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Cooperative UWB Environmental Sounding for High Precision Localization and Reliable Communications

Research Proposal

Research stay over more than 6 months to conduct joint research on the use of Ultra Wide-Band (UWB) for cooperative localization and reliable communications.

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Klagenfurt, September, 2018

Acknowledgments

Prior to the research report, I want to acknowledge the people and funding agencies. Firstly, I would like to express my sincere gratitude to Prof. Christian Bettstetter and Prof. Andreas Molisch for their remarkable support throughout the entire research stay. Without their help and support I would not have been able to perform this research stay. Next to the professors, a genuine thanks to both universities; Alpen-Adria Universität (AAU) und the University of Southern California (USC) for granting and supporting this research.
I am thankful not only for the support and the great collaboration between both universities but also between both professors. The unique knowledge of Prof. Christian Bettstetter and Prof. Andreas Molisch considerably contributes to the project. Their expertises on Ultra-Wide Band (UWB) technology, localization, synchronization or reliable wireless communications add significant value to the project. I feel very pleased for the opportunity to work with both professors on various topics. All topics merge into the project to address open research questions and further explore evolving technological opportunities.
A very particular thanks goes to the AAU for supported this stay abroad with continuous salary payments and by granting a mobility fund to cover travel expenses. Additionally, this work was funded by the Federation of Austrian Industries (Industriellenvereinigung Kärnten) and the Austrian Economic Chambers (Wirtschaftskammer Kärnten) to encourage collaborations and research activities on this particular field of expertise.
Additionally, my deepest gratitude to my family who not only supported this research stay but encouraged and promoted my work at any time throughout my career. Also I thank my friends, colleges and secretaries for their contributions.
Thanks for all your help and great support to make this research stay possible.

Contents

1 Preparatory Work

The research on Ultra Wide-Band (UWB) communications started off as a collaborative project with Airbus in Munich and Hamburg, Germany. In this Project, we were interested in exploiting UWB features to explore the potential use for indoor aircraft applications. A major application was to develop a wireless sensor network to substitute existing wired connections to reduce weight and maintenance costs of a plane. We therefore focused our research on communicational reliability and utilized UWB; a technology less prone to narrow-band interferences and jamming. To complement the physical features of UWB, we introduced different diversity schemes on top and evaluated their impact on Packet Error Rates (PERs) and Reception Signal Strengths (RSS) in an aircraft. The sensor network comprises IEEE 802.15.4-2011 UWB transceivers with a fully implemented Time Division Multiple Access (TDMA) stack to detect, schedule and operate arbitrary numbers of nodes within an access point's coverage area. Additional nodes serve as redundant data collectors to mitigate effects of single link faults (i.e., spatial diversity). It is to be mentioned that sensor nodes and access points utilize the same hardware platform. The individual rolls are defined by software only which makes the system more flexible. Also, this allows to take over certain tasks or to assign individual unused sensor nodes as additional access points to enhance the spatial diversity and hence the reliability (in terms of packet loss). The system is also able to utilize pseudo code division multiple access (CDMA) code, that have the ability to apply orthogonality between multiple, simultaneous transmissions. This is beneficial for unpredictable events where sensors need to transmit data at any given time, regardless of their assigned TDMA slots. One application for this is the use of emergency or event driven messages that appear to be unpredictable. However, the CDMA structure can be applied to the sensor network with regard the application specific demands. For instance, different CDMA codes could be used to enhance the throughput by assigning multiple time slots and different CDMA codes to nodes. The flexibility of the system and the proprietary CDMA and TDMA stack makes it possible to adjust to application requirements and to adapt for different use-cases. We explored certain use-case of UWB for industrial applications in harsh and reflexive environments and evaluated the use of UWB for localization. The use of UWB communication for localization, ranging and tracking is very common. We therefore took a look into localization of UWB sensors in realistic deployments for industrial or airplane scenarios. This is when we experienced significantly different distance estimations with regard to the area of operation. While we obtain more accurate measurements in an office scenario, we experience a much larger inaccuracy and variation of distance estimations for measurements performed in an airplane.

2 Introduction

The developed sensor network, contemplates off-the-shelf UWB transceivers to promote a cost efficient solution which scales with a rising number of deployable sensors. The total number of operating nodes is approximated to be many thousand but not limited to serve emerging applications as well. In contrast to other available solutions, which mainly compose of expensive measurement equipment that yield to static point-to-point measurements, we are able to evaluate the performance of a network of nodes over arbitrary measurement points to obtain more conclusive results. Consequentially, the sensor network was extended to suite a broad range of tasks, covering industry 4.0 but also space applications. Follow up projects and a variety of measurement campaigns for a diverse field of applications led to continuous refinements of the system. Some project partners are enumerated below to exemplify the system's capabilities and its broad field of operation:

1. **Airbus**
   Replacing wires in a cabin by wireless communication. Focus is on reliable communications and interference mitigation as well as diversity schemes.

2. **EADS Astrium/ Ariane Group**
   Evaluation of UWB's physical layer properties and the potential use in the vehicular equipment bay of an Ariane carrier rocket.

3. **3M/ Center of Applied Aeronautical Research (ZAL)**
   Assessing and compare capabilities of candidate technologies against UWB as potential technology for Industry 4.0 applications.

To fulfil the strict service demands of particular target applications, it is essential to cope with harsh environments. Such environments may involve non-optimal wireless channel properties, appear to be highly dynamic, interference prone or demand for guaranteed coexistence with other wireless technologies. We asses those demands and work on a diversity concept to be added on top of the existing ones to sustain functionality in varying and dynamic environments.

Beside the communication aspects of UWB and its resilience to narrow-band interference due to its broad bandwidth, another feature is of interest; The short signal pulse in time when comparing it to technologies employing a smaller signal bandwidth. This feature is especially important for applications that are critical to propagation durations such as localization, tracking or distance measurements. An example area where localization is gaining more interest is the industrial sector. Existing UWB solutions for such applications are expensive and big (e.g., often comprise of function generators and signal analyzers) or do not support expedient data communications. Those factors imply barriers to potential use cases. Our solution with low priced off-the-shelf sensor nodes support high data rates, reliability and can be used for an arbitrary number of participating nodes. This enables new opportunities and opens the research for new services and applications. One application is high precision localization as necessity in arising industry applications such as logistics or robotics. Cooperative localization concepts where multiple nodes collaboratively enhance the precisions and accuracies of distance measurements is an evolving research topic. Most localization concepts focus on optimal or simplistic environments without dynamics and consistent Line of Sight (LOS) paths. The case of non-LOS is often not covered and presumed exceptional. Our cooperative approach is supposed to mitigate multi-path effects by reducing the likelihood that obstructed links occur simultaneously over spatially distributed locations. Given that point-to-multipoint distance measurements are conducted and LOS paths emerge, they can serve as reference measurements with high precision/ accuracy. Obstructed links with their resulting multipath components (i.e., non-LOS paths) are categorized based on their link quality to draw assumptions on the credibility of the distance estimation. To collaboratively improve/correct inaccuracies (e.g., caused by reflections or obstructions) plausibility checks are conducted by laterating multiple distance

