Towards Reliable and High-Frequency Ultra-Wideband Ranging in Agile Swarms of Micro Aerial Drones

Christian Richter[1,2], Patrick Rathje[2], Olaf Landsiedel[1,2]
[1]*Hamburg University of Technology, Germany* [2]*Kiel University, Germany*
christian.richter@tuhh.de, patrick.rathje@cs.uni-kiel.de, olaf.landsiedel@tuhh.de

***Abstract*—Highly agile drone swarms operating without GNSS require both high-frequency and reliable distance measurements to coordinate complex maneuvers and prevent collisions. Ultra-Wideband radios uniquely act as sensors by leveraging communication to provide centimeter-accurate localization information while simultaneously serving as a wireless medium for data exchange. However, today's approaches to UWB swarm ranging do not provide sufficient update rates and the scalability required for complex maneuvers in large swarms. This paper presents a medium access control protocol designed for high-frequency and reliable distance measurements in highly mobile environments. Designed for mobile ad-hoc networks, it does not require static infrastructure and builds on the scalability of Many-to-Many ranging and precise time synchronization based on Glossy. Our evaluation on two testbeds shows that our proposed MAC achieves high update rates with up to 30 Hz per neighbor in a dense environment of 13 nodes.**

***Index Terms*—Ultra-Wideband Ranging, Micro-Drones, Aerial Swarms**

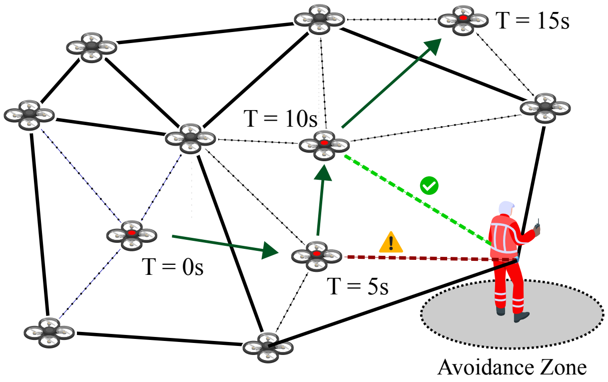

Fig. 1: SynchroFly is designed for dense aerial swarms of drones. Drones use SynchroFly to estimate distances towards all neighbors with high frequency, enabling, e.g., highly reactive collision avoidance.

I. INTRODUCTION

Drones have become ubiquitous in everyday life, performing tasks such as autonomous delivery, aerial surveying, and even entertainment through drone shows. Miniaturization of drones and the increase in swarm sizes lead to dense collectives of micro-drones which autonomously navigate around obstacles and perform complex tasks through cooperation.

For safe operation, it is crucial that drones avoid collisions not only with the environment but also with each other, see Fig. 1.

For this purpose, Ultra-Wideband (UWB) based radios can accurately measure distances by communicating with each other, serving as input to collision avoidance and localization algorithms [1]. As swarms become increasingly agile, they demand measurements with: (1) low latency, (2) high frequency, and (3) high reliability. Various strategies for medium access and ranging have been proposed optimizing for tag battery life, update rate, scalability [2] or accuracy [3]. However, most solutions are designed for indoor localization, making them unsuitable for localization and collision avoidance tasks in infrastructure-less or ad-hoc dynamic aerial networks.

In this work, we propose SynchroFly to fill this gap. SynchroFly is designed to provide high-frequency Two-Way-Ranging (TWR) measurements derived directly on the devices. We improve the scalability of TWR by employing Many-to-Many (MTM) ranging [4]. However, MTM with long ranging block durations increases measurement latency and induces non-negligible errors in the distance estimation in high velocity settings [5], [6]. Thus, the main challenge for a scalable ranging system in agile swarms is keeping measurement ranging blocks short while supporting enough nodes. We tackle this problem by employing Glossy [7], a primitive for efficient network flooding and time synchronization, which was recently shown to allow for highly accurate and scalable time synchronization on UWB [3], [8]. Using the high timing accuracy, we schedule frames extremely tightly during an MTM block, thus reducing the impact of long ranging blocks on the latency and velocity-induced errors.

In summary, we make the following contributions:

- We present our initial work towards SynchroFly.
- We implement SynchroFly on the DW1000 UWB transceiver and nRF52832 MCU.
- We provide preliminary results of SynchroFly in a static and node-dense testbed environment.
- We identify key research areas for SynchroFly's full implementation, evaluation, and extension.

The remainder of this paper is structured as follows. In

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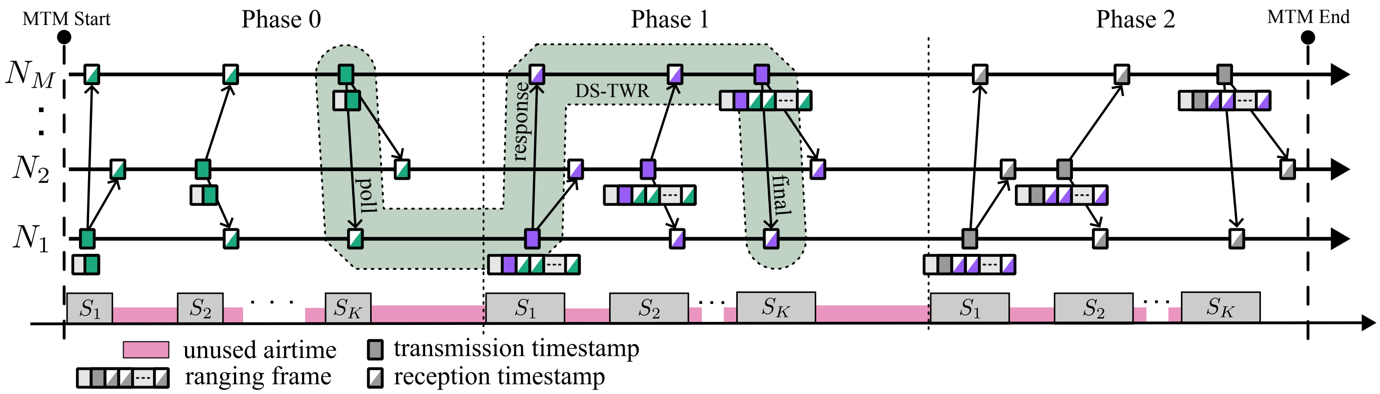

Fig. 2: Many-to-Many (MTM) ranging block structure. Network nodes N_1 to N_M transmit in time slots S_1 to S_K across multiple phases. The example depicts $K = M$ slots, matching the number of participating nodes. Slot durations increase progressively as frames must carry more timestamps from previous receptions, increasing frame transmission duration. Filled/half-filled rectangles denote transmission/reception timestamps, color-coded by capture phase. A DS-TWR protocol execution between two nodes consists of initiation, response and finalization frames. The shaded green area shows the frames exchanged for performing DS-TWR between the nodes N_M and N_1. Red areas indicate unused airtime gaps that contribute to velocity-induced errors. The final phase is required for complete measurement exchange.

Section II we introduce the basics of ranging and concurrent transmissions. In Section III, we present SynchroFly's low-level design implementation. Section IV presents a preliminary evaluation of SynchroFly, in a static setting. Finally, in Section V we outline future directions for extending and evaluating SynchroFly.

II. BACKGROUND

To understand SynchroFly's inner workings, this section presents UWB ranging and concurrent transmissions.

a) UWB Ranging: UWB's distance estimation typically relies on Two-Way Ranging (TWR), a back-and-forth message exchange, which allows us to calculate the Time-of-Flight (ToF) by utilizing the high temporal resolution provided by the high bandwidth of UWB signals. To mitigate clock frequency differences between ranging devices, Double-Sided Two-Way Ranging (DS-TWR) employs a third message exchange, cf. Fig. 2. To calculate distances, both ranging participants need access to all captured timestamps, requiring additional message exchanges to share timestamping data.

b) Concurrent Transmissions: Glossy [7] introduces concurrent transmissions, preventing destructive interference by transmitting identical packets nearly simultaneously (less than $0.5\,\mu s$ apart). Glossy triggered new communication paradigms with high energy-efficiency, low latency, and high reliability [9]. Concurrent transmissions are also applicable to UWB: For instance, synchronously transmitting short identical frames on identical complex channels enables practically a 100% packet reception rate (PRR) [8].

III. SYSTEM DESIGN

This section introduces SynchroFly's system design and begins with a short design overview. Our design incorporates two main building blocks: (1) time synchronization to provide a fine-grained scheduling base, and (2) ranging blocks of tightly scheduled transmissions. We consider a network of M nodes (labeled N_1 to N_M) that participate in ranging operations. Ranging and communication in SynchroFly follow a superframe structure. SynchroFly executes Glossy at the beginning of every superframe, followed by a user-defined number of ranging blocks, see Fig. 3. The resulting clock synchronization allows for very tight system-wide scheduling, with practically no guard spaces. In the following, we focus on time synchronization, introduce our efficient Many-to-Many ranging, and discuss implementation details.

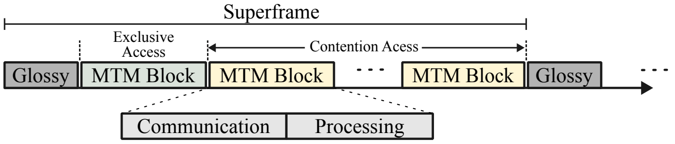

Fig. 3: Possible Superframe structure in SynchroFly. Glossy is executed for time synchronization. Afterward, one MTM block with exclusive channel access is executed, followed by multiple contention blocks.

A. Time-Synchronization

Inspired by Surepoint [3], we use Glossy's flooding approach to derive a network-wide time base. Starting from a central coordinator, we flood the network with periodic synchronization frames. Each node receiving the frame retransmits it, with a deterministic constant delay. Using an included hop counter, nodes correlate their local clock with the coordinator's reference clock. Using Glossy, it is possible to derive an extremely accurate clock synchronization within a few nanoseconds [2], [8]. Since flooding does not depend on the underlying topology, Glossy provides a reliable time base, even in highly mobile swarms.

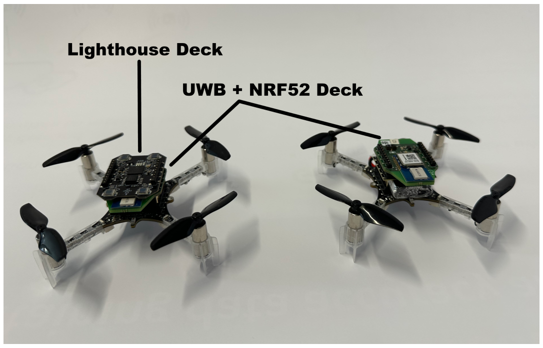

Fig. 4: Setup of a Crazyflie drone with our custom nRF52832-based UWB deck.

B. Many-To-Many Ranging Block

SynchroFly introduces ranging blocks (MTM block), in which we perform ranging with a whole group of nodes at a time, see Fig. 2. Compared to regular TWR ranging, an MTM block lets multiple nodes receive a node's transmission, allowing all receivers to derive a reception timestamp. Ranging blocks are characterized by a variable number of slots K, which are repeated for three phases. When the number of slots K differs from the number of participating nodes M, the system is either underprovisioned ($K < M$, meaning that nodes either do not participate during a ranging block or multiple nodes are assigned to the same slot, causing contention) or overprovisioned ($K > M$, wasting airtime). Nodes are assigned to slots and repeat the same schedule every phase. After executing a ranging block, all nodes have enough information to calculate distances to any of their neighbors. Increasing the number of slots allows for ranging a larger group of nodes at a time, but it also increases the latency. This is possible because for frequency compensated and static nodes, the error on distance for TWR is nearly invariant against prolonged protocol durations [10]. Our superframe structure employs two distinct slot assignment strategies based on the block type. For exclusive access blocks, we use a permutation assignment where nodes are assigned transmission slots in a deterministic fashion. This ensures collision-free access as only one node transmits per slot, but does not allow for spatial slot reuse. For contention blocks, nodes randomly decide both their transmission slot and whether to participate in a ranging block. This random approach allows for potential spatial reuse but introduces the possibility of frame collisions.

C. Implementation

We implement SynchroFly on a system based around the Qorvo DW1000 UWB radio, the nRF52832 MCU (a $64\,\mathrm{MHz}$ Cortex-M4 CPU) and Zephyr RTOS. Our implementation leverages DW1000's delayed transmission and reception features to precisely schedule communication on the radio itself, eliminating the microcontroller from the critical timing path. Fig. 4 shows our experimental setup with custom UWB hardware integrated into the Crazyflie platform. By stacking a Lighthouse deck on top, we are able to get a second independent localization source.

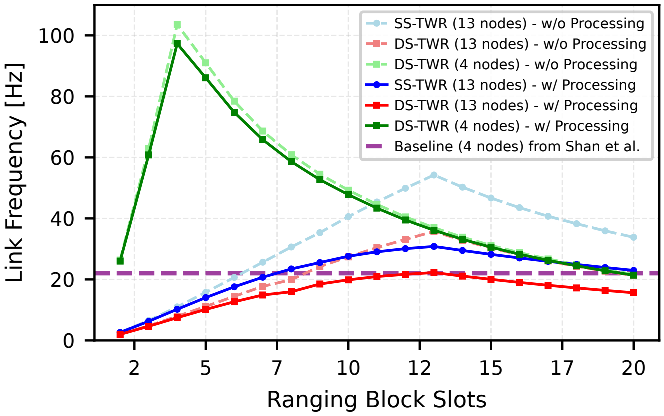

Fig. 5: Update rate towards any single neighbor when nodes are clustered, resulting in a fully connected topology. Results shown for networks of 13 and 4 nodes, demonstrating the relationship between MTM block size and achievable frequency.

IV. PRELIMINARY EVALUATION

A. Exclusive Access Performance

We evaluate SynchroFly's exclusive access blocks on the FIT IoT-LAB Lille testbed site [11] with 13 nodes in a dense cluster configuration. Compared to the solution by Shan et al. [6], we achieve significantly better results with a per-link update rate of $30.1\,\mathrm{Hz}$. These improvements are partially attributed to our timing optimizations, but more importantly to our ability to tightly control frame executions by relying on a stable Glossy-based time base. As shown in Fig. 5, optimal performance is achieved when the MTM block size matches the number of nodes in the network.

B. Contention Block Analysis

We evaluate contention blocks on our local testbed with 8 nodes in a fully-connected topology, testing both 4 and 12 slot configurations. Our experimental results demonstrate that the capture effect and other physical layer phenomena enable partial reception success even when all nodes transmit simultaneously. In Fig. 6, we show the relationship between under- and overprovisioning the number of slots. Our results reveal two notable trade-offs: collision-induced measurement errors lead to outlier distance estimates, and the measurement distribution exhibits spatial bias favoring nearby nodes due to their higher reception probability in collision scenarios. While results generally show a correlation between distance and error rates, the outlier at 1.7m distance exhibits higher than expected errors, suggesting additional factors such as antenna orientation or multipath effects may influence ranging accuracy.

V. OUTLOOK

We designed SynchroFly for scalable ranging in highly mobile settings. However, so far our evaluation has been

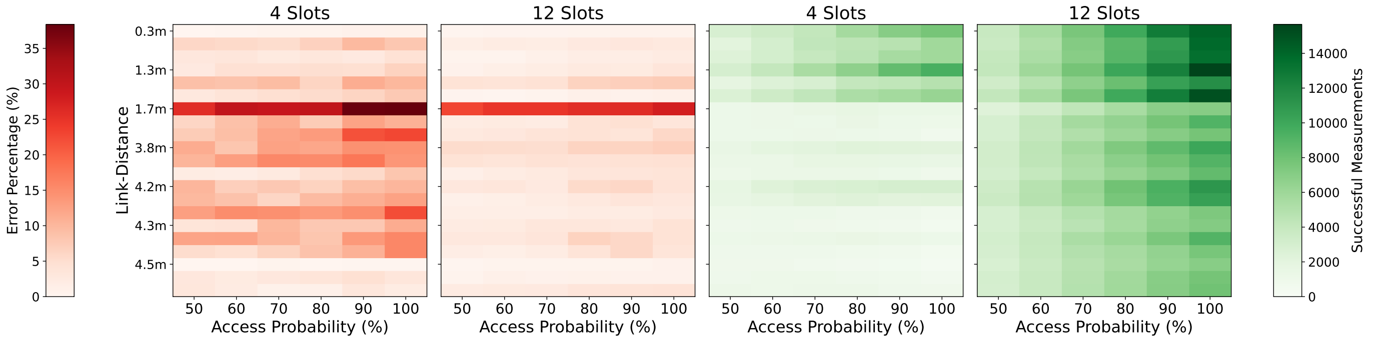

Fig. 6: With increasing probability of nodes joining a ranging block, the probability of collisions increases. Both ranging blocks of 4 slots and 12 slots are evaluated, corresponding to an underprovisioning and overprovisioning of available ranging slots. When slots are underprovisioned, the probability of receiving transmissions from nearby nodes tends to increase, causing an increase in measurements relative to more distant nodes.

constrained to solely static environments. Our current work focuses on building infrastructure to verify our design also when deployed on real micro drones. Furthermore, ideally, evaluation of our system should happen together with a higher-level processor of the ranging information like a collision avoidance algorithm. SynchroFly's measurement rates indicate promising performance in this setting, potentially allowing drones to fly with higher speeds and reducing the required size of safety zones. An interesting approach for increasing scalability of SynchroFly in such use case could also be to use the distance dependency of the measurement rate when using contention to automatically prioritize closer nodes during ranging. Further work is also necessary comparing SynchroFly against other solutions. For this it is necessary to evaluate systems fairly in various system contexts. To alleviate this, we are actively working on integrating other baselines into our software stack, so that fair comparisons with other works are possible.

Furthermore, we are still working on deriving more sophisticated upper-layer scheduling strategies for the MTM ranging blocks, which make stronger use of spatial slot reuse. An interesting direction are the contention based methods we evaluated in our preliminary evaluation. However, a standing problem is the increased production of measurement outliers. For localization use cases, we may achieve even higher scalability by employing Time Difference of Arrival (TDoA) measurements. TDoA measurements can be derived as a by-product from TWR exchanges: By overhearing the active exchanges in a ranging block, an unlimited number of passive nodes can derive TDoA estimates to the active nodes. No modifications to SynchroFly's medium access have to be done to support this use-case. However, an open challenge lies in a scalable strategy for selecting and scheduling active nodes.

VI. CONCLUSION

This paper introduces the first steps towards SynchroFly, a MAC for scalable, high-frequency ranging in ad-hoc aerial swarms. SynchroFly does not require static infrastructure and builds on the high scalability of MTM ranging and highly accurate Glossy-based time synchronization. SynchroFly achieves promising results, especially when deployed in dense settings. However, inefficiencies in our current hash-based scheduling become apparent in sparse multi-hop settings, leaving room for future improvements. The results form the basis for our ongoing work of devising sophisticated upper-layer scheduling strategies and drone coordination algorithms.

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