to be considered. However, this metric has not been considered very widely in infrastructure-less networks. Many of the infrastructure-less technologies are not focusing on optimising the throughput but on energy efficiency or delivery rate. A related term is *Network Capacity*, which is the throughput of the complete network. This has been used only for MANETs.

5.1.5 | Route length (hops)

Packets hop over other nodes to reach their destinations. This metric measures the number of hops travelled by a packet. Its interpretation is not trivial. A high number of hops might mean a very large network, but also an inefficient selection of next hops by the routing protocol. Thus, it only makes sense when several routing protocols are compared to each other in the same network. It is also a proxy for energy efficiency, as a higher number of hops requires more energy. However, short routes with a small number of hops are also not always the best solution, as delays can still be higher and link speeds be lower.

5.1.6 | Route/link lifetime (time)

Nodes in a communication neighbourhood connect with each other to exchange packets. Since nodes are mobile, direct connections to other nodes become possible only when they are in communication range with each other. Thus, once the individual links change (appear, disappear or change their quality), routing algorithms will adapt and change the routes. This metric only refers to ad hoc concepts, which use end-to-end routes, such as MANETs or AANETs. Sometimes, also the individual link duration is of interest, as for WUWSNs.

5.1.7 | Route discovery time (time)

In networks where end-to-end delivery of packets is a requirement (e.g., MANETs), nodes initiate a path discovery mechanism to determine the set of optimum intermediate nodes over which to hop packets. This activity is performed by sending signalling packets. Data exchange can occur only after the path is established. This metric measures the duration of the discovery of the path. Higher values coupled with other metrics, such as low contact durations may result in poor data delivery rates. Again, this metric is used only for ad hoc concepts, where end-to-end routes are established and do not make sense for many others, such as OppNets.

5.1.8 | Duty cycle (%)

Nodes in networks such as WSNs employ duty cycling to save energy. Duty cycling is a method where nodes split the operation time into active and sleeping phases. During a sleeping phase, a node (or at least critical hardware components) is switched off, in an active phase the node is awake and ready to communicate. This metric computes the percentage of time in which a node is active. Higher values indicate nodes performing more work and showing better performance but at the cost of faster battery drainage. Lower values indicate a lower energy consumption, at the cost of a reduced ability to participate in network activities.

5.1.9 | Node/network lifetime (time)

The duration after which a network or a node is considered as being unusable is measured using this metric. While the lifetime of a node is straightforward to define, for the network lifetime, there are many possible definitions. A node may become inactive due to factors such as battery drainage or shutdown. Regarding the network lifetime, common criteria for "network death" include: death of the first node, death of a given percentage of nodes, the time at which the network becomes partitioned first, the time at which the network is not able any longer to observe a given physical phenomenon at a prescribed accuracy, and so on.

5.1.10 | Energy consumption (joule)

The energy consumption is the intake of electrical energy by a network node. It can be measured relative to a certain time unit in order to compare how much energy different protocols or nodes from different manufacturers require to transport a given amount of data, which is useful for finding the most energy-efficient solution. It can also be measured w.r.t., different actions that a node performs, such as reading a value from a sensor or transmitting a packet. This is useful for identifying which action causes the highest battery drain. If it is for example, observed that the radio interface has a high energy consumption, it should be checked how the power-on times of the radio can be reduced.

5.1.11 | Cache occupancy (% or bytes)

Networking architectures such as OppNets depend on the *store-carry-forward* principle to disseminate data. Since caching of data is important, dimensioning caches becomes an important aspect of resourcing nodes. Under-dimensioning caches may result in increased pressure on caches, thereby degrading performance (due to constant cache removals) while over-dimensioning results in wasted resources. Therefore, this metric provides a means of assessing the optimum cache sizes to use. The cache occupancy can be measured as a percentage when the cache is limited or in bytes when it is unlimited.

5.1.12 | Cache drop rate (bytes/time)

Cache drops occur when new data received by a node has to be inserted into an already full cache. This metric measures the number of dropped bytes over a certain period. Higher values may appear periodically when large volumes of data are exchanged, and the caches are overwhelmed. Therefore, this metric is useful in determining the best caching policy to employ, to obtain an optimum performance with data delivery.

5.2 | Evaluation techniques

Generally speaking, there are three main alternatives to evaluate infrastructure-less networks and networks, in general: Real-world measurements, simulations, and theoretical models (Figure 14). When discussing the advantages and disadvantages of these three options, we need to consider the following properties:

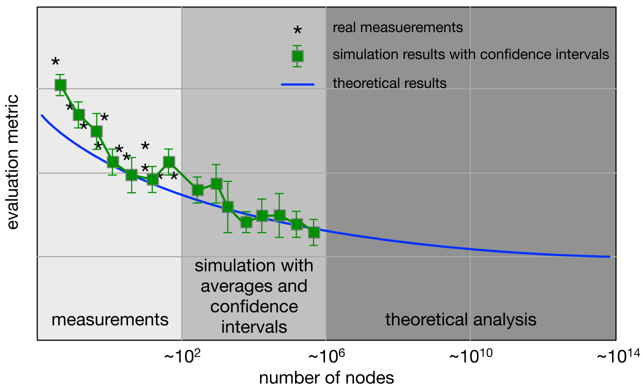

FIGURE 14 Evaluation techniques for different sizes of infrastructure-less networks.

5.2.1 | Repeatability

The ability to repeat an experiment in the exact same environment and scenario [316]. In the case of computer systems, this means literally the same computing system without any changes. This is very useful to compare the performance of a particular component (such as a communication protocol) with different parameter settings, for debugging, etc.

5.2.2 | Reproducibility

The ability to reproduce an experiment in similar environments [316]. In the case of computer systems, this means transferring the implementation to another computing system, which is typically harder than to *repeat* the experiment. This is very important to validate the implementation of a particular component.

5.2.3 | Visibility

The ability to inspect deeply the state of all components involved in an experiment.

5.2.4 | Time

Time needed to conduct an experiment, including preparation and processing of results.

5.2.5 | Costs

The financial and time cost for preparing and running the experiment.

5.2.6 | Representativeness

The degree of similarity between the experimental environment and the targeted one.

5.2.7 | Sensitivity

The parameters that exert the most significant influence on the system.

We have summarised these properties for all three options in Table 3.

TABLE 3 Properties of the three main evaluation techniques for infrastructure-less networks.

	Measurements	Simulation	Theory
Repeatability	–	++	+++
Reproducibility	–	+	++
Visibility	–	+++	+++
Time	–	+++	+
Costs	–	+++	+++
Representativeness	++	+	–
Sensitivity	–	+	+

Repeatability of experiments is best for theoretical studies but also very good for simulation studies. The reason is that the models can be repeated typically without any problems on different machines. For simulation, when moving the experiment from one machine to another, some inconsistencies might occur, for example, hidden parameters. Theoretical studies are typically closed-form expressions that yield the same results independently of the machine which computes them. For measurements, repeatability is hard since the environment never stays exactly the same. For example, real measurements with sensor networks would yield different sensor values since they are conducted under different weather conditions, and those slight changes might have an unpredictable impact on the final results. **Reproducibility** is harder for any of the environments, and the reasons are the same as for repeatability.

Visibility is an important property, especially in case of errors. It allows the developer to inspect her system closely. This is most easily done for simulation and theoretical studies, as you can analyse the exact state of the system at any time, including all parameter and state variables' values. For measurements, this is done by writing out log files to be analysed later. However, the log files have to be carefully designed, as their output might actually influence the work of the system under test. Thus, the visibility of measurements is generally low.

Time and costs to conduct an experiment are important to consider. Measurements are very costly, as they require real hardware and long setup times, and the time for one measurement is dictated by the environment and the scenario. Theoretical studies are very fast to conduct since they are completely detached from the environment and the scenario. However, they are usually designed from scratch, and their mathematical derivation takes a long time. Simulation is very cost-efficient (if we assume free, open-source tools) and faster than theoretical studies because tools and models typically already exist to support the development.

Representativeness is crucial for any evaluation method since it tells you how close you are to the final or targeted environment and scenario. A theoretical study gives you only an approximate idea about the behaviour of a system, usually in extreme conditions or on average. Depending on the models used, simulation can be close to a theoretical study or measurement. Measurements are very representative, but only if conducted in an appropriate environment. Otherwise, the results might change dramatically.

Sensitivity of the methods means, how much do the results change when you change the experimental setup? As discussed, measurements are very sensitive, even to slight changes. Simulation and theory studies are not necessarily more stable, but at least their sensitivity can be evaluated in a more extensive and structured manner. This is typically done with a sensitivity analysis, a method from Design of Experiments [317].

In summary, simulation exhibits some sort of a sweet spot, where development is fast and cost-efficient, comfortable because of high visibility and repeatability, and when conducted professionally with sophisticated models, also representative. Thus, most researchers and developers turn to simulation first. Theoretical studies are conducted usually as part of PhD theses to prove particular properties and are relatively rare. Most researchers in infrastructure-less networks are more interested in the practical applicability of their work in real-world implementations and deployments. Thus, more practical measurements than theoretical studies are conducted.

In the next section, we provide an overview of available and popular simulation tools for infrastructure-less networks. We do not dive deeper into theoretical studies, as there are only general mathematical tools (like Matlab, Python libraries, and linear programming tools), which are not dedicated to infrastructure-less networks in any way. We also do not dive deeper into measurements, because those are very application-specific and there are simply too many to be summarised in a single paper. The interested reader is invited to inspect closely the provided literature in Section 3 to explore which tools, testbeds, and hardware researchers use in their work.

5.3 | Simulation tools

There exists a myriad of network simulators. Here, we will focus on freely available ones, as they are most accessible to researchers worldwide.

OMNeT++[7] is a general-purpose discrete event simulator (DES) written in C++. OMNeT++ has a free academic licence and provides the mechanisms for building and simulating any type of network, from simulating epidemics to wireless networks. The OMNeT++ simulator by itself only provides the blocks for building nodes in networks and modelling their behaviour and interactions. So-called frameworks have emerged over the years that make available pre-defined nodes with some special behaviour: sensor nodes, IP-based nodes, satellites, cars, etc. Examples include INET[8] for IP-based networks and sensor networks, Veins[9] for VANETs, OPS[10] for opportunistic networks, and FLoRa[11] for LoRa networks. OMNeT++ has some important advantages. It offers a sophisticated user interface, with many possibilities for visualising and inspecting various scenarios, including 3D visualizations. It is also highly modular while clearly separating node behaviour from node parameters, making it easier to run large parameter studies. It runs on all major operating systems and has very well-maintained documentation, including user guides, tutorials, wiki pages, etc. At the same time, OMNeT++ does not offer the possibility of transferring simulation models to real implementations, for example, directly to Linux distributions.

Network Simulator 3 (ns-3)[12] is a DES primarily focused on simulating IP-based networks with an emphasis on the network layer (layer 3) and the above layers of the protocol stack. The simulation scenarios can be created using C++ or Python, and run as command-line applications without a GUI. However, *NetAnim* is a tool that ships with ns-3 for visualising node mobility during or after a simulation. Network Simulator 3 is licenced under the GPLv2 open-source licence. Network Simulator 3 was completely rewritten, although it is considered the successor to ns-2. For this reason, ns-3 is incompatible with ns-2, and the simulation models must be adapted to be used in ns-3. At present, ns-2 is only lightly maintained as the focus of the developers is on ns-3, which should therefore be used for new projects. The available libraries and communication modules are maintained by the community and cover many different areas and goals. Modules included in the official ns-3 releases provide design documentation and include unit tests. For example, MANET routing protocols, 6LoWPAN-based WSNs, the WAVE model for VANETs, and an LTE library to model D2D technologies are available. One important advantage of ns-3 against other simulators is that all communication modules have been designed in such a way as to easily match the network interfaces to the standard Linux APIs. For this reason, it is possible to easily move a simulation setup to the real world and vice versa. It is also possible to interact with existing real-world networks using virtual TAP (layer 2) devices, connecting simulated and real nodes. On the negative side, ns-3 clearly misses sophisticated visualisation. Furthermore, the simulator structure is rather complex and not easy to parametrise or change, even for experienced researchers.

The Opportunistic Network Environment (ONE) [318], is a simulation tool designed specifically for OppNets. It was first developed in 2009 at Aalto University, and it is now maintained cooperatively by Aalto University and the Technische Universität München. The current version is 1.6.0, released in July 2016, and is available on GitHub[13]. It is written in Java. The ONE is designed specifically for OppNets and therefore offers a wide variety of models for these networks that continues to grow. It is especially rich in data dissemination models for OppNets. The ONE allows for the generation of node movements using different models, the reproduction of message traffic and routing, cache handling, and the visualisation of both mobility and message passing through its graphical user interface. It can also produce a variety of reports, such as node movements to message passing and general statistics. However, the ONE does not perform well for large simulations, mainly because of the programming language. In terms of models, it has neither any link technology models nor radio propagation models. Thus, it is not well suited for

[7] https://omnetpp.org.
[8] https://inet.omnetpp.org.
[9] https://veins.car2x.org.
[10] https://github.com/ComNets-Bremen/OPS.
[11] https://flora.aalto.fi.
[12] https://www.nsnam.org.
[13] https://akeranen.github.io/the-one.

evaluating other infrastructure-less networks, such as MANETs or WSNs. It is partially well suited for VANETs, where link technologies are not the focus of the research.

Cooja[14] is a simulator for WSNs, based on the WSN operating system Contiki and its most recent branch Contiki-NG[15]. It runs compiled Contiki code on various simulated hardware. It has a simple graphical user interface and supports some channel models and trace-based radio models. The main advantage of Cooja is that Contiki code can be run on real hardware and in Cooja without adaptation, and Contiki itself supports a good variety of WSN hardware.

In addition to the simulation tools described above, there are some other mobility-oriented tools that are also very useful for simulating mobility-driven infrastructure-less networks.

- **BonnMotion** is a tool that can create and analyse mobility scenarios and is most commonly used for researching MANET characteristics [319]. BonnMotion's main objective is to create mobility traces using mobility models, as well as trace-based mobility scenarios. Furthermore, the generated traces can be exported to a notable number of formats used by network simulators, such as ns-3, Cooja, The ONE, OMNeT++, etc.
- **PedSim** (Pedestrian Simulator) [320] is a tool for generating mobility scenarios used by architects and civil engineers for urban and traffic planning. Using this mobility simulator, we can create our own scenarios (mainly buildings or city areas) and define the number of pedestrians/vehicles, their type of movement, and their destination. The generated output can be used as input to a network simulator after re-formatting.
- **Simulation of Urban MObility** is a mobility traffic generator written by the German Aerospace Centre (DLR) [321]. The main focus is on the simulation of public transport, pedestrians, and vehicles, including speed limits, traffic lights, etc. From these simulations, mobility traces can be exported for trace-driven mobility in ad hoc network simulations.

There are some important parameters to consider when selecting the right simulator to use. In most cases, none of the available simulators provides all the needed features and models. Thus, it is more important to consider existing experience (own or from close colleagues), support and documentation, graphical user interface, and scalability/extensibility of the models. Sometimes researchers decide to implement also their own simulators, but this should be the last resort. Such a solution requires much more time to implement, is rarely reliable and the acquired results are not reproducible. Reproducibility of research has become more and more important, and many publication venues and publishers have started placing strict requirements for publishing programme code and data.

[14] https://github.com/contiki-os/contiki/wiki/An-Introduction-to-Cooja.
[15] https://github.com/contiki-ng.

6 | CONCLUSION

In this paper, we have attempted to give a broad overview of the infrastructure-less networking concepts and their main properties. We have highlighted their differences and commonalities, and have discussed shortly their main targeted applications and their history. We have placed special focus on some important system properties, such as mobility, connectivity, scale, density, traffic, and power, and highlighted the differences in the assumptions of the presented infrastructure-less concepts in these terms.

While our primary objective was to provide a source of concentrated information for novices in this area, such as graduate students, we also discussed open issues and challenges. As we have seen, all of the presented infrastructure-less concepts are still under active development and far away from becoming standardized and stable solutions. We hope that the provided discussions will inspire researchers to not only attack the identified issues and problems but also to transfer concepts and solutions across the topics.

AUTHOR CONTRIBUTIONS

Anna Förster: Conceptualization; funding acquisition; methodology; project administration; resources; visualization; writing – original draft; writing – review & editing. **Jens Dede**: Visualization; writing – original draft; writing – review & editing. **Andreas Könsgen**: Visualization; writing – original draft; writing – review & editing. **Koojana Kuladinithi**: Visualization; writing – original draft; writing – review & editing. **Vishnupriya Kuppusamy**: Visualization; writing – original draft; writing – review & editing. **Andreas Timm-Giel**: Funding acquisition; resources; writing – review & editing. **Asanga Udugama**: Visualization; writing – original draft; writing – review & editing. **Andreas Willig**: Conceptualization; funding acquisition; resources; writing – original draft; writing – review & editing.

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ORCID

Anna Förster https://orcid.org/0000-0001-5755-2672
Jens Dede https://orcid.org/0000-0002-8422-265X
Andreas Könsgen https://orcid.org/0000-0003-0614-7380
Koojana Kuladinithi https://orcid.org/0000-0001-6083-4048
Vishnupriya Kuppusamy https://orcid.org/0000-0002-8583-7648
Andreas Timm-Giel https://orcid.org/0000-0002-5998-6113

Asanga Udugama https://orcid.org/0000-0001-8159-5146
Andreas Willig https://orcid.org/0000-0002-0042-5207

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APPENDIX A

Existing communication technologies for ad hoc networks

Figure A1 gives a list and an overview of the most important properties of the wireless technologies used to implement the different flavours of ad hoc networks. Table A1 maps the technologies against concepts discussed in this paper and where they are mostly used.

	Standard	OSI Layer	Freq Band	Power Cons	Data Rate	Comm Range	Netw Size[n]	Supports Routing	Payload Size (B)	Adhoc / Infrastr	Duty C Enabled
WiFi	802.11ac[s]	MAC PHY	5GHz	High[a]	≈1Gbps[t]	<100m	<100	No	7912	Both	No
	802.11p VANET	MAC PHY	5.9GHz (ITS band)	High[a]	27Mbps	<1km	<100	No	2304	Both	No
	802.11ad W Gigabit[s]	MAC PHY	60GHz	High[a]	≈2Gbps[t]	<10m	<10	No	7912	Both	No
WPAN (802.15)	802.15.1[s] Bluetooth	MAC PHY	2.4GHz	Medium[b]	1Mbps	< 100m (Class 1)	8[h]	No	33(v4.0), 242 (v4.2)	Adhoc	Yes
	802.15.4[s,o]	MAC PHY	2.4GHz, 868MHz, 915MHz	Low[c]	250Kbps	< 100m	NS[i]	No	127	Both	Yes
	ZigBee Alliance	APP-NET	Related to 802.15.4	Low[c]	Related to 802.15.4	Related to 802.15.4	65k[h]	Yes	Related to 802.15.4	Both	Yes
	6LoWPAN	IP	Related to 802.15.4	Low[c]	Related to 802.15.4	Related to 802.15.4	NS[i]	Yes	33-74 (per packet)	Both	Yes
	Wireless HART	APP - DLL	2.4GHz (802.15.4)	Low[c]	Related to 802.15.4	< Related to 802.15.4	250[h]	Yes	50	Adhoc	Yes
	ISA100.11a[p]	APP - MAC	2.4GHz (802.15.4)	Low[c]	Related to 802.15.4	Related to 802.15.4	NA	Yes	59	Both	Yes
	802.15.6 WBAN	MAC-PHY	21/42MHz, 402-405MHz, 420-450MHz, 863-870MHz, 902-927MHz, 950-958MHz, 2.4GHz, 3.1-4.8GHz, 6-10GHz	Low[c]	10Mbps	< 10m	64	No	255	Master-slave	Yes
ANT	ANT[p]	TRA - PHY	2.4GHz	U. Low[d]	1Mbps	< 30m	65533[h]	No	8	Master-slave	Yes
EnOcean	ISO/IEC 14543-3-10[p]	NET-PHY	315MHz, 868.3MHz, 902MHz, 928MHz, 2.4GHz	passive	125kbps	< 30m	<100	No	14	Paired mode only	NA
Z-Wave	Z-Wave Alliance[p]	TRA-PHY	828MHz, 908MHz	Low[c]	100Kbps	< 30m	232[h]	Yes	64	Adhoc	Yes
LoRa	LoRa-PHY[p]	PHY	433MHz, 868MHz, 908MHz	Low[c]	50Kbps	< 20km	120 (sc)	No	255	Both	Yes
Weightless	Weightless-P	TRA-PHY	470Hz-790MHz (EU)	Low	200bps-100kbps	2km	NS[i]	No	10	Adhoc	Yes
DASH7 (D7A)	DASH7 Alliance[p]	Full stack	433MHz, 868MHz, 915MHz	Low	167kbps	< 5km	NS[i]	No	256	Adhoc	Yes
LDACS (A2A mode)	L-band digital Aeronautical Comm Sys	LL- PHY	960MHz-1164MHz	V. High	315-1428kbps (ground-air), 294-1390kbps (air-ground)	< 370 km	512 per cell[h]	No	34- 968 (ATS)	Adhoc	Yes
WAIC	wireless avionics intra communication	LL- PHY	4200MHz-4400MHz	Low	< 5Mbps	< 20m	1000[h]	No	App dependent	Both	Yes

[a] High: >1000mW
[b] Medium: 500mW−1000mW
[c] Low: 1mW−500mW
[d] Ultra Low: 0−1mW
[s] Standard
[p] Proprietary
[t] Typical setup and data rate
[h] The network size is limited by the standard
[i] Not specified by the standard

FIGURE A1 Comparison between different wireless technologies.

TABLE A1 Technologies and applications. (✓: Used in research, O: Partly used in research).

	MANETs	VANETs	FANETs	OppNets	AANETs	WSNs	BSNs	WUSNs
IEEE 802.11ac	✓[c]	✓	✓	✓ [c]		O[b]		
IEEE 802.11p (VANET)		✓	✓					
IEEE 802.11ad (wireless gigabit)						O[e]		
IEEE 802.15.1 bluetooth				✓			✓	
IEEE 802.15.4			✓	O[a]		✓	✓	O
Zigbee alliance						✓	O	
6LoWPAN						✓		
WirelessHART						✓		
ISA100.11a						✓		
IEEE 802.15.6 WBAN							✓	
ANT						✓	✓	
EnOcean[p]						✓	✓	
RFID						✓[d]	✓	
NFC						✓[d]	✓	
Z-wave						✓		
LoRa-PHY				✓		✓		✓
Weightless-P						✓		
DASH7 (D7A)						✓		
LDACS (A2A mode)					✓			
WAIC						✓		

[a]Not available on end user devices.
[b]Not used in research but in real applications.
[c]Ad-Hoc direct mode.
[d]Partly/edge technologies.
[e]Currently not used but might be an option depending on the distribution on end-user devices.