measurements onto a globally valid coordinate system. To solve the issue of the sensor network's orientation, two or more known reference points (often referred to as anchor points) are required to span a global coordinate system over the entire sensor network. Beside the collaborative approach, nodes may evaluate their environment prior to the distance measurement using a channel sounding approach. We call this Environmental Sounding Parameter Sweep (ESPS) which serves as a mitigation technique to detect environmental properties to tune transceivers (e.g., frequency, packet length, preamble) to achieve best link qualities yielding to a more precise distance measurement. The development is part of the afore mentioned Environmental Aware Communication (EAC) and subject to the joint research with the University of Southern California.
For this research proposal we mainly focus our work on cooperative localization concepts and the development of the Environmental Sounding Parameter Sweep (ESPS) which merges directly into the Environmental Aware Communication (EAC). It is to be mentioned that the sweeping of the environment and the localization is performed during an ongoing data communication without requiring additional messages to be exchanged. Thus, the system integrates reliability, coexistence, interference mitigation techniques and precise localization simultaneously while exchanging user/application data with high speed.

2.1 Problem Statement

We introduced some Ultra-Wide Band (UWB) capabilities and outlined their potential for system applications towards industry 4.0 and their utilization in aircraft or carrier rockets. A major focus thereby is on interference mitigation and high reliability while performing high data rate tasks. As afore mentioned in the introduction section, those requirements are partly solved or will result from the environmental sounding development. Most state-of-the-art localization approaches rely on time-of-flight measurements. Resulting propagation times paired with the transmission speed (i.e., speed of light) yield to an approximated distance measure between sender and receiver. Beside antenna delays and processing times which imply tolerances, the physical features of the propagation wave contributes significantly to achievable precision and accuracy. Due to a signal's reciprocal bandwidth- time relation, a higher bandwidth yields to a shorter signal pulse in time. Such a pulse driven communication enables more accurate propagation times and hence implies considerable benefits for localization. Although UWB communication encourages high precision localization with its physical properties, bad channel conditions or harsh environments imply inaccuracies to the measurements.
As long as LOS paths exist yielding to the shortest way between two communicating partners, localization approaches merely based on time-of-flight information work solidly. But what happens if the LOS path is removed (e.g., obstructing object) and the communication solely relies on reflections? The resulting signal path does then comprise of the way to the reflexive object (e.g., a wall) and all the way to the receiver as depicted in Fig. 1. The resulting distance approximation for such a scenario does not longer fit to the actual relative space between the two communicators. This problem furthermore scales with the reflexivity of the environment. Consequently, we focus our research on this issue to consolidate an cooperative localization approach with some degree of environmental awareness.

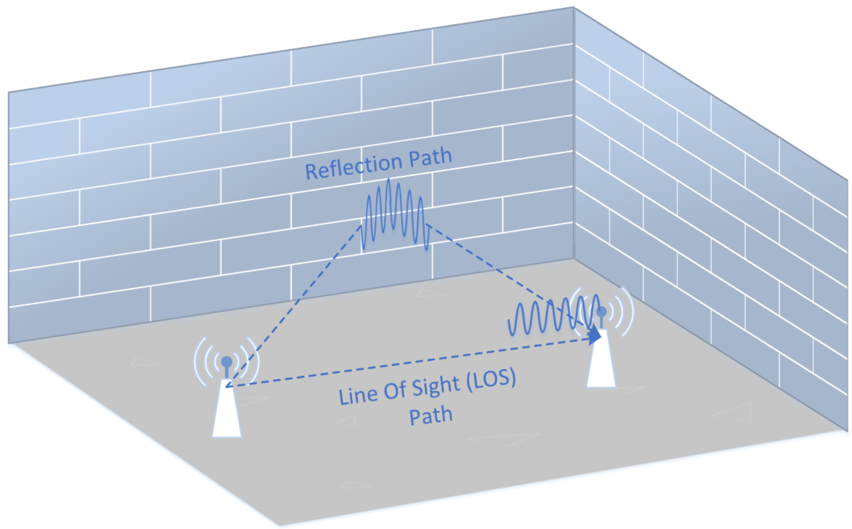

Figure 1: Line-of-sight (LOS) and reflection (non-line-of-sight) of propagated waves.

2.2 State-Of-The-Art

Location awareness is of increasing importance for wireless systems. Especially the area of indoor positioning is growing for various scenarios and applications. Progressive sectors are industrial applications where the demand is for short range (i.e., 5-10 m) localization with accuracies in the mm-range [1]. Ultra Wide-Band (UWB) communications employs various physical benefits to address those challenges and appear to be a promising candidate to serve for high accuracy and high precision demands. The work of Taponecco et al. presents an UWB based Time Of Arrival (TOA) approach in the cm range and shows that accuracy is decreased as the signal bandwidth increases [2]. Similarly, Zhang et al. present a Time Difference Of Arrival (TDOA) approach compliant to FCC UWB regulations [3]. Although, this method provides sub-cm accuracy and could potentially be used with sub-mm resolution by employing time domain measurements to suppress multipath effects, it assumes a Line of Sight (LOS) link. The assumption of a LOS link is a major hurdle when it comes to harsh environments where LOS paths are likely to be obstructed. Most researchers tackle this issue by employing modified localization concepts to achieve more accurate distance or angle estimations. Such approaches do not use waveform information to mitigate multipath effects. Differently to the work of Wymeersch et al. were an approach is proposed to mitigate ranging errors directly in the physical layer using non-parametric regressors [4].

The research on cooperative localization approaches is rather extensive and focuses on a variety of issues. Although comprehensive research is conducted by Conti et al. [5], Wymeersch et al. [6] or Garcia et al. [7], results are commonly based on UWB models and not verified with real UWB sensor networks. Our work would not only complement or extend those findings and evaluate cooperative algorithms to present measurements, but also employ new approaches with an advanced UWB sensor network. There is no other comparable UWB network presented to reproduce our work and hence to perform such measurement campaigns.

3 System

The research is part of our ongoing efforts to develop a wireless sensor network to replace a number of wired systems in commercial airplane. The reduction of wires benefits in 1) the total weight reduction of the aircraft, making it more economical and 2) a reduction of maintenance costs. The latter case also conceptualizes the special interest for localization in order to promote autonomy of the system. With hundreds or even thousands of sensors in a passenger cabin, it is eminent to map sensors to known positions in the plane. This is to obtain useful information with respect to the area a sensor is deployed at. One example for this is a passenger's call for the flight attendance, where we have to map the obtained information to a certain seat location. The mapping of sensors to their absolute position should therefore be done in an autonomous manner to learn about positions rather than rely on databases and fixed IDs. This is to reduce the maintenance effort by diminishing the requirement to ID a sensor node and assign it to a certain position in the plane.

3.1 Hardware Platform

In this section we introduce the hardware platform used for the measurements. To compensate for reflections and interference, we employ ultra-wideband communication. The broad bandwidth of 500-1300 MHz translates to a very short transmission in time. Thus, reflections and multi-path effects can physically be mitigated which aids in measurement accuracy. Further, the broad bandwidth shows improved penetration properties (compared to narrow-band communication), yielding a higher likelihood to maintain a line-of-sight path between sender and receiver. This is of special interest in the above described airplane project where localization shall be performed in a cylindrical cabin with a large number of passengers who obstruct, scatter or reflect signals. Further, the passengers are very likely to move which would manifest in changing distance measurements, higher inaccuracies and hence cause issues with the system's operation. This is to be avoided and a major consideration in our localization approach.

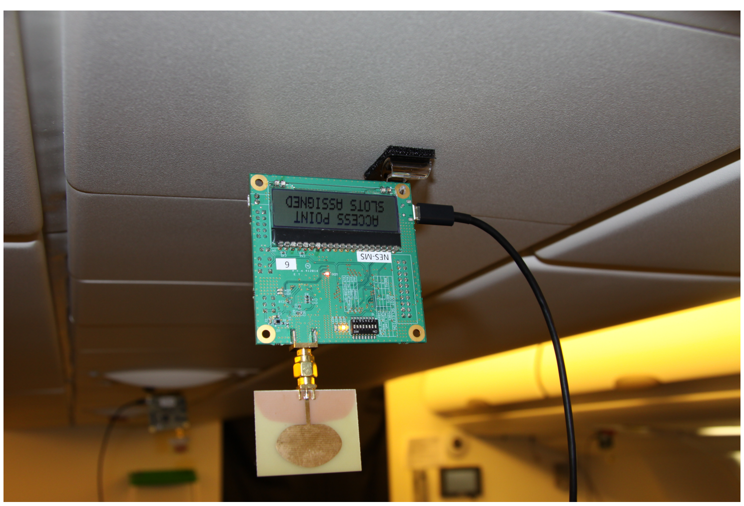

Figure 2: A DecaWave EVK 1000 evaluation board with IEEE 802.15.4-2011 UWB transceivers deployed in an airplane cabin.

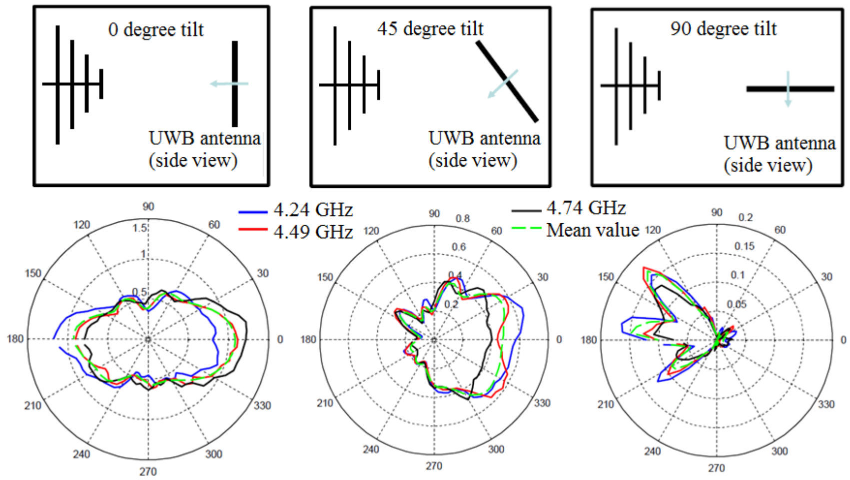

Figure 3: Characterization of the antenna radiation pattern.

Our network therefore builds on IEEE 802.15.4-2011 UWB compliant transceivers commercialized by DecaWave [8]: the EVK1000 boards (see Fig. 2). The main application and purpose of these boards is indoor localization. They however are not calibrated for reliable and efficient data communication. Hence, significant development efforts were needed to adapt these boards to our use case. Even though different nodes may have different tasks within the system, they all consist of the same hardware and differ solely in their software configuration. This enables us to dynamically switch nodes to take over different tasks in different setups.
As preliminary work, a characterization of the antennas is needed to ensure that unintended signal attenuation, due to the orientation of the antennas is avoided. Such a characterization determines the maximally permitted tilt axes so as not to compromise the quality of the measurements. The antenna characterization is depicted in Figure 3, exhibiting a deep notch on the vertical axis and a maximum gain on the perpendicular directions. Nodes are deployed in a way that their relative antenna orientations are aligned optimally with the main lobe.

3.2 Network Architecture

Fig. 4 shows the architecture of the network. Sensor nodes monitor the environment and report their data to one of several wireless data concentrators (WDCs). These WDCs are connected to an application server, which collects, merges, and ultimately controls the system. Whenever appropriate, data is sent to the human machine interface for visualization purposes. The WDCs are responsible for controlling, monitoring, and keeping time alignments among nodes. The WDC positions are fixed in the network, which allows for relative position estimations of sensors to these known locations. To obtain accurate distance estimations, two ore more fixed WDC positions are required to laterate to individual sensor locations. The lateration process is performed offline at the application server which receives and merges the distance estimations of all sensor nodes to all available fixed reference positions (i.e., WDC). After the lateration process, a globally valid coordinate system is established, indicating the individual node positions. This information can be visualized

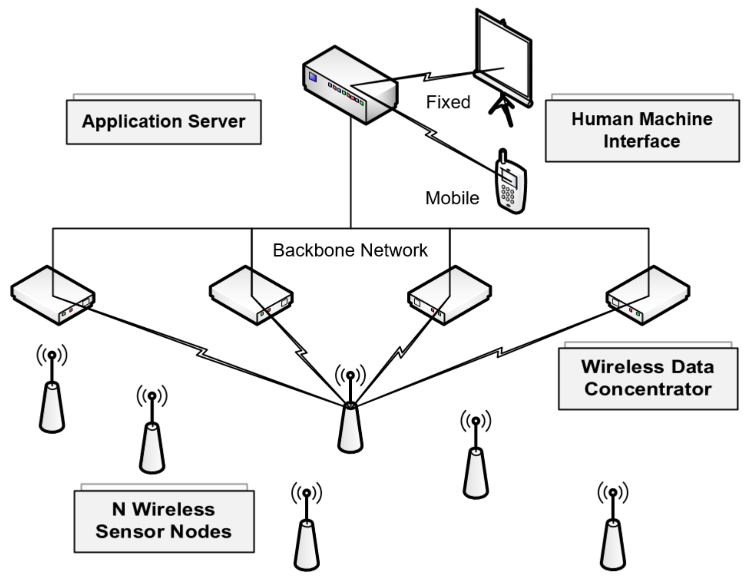

Figure 4: Network architecture depicting multiple sensor nodes, data concentrators and the application server with human machine interface.

at the human machine interface.

4 Research

By using IEEE 802.15.4-2011 UWB transceivers, we establish pulse shaped communications which increases localization accuracies. To mitigate misleading effects of multipath signals in highly reflective environments, we contemplate a channel sounding approach prior and/or during a distance measurement. The resulting environmental information yields to adjustments in transceiver configurations to obtain best possible distance approximations. Some key environmental information to be considered are enumerated:

1. Existence of LOS vs. non-LOS paths
2. Proximity of objects and resulting multipath lengths of reflected waves
3. Properties of reflective-object

    Reflections

    Scattering

    Absorption

4. Object penetration properties on different

    Transmission frequencies

    Transmission powers

Furthermore, we evaluate the impact of cooperative communication and its potential to increase the precision and accuracy of distance measurements. When operating a multipoint-to-multipoint sensor network instead of performing point-to-point measurements, the likelihood of some LOS paths between nodes increases. We utilize this to locate the most optimal links between nodes to establish reference distances among pairs of nodes. Figure 5 illustrates three nodes with two LOS links and one NLOS link that is obstructed. The obstruction causes a faulty distance measurement as the measured time-of-flight estimation results from a reflection (e.g., with the wall as depicted in Fig. 1). Hence, the absolute distance between the two nodes (i.e., the obstructed link path) is not accurate. Originating from the two LOS distances which are presumed to be credible, plausibility checks can be conducted by mapping all distances on a global scale. Given that the measurement of the reflected signal yields an inaccurate distance, a global plausibility check is able to detect and correct this error by laterating with credible link sources (i.e., the two reference LOS paths). As the network of sensors increase, the likelihood of LOS paths scales too, yielding more credible links with the potential to compensate for inaccurate measurements caused by environmental influences.

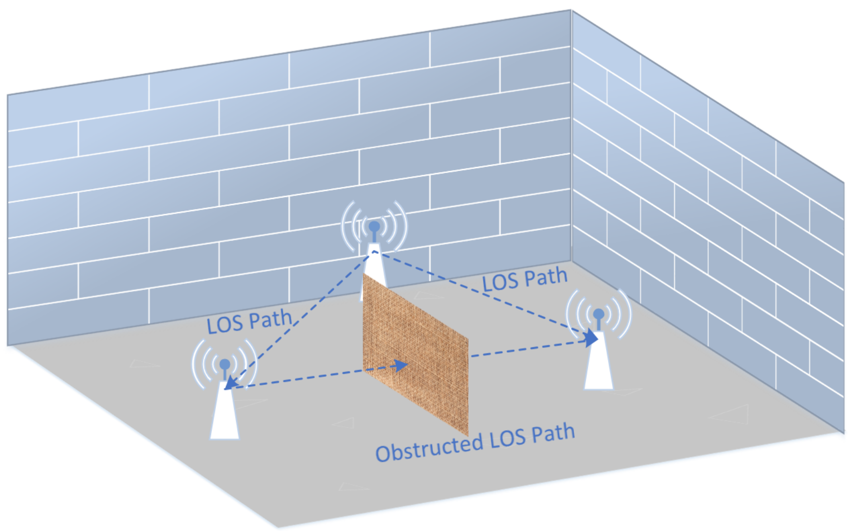

Figure 5: Illustration of a cooperative localization scheme to improve the accuracy of node positions by mapping distance information on a global scale and by performing plausibility checks.

We therefore improve localization accuracies in three ways. First we employ UWB compliant transceivers to enable pulse shaped communication to enhance time-of-flight estimations. Secondly, we perform channel sounding to find optimal transceiver configurations to establish best possible link qualities to aid in distance estimations. Thirdly, we conduct multipoint-to-multipoint measurements among all nodes to collect and further classify their links and measurement credibilities. The distance measurements and the credibilities are further exchanged among all available nodes to map distances on a global scale. A subsequent plausibility check is conducted to reduce uncertainties and to increase the resulting distance precision.

4.1 Point-to-Point Localization

In a first step, we implemented a double-sided [9] localization approach to evaluate the precision and accuracy of distance measurements between a pair of nodes. This approach involves more packets to be exchanged (compared to typical single-sided localization) but benefits in a more precise distance estimation without the requirement of time synchronization among sensor nodes. When running the localization with the highest data rate and the double-sided localization approach, it was possible to perform one measurement within 2 us. However, multiple distance measurements in a static environment without reflections and a strong line-of-sight path feature significant fluctuations. These fluctuations in distance readings are due to inaccuracies of the obtained received power profile. As a message is received, the energy detectors at the analog part of the receiver are accumulated and windowed to represent the power profile. Hence, the accuracy of the estimation is reduced which directly affects the timestamping of the message. As a result, we obtain slightly different timestamps that have an impact on the distance estimation. A timestamp deviation of only 1 ns already yields a distance inaccuracy of 30 cm. This inaccuracy seems to scale with the reflectiveness of the environment. For scenarios with no line-of-sight paths, we also experienced a higher variation in distance estimation. We therefore perform 1000 consecutive double-sided distance measurements and average their estimations, yielding considerably lower variances and some degree of outlier compensation. Consequently, we obtain one distance measurement each 2 ms in time. As we do not consider time critical applications at this point, windowing of distance measurements aids in accuracy and is therefore used in all further evaluations.

4.2 Multipoint-to-Multipoint

To benefit from network-wide global positioning and to verify and possibly correct inaccuracies in distances, we enhance the point-to-point localization to serve arbitrary numbers of nodes. Thus, we implemented a node detection algorithm to promote the system's autonomy by allowing for dynamic expansion or reduction of sensor nodes in the network at any given time. The algorithm contemplates a node-detection phase in the beginning, where an arbitrary number of nodes can join the network. During operation, a dedicated time is reserved to add or remove sensors to or from the network. Changes in the number of nodes or communication schemes can be communicated over control messages. All participating nodes are assigned to unique time slots within a time division multiple access (TDMA) protocol and synchronized to the managing WDCs. These WDCs are also responsible for scheduling and controlling the network-wide distance measurements. All nodes in the network adhere and finally report their measurements to the available WDCs. The individual distances between pairs of nodes are measured in a point-to-point fashion, where the WDCs ensure that each node completes its distance measurement to any other node within its coverage range. The TDMA structure thereby allows for collision free distance estimations. The obtained multipoint-to-multipoint distance information is then forwarded to a computer where the data is being merged onto a global scale.

4.2.1 Overhearing

The process of performing point-to-point measurements in a network-wide fashion including all participating nodes requires a significant amount of time. Especially when certain gap times are included within the TDMA structure ensuring no overlapping communications and interference among nodes. Therefore, an overhearing approach was implemented where nodes listen to ongoing distance measurements to learn and log the distances between the two communicating nodes. This reduces the overall communicational effort significantly and abolishes the need for network-wide propagation of distance information. Further, listening nodes are able to estimate their own distance to both of the communicating nodes by overhearing their messages and using the transmitted timestamps therein. Consequentially, nodes hold their own distance tables which could be used to operate distributively to perform tasks without involving a centralized WDC. Such tasks could be to exchange information that are not relevant to the system or a majority of sensors.

4.3 Channel Categorization

Regardless of a point-to-point or multipoint-to-multipoint setups, the distance measurements indicated fluctuations even in static environments. This effect increases as we enhance the absolute distance between the two operating nodes. This problem we believe, can be accounted to two main reasons: 1) inaccuracies on the analog receiver part and 2) multipath effects caused by the environment (i.e., reflections, absorption and scattering of signals). Firstly, the inaccuracies on the analog part of the receiver may best be explained by outlining the general structure of the receiver. A receiver recognises a message by detecting the transmitted energy with an array of energy detectors. These energy detectors are then correlated, accumulated and averaged before estimating the channel impulse response (CIR) or detecting the signal's preamble. Those parameters however are necessary to find the first detected peak power (e.g., time when the message is first detected in the air) to timestamp the precise moment to calculate the propagation time. The propagation time or time-of-flight describes the duration a message travelled over the air to reach it's destination. As the transmission-speed is known, the propagation time allows to calculate the distance between sender and receiver. Due to the correlation, accumulation and the windowing as depicted in figure 6, there are small inaccuracies involved that add up causing inaccurate distance estimation. This is especially the case where the first peak-power is not clearly distinguishable from subsequent oscillations.
Secondly, multipath effects have a significant impact on the precision of the measurement. When operating in a reflective environment, the reflections of a signal at various objects cause different pathways between sender and transmitter. When such reflections appear at the receiver, they either superimpose constructively (add up in power) or deconstructively (diminish the individual signal power). As a result, the reception of a signal depends significantly on the superimpositions and hence the environmental influences. For example, we present two common signal forms: 1) high peak power in the beginning of the message, which yields a distinct moment of packet arrival and 2) a lower and potentially spread peak power in the beginning of the message, which yields an inaccurate timestamp when the message was received. The imprecise message reception time of the latter case yields an inaccurate propagation time which ultimately is the key to the distance estimation. A propagation time inaccuracy of only 1 ns already yields to a distance deviation of 30 cm

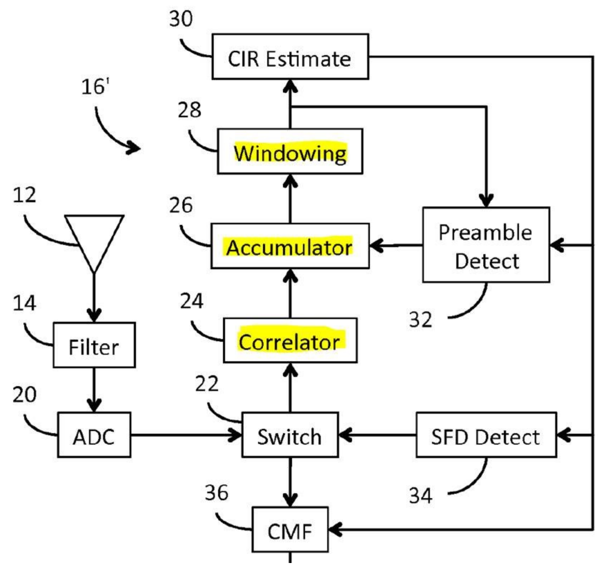

Figure 6: Message reception on the analog part of the receiver.

due to the propagation speed between sender and receiver (speed of light). This issue is of special interest for reflective and dynamic environments where movement causes additional changes over time.

4.3.1 Channel Impulse Response

To investigate the afore mentioned behaviour, we implemented a channel sounding approach. This is to obtain more precise distance estimations by levering the relative signal strength upon packet reception. As mentioned above, multipath components cause distinct effects on the received signal strength and form. Those characteristics can further be used to learn about the environment. The Channel Impulse Response (CIR) is therefore used to represents the relative power over time. This power profile can be obtained for a resolution of 1 ns which allows for precise feature abstraction.
Figure 7 shows line-of-sight measurements where an object was placed in the proximity of a receiver. As a result, multipath components superimpose during reception and can clearly be indicated. Interestingly, multiple measurements performed in the exact same static environment yield different channel impulse responses. The individual CIRs indicate slightly different peak-power levels and employ a time spread of 7 ns among them. This we believe is due to the afore described accumulation and windowing of detected energies prior to the CIR estimation. The inaccuracy tends to increase for more reflective environments. However, the shape and behavior of the conducted power profile measurements (exemplified in figure 7) are comparable, featuring a strong first peak-power and the reception of a prominent multipath component. These similarities are exploited and used to abstract features that allow for an identification of environmental characteristics in which the system is operated at.

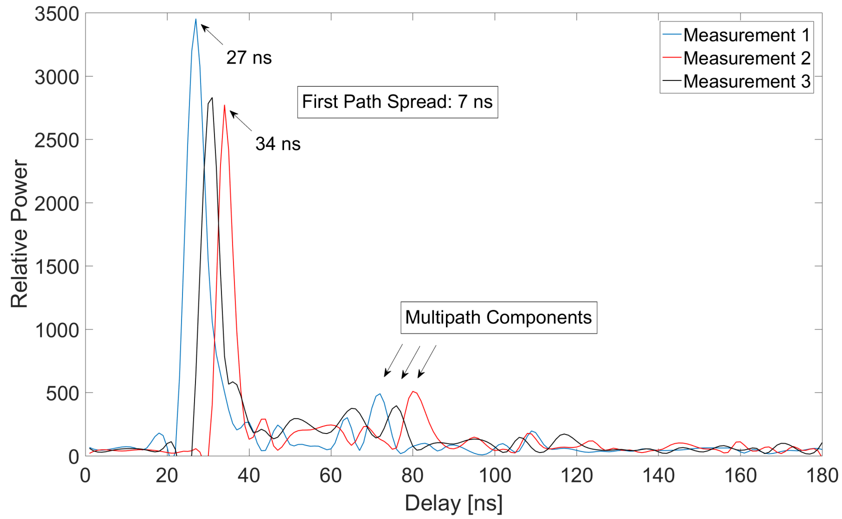

Figure 7: Line-of-sight measurements with multipath components.

4.3.2 Environmental Effects

As we repeat our measurements in slightly different environments, we obtain different distance estimations and fluctuations therein. This, to some extend can be related to multipath effects resulting from the changing environment that imply varying accuracies for the obtained CIRs. Thus, the goal is to learn about the environmental influence to conjecture a classification describing the accuracy of the reading. We utilize the channel impulse response of a received message to compare its power profiles.

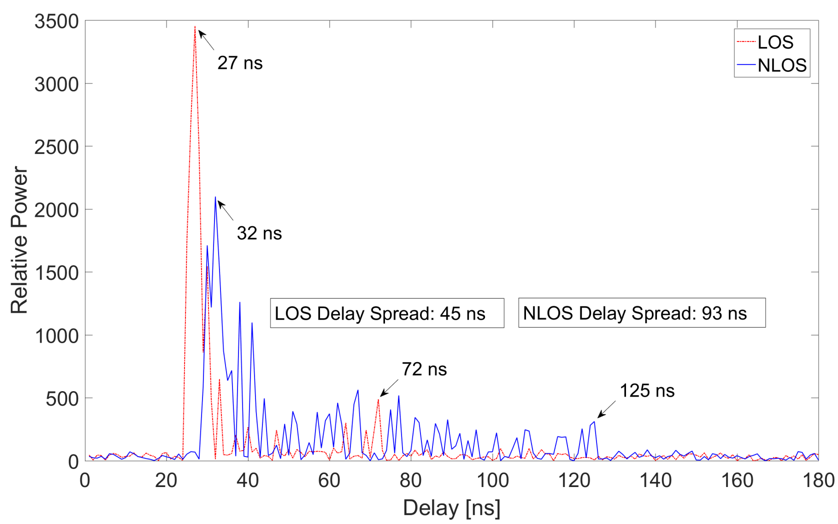

Figure 8: Delay spread of LOS and NLOS.

An example for a LOS and NLOS scenario is depicted in figure 8, indicating a significant difference in their CIR power profiles. The measurement setup was performed in a static office environment with identical nodes and transceiver configurations. Only a metal object was introduced to obstruct the line-of-sight path in case of the NLOS measurement. Consequentially, the peak power dropped and the power remained elevated over the subsequent oscillations. The elevated power level is a direct result to the accumulation of signal components arriving at different instances in time. This indicates a multipath environment without a distinct peak power at the beginning of the reception.

We further exploit the significant differences among CIRs obtained for the LOS and NLOS scenario. While a prominent power can be observed in the beginning of the message for the LOS scenario, a smaller peak power with higher fluctuation at subsequent oscillations is observed for the NLOS scenario. This setup accounts for two extreme scenarios: first a perfect LOS transmission with no multipath components being reported at subsequent oscillations; and second a NLOS scenario where the LOS path is blocked and message transmission is only feasible using reflections of the transmitted signal. In this document, we mainly consider those two extreme conditions. This is to simplify the testbed and to reduce additional affects that may yield unexpected behaviors at the receiver. Although many different scenarios between the almost perfect LOS and NLOS scenarios shall be covered, we use this as starting point in order to study the effect of multipath components on distance estimations. Also, hardware specific particularities have to be considered when operating in a setting upon which the transceiver was designed for.

4.3.3 CIR Adaptation

The varying CIR power profiles manifest in different delay spreads, peak powers and widths as indicated in figure 8. In order to compare these features to conjecture environmental influences we perform an adaptation prior to the feature abstraction. This is to remove unwanted effects caused by the accumulation and windowing at the analog receiver part. Multiple diagnostic parameters are utilized to perform the CIR adaptation to obtain most accurate readings.

The resulting CIRs as presented in figure 9 show an alignment in time on ns precision. We depict two adaptations in the figure, featuring a LOS scenario with and without an obstacle in the vicinity. Multiple measurements for both scenarios were conducted. The subplot on the right shows the CIR for an obstacle free environment, resulting in a high peak power with most of the signal's energy being concentrated in the first oscillations. The left subplot shows the power profile when an obstacle is half the distance between sender and receiver away. The resulting peak power is slightly attenuation and more oscillation appear compared to object-free scenario. Both scenarios however, show comparable quantitative CIR behaviors for all their measurements. This is due to the adaptation process which manages to correct and hence align the individual measurements. The resulting adjusted peak power delay (the exact moment when the peak is detected) is visualized by a green star in the figure. The adjusted signals for all measurements line-up perfectly for both scenarios (e.g., superimposition of the adjusted peak-power delays in the figure). The peak-power delays prior to the adjustment are represented by red stars in the figure. As a result to the adjustment process, all CIRs are aligned over time which allow for precise feature abstraction.

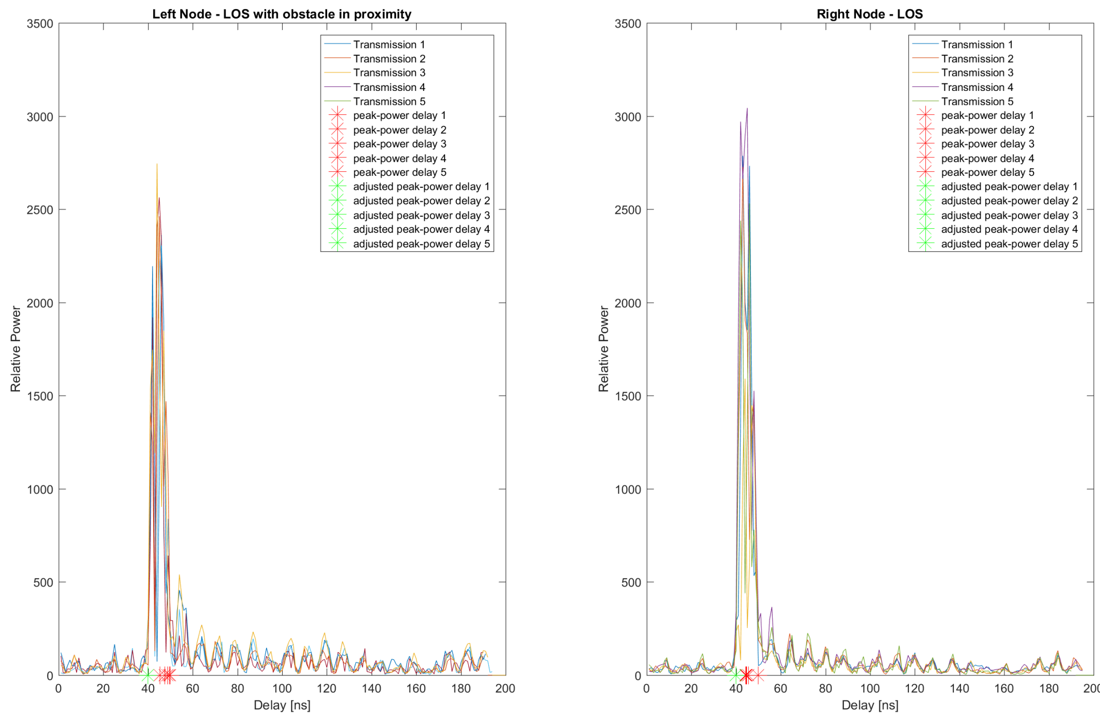

Figure 9: CIR adaptation to improve the accuracy of power readings for LOS scenarios with (left) and without (right) obstacles in the proximity.

4.3.4 Feature Abstraction

In order to classify the estimated distance measurement, we need to learn about the environment. Distinct CIR features allow us to conjecture environmental influences and hence the accuracy of the obtained measurement. For this report we consider two possible classifications, although many variation in between are possible and considered. For simplicity, we assume that an environment either constitutes of 1) a perfect LOS path between sender and receiver or 2) a NLOS path with a metal object between sender and receiver. All obtained CIRs for both scenarios and multiple measurements are each passed to the adaptation algorithm and fitted with an envelope curve. The envelope is useful to reduce outliers and fluctuations that may occur due to the accumulation process of energy detector readings. The resulting envelop represents the power profile of each CIR to perform reliable feature abstraction.

The outcome of the fully autonomous feature abstraction algorithm is depicted in figure 10. First, all peak powers with a considerable rise time and an energy above a certain threshold are detected. These peaks are termed *prominence peaks* and outlined as blue triangles. As a next step, they are arranged in a descending order based on their peak energies to obtain information about the energy distribution and occurrence of oscillations. This is where we already see a different behaviour comparing LOS and NLOS scenarios. With the LOS scenario, we see equally spread prominences which decline with every oscillation in an ordered fashion. The NLOS scenario however, indicates unequally spaced prominences

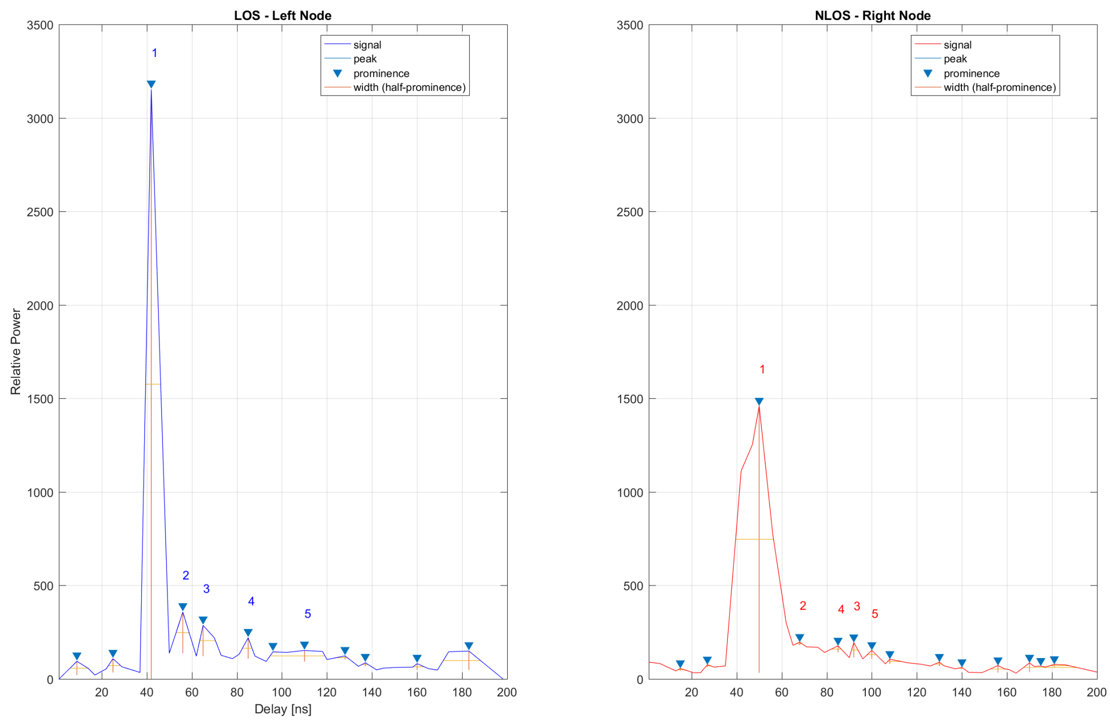

Figure 10: Feature abstraction of a LOS and a NLOS scenario.

which do not decline orderly. In the figure presented above, only 5 prominences are depicted, but the behavioral difference between LOS and NLOS scenario remains valid as more prominences are considered. But not only are height, order and relation between prominences good indicators, also the widths of them hold valuable information. The feature abstraction algorithm therefore calculates the widths of each prominence at half its peak height. For the LOS scenario, this results in a small but high peak power (i.e., prominence 1) and equal widths for subsequent oscillations (i.e., prominence 2-5). Further, the oscillations feature distinct peaks and are clearly noticeable. The NLOS evaluations shows a different behavior with smaller prominence widths and variances therein. This behavior is explicable as there is no distinct first peak power (no line-of-sight) and multipath components, caused by reflections are superimposed at the receiver. This superimpositions appear constructively and deconstructively, causing a high fluctuation which manifests in the scattering or blurring effects after the envelope is fitted. Hence, oscillations add up and are not clearly distinguishable from each other. All abstracted features are interrelated to obtain information to conjecture environmental influences. Pattern matching is one way to approach this problem.

4.3.5 AI Feature Classification

Another way to perform the feature abstraction is to use a neural network. We therefore use obtained CIR envelopes for known environments to train and verify the network. Again, in this report we outline the behavior for only two distinct scenarios: LOS and NLOS. During the training, known LOS and NLOS envelopes are fed to the neural network where the energy at each delay tap (i.e., each ns) serves as parameter. We operate with minimalistic training data of only 15 datasets for each scenario and a 200 ns CIR duration, resulting in 6000 data points to train the network with. This is to evaluate the capabilities of the neural network to distinguish two use-cases for arbitrary inputs with a limited amount of prior training.

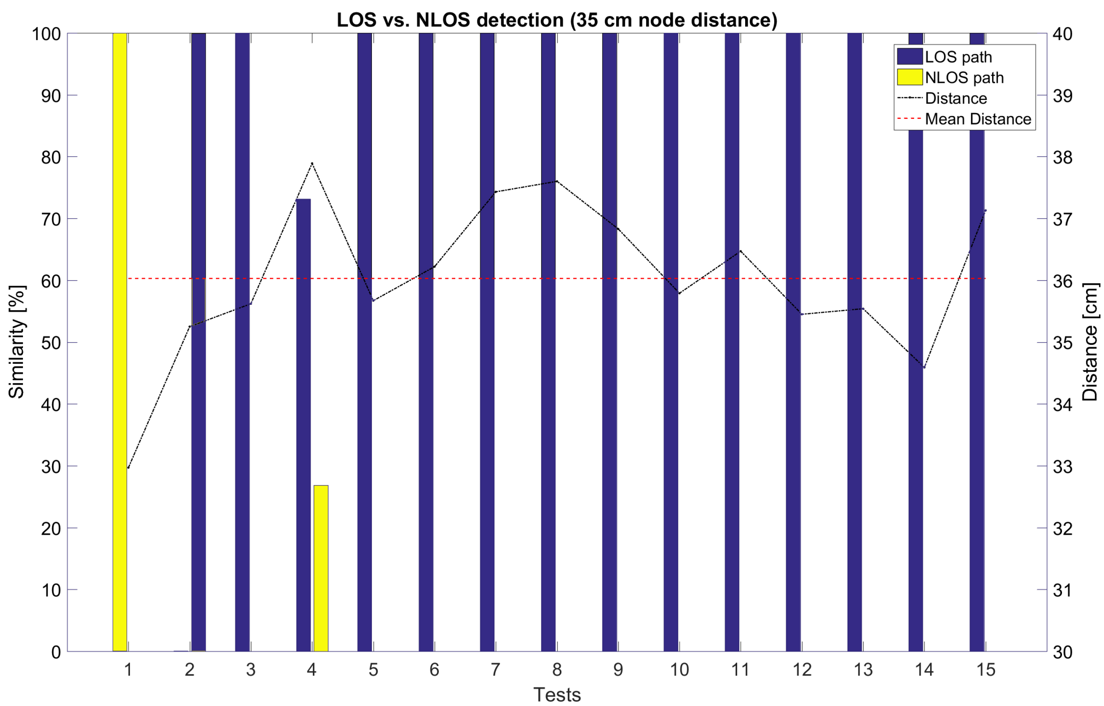

Figure 11: Neural network feature classification for two use-cases: LOS and NLOS.

After the network was trained, we setup a test with a metal object between sender and receiver (i.e., NLOS). The system was operated in a peer-to-peer mode and estimated the time-of-flight and further the distance between the two communicating nodes. After a first iteration (test 1 in figure 11), we removed the object (test 2-3) and placed it again close to the testbed (test 4) before removing it entirely. The results are promising and show that the neural network is able to differentiate between the two scenarios effectively. Needless to say that more extensive datasets yield more training data which eventually improve the accuracy of the neural network. This first concept however, demonstrates the utilization of such a neural network to learn and further predict or conjecture environmental effects. Those effects can than be mapped to a correction factor to improve the distance readings. Figure 11 also depicts the obtained distance estimation for each test environment. The inaccurate distance estimation for the NLOS (test 1) as well as for the reflexive environment (test 4), could be corrected considering the environmental influences. This however is a first attempt to utilize learning algorithms to estimate environmental effects and hence conjecture correction factors. More training data have to be generated, covering different environments to train the network properly yielding precise predictions. This is subject to further investigations including more complex environmental with moving objects.

4.4 Localization Tool

When we combine the developed CIR adaptation and the classification algorithms with the multipoint-to-multipoint approach, we are able to establish an environmental aware localization network. This network constitutes of an arbitrary number of nodes and improves it's accuracy by levering environmental information. The gathered information of the network can than be mapped onto a global scale to obtain absolute distances to more than two known points of reference. This is to create a coordinate system, marking the positions of nodes within it.

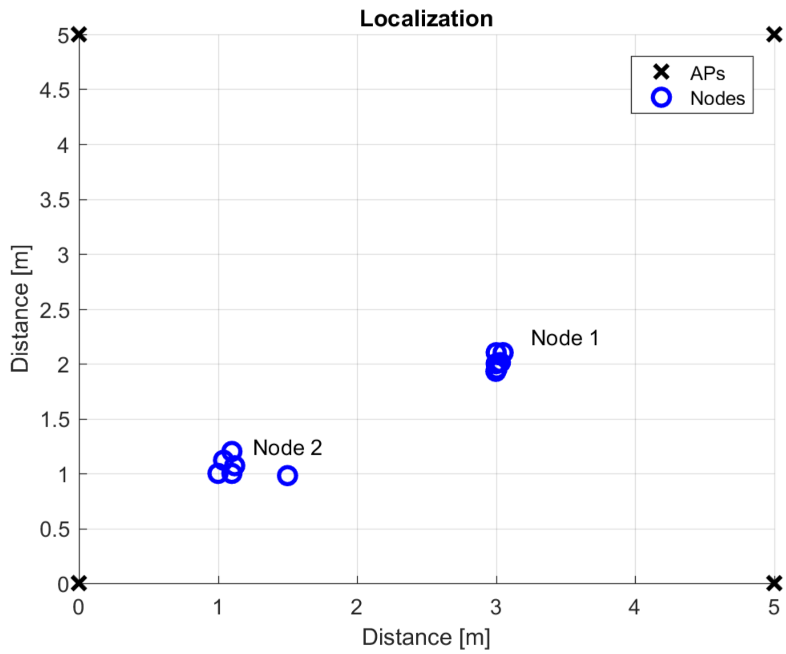

Figure 12: Visualization tool for multipoint-to-multipoint localization.

We therefore developed a localization tool which reads the measured distances in the sensor network to visualize node positions. For this, two or more reference points have to be defined to create a globally valid coordinate system. The obtained distance information is then utilized to mark the relative positions of nodes to a given number of reference points. This employs an additional layer of plausibility checks which becomes more refined when gathering accurate assumptions of a node's environment to spot inaccuracies and unreliable distance estimations. In simple terms: a higher environmental effect, yields a higher inaccuracy which ultimately can be considered in the mapping and plausibility process. Therefore, the classification of obtained distance readings based on their credibility is a key factor to reduce tolerances in the mapping process. An example for the localization tool is depicted in Figure 12, where 4 reference points (e.g., APs) are placed at the corners of a table. These reference points are used to span a coordinate system among them and marked as crosses in the figure. Two nodes are placed on the coordinates (1,1) and (3,2) and 5 distance measurements are performed. Node 1 thereby accounts for environmental effects, where as the second node only reports the raw distance measurements. As a result, the first node reports a smaller variation in the obtained position than the second node.

This example however accounts for an almost static environment, with minor environmental effects. Further experiments have to be conducted to refine the environmental awareness to conjecture more accurate correction factors to further reduce the inaccuracy caused by reflections, absorption or the scattering of signals in the environment. The inaccuracy of a single node furthermore propagates through the network as it affects the mapping process. Therefore, inaccuracies are supposed to scale with the network size. Also, it is to mention that the mapping process as well as the establishment of a valid global coordinate system is performed fully autonomously to work with a large number of nodes.

5 Conclusions

During the research stay at the University of Southern California (USC), we investigated the reasons for inaccuracies of distances measurements in arbitrary environments and attempted to diminish those effects to obtain more accurate readings. We therefore employ ultra wide-band (UWB) communications to exploit it's physical properties to improve the accuracy of measurements. This is based on the utilization of a broad bandwidth of 500-1300 MHz which relates to a short signal pulse in time. This pulse-shaped communication features more accurate distance estimation when compared to typical narrow-band communication schemes. Further we developed a multipoint-to-multipoint sensor network to improve distance measurements with post-processing and plausibility checks. This is done by obtaining distances between all nodes to each other and merging these distances onto a globally valid coordinate system which spans over the testbed. The coordinate system is autonomously created and node positions are marked in relation to two or more reference points (e.g. known positions of nodes) within the network. The positions of nodes are obtained by laterating available distance information of the entire network. The outcome is visualized in a visualization tool which was developed to illustrate the functionality of the system. To visually depict inaccuracies, the tool constantly updates and overlays the position estimations in the map, resulting in a cloud of positions around the actual node's location. This visualizes the spread and hence the inaccuracy of the measurements to test and verify different approaches to improve the system's accuracy.

A major reason for inaccurate distance estimations is the effect of the environment. As described above, the environment imposes two main considerations for distance measurements. First, obstructing objects between sender and receiver yield distance estimations of the propagated message to an reflective object and then to the receiver. Without a direct line-of-sight, the measured distance is hence the distance to an object in the environment and then to the receiver. Second, reflexive environments yield to constructive and deconstructive superimpositions of emitted messages on the receiver. This results in a blurring or spreading of the received signal with higher oscillations and lower peak powers at the start of the message. This in turn implies imprecise timestamps at the receiver which is essential to determine the distance to a sender. As a consequence, distance estimations may vary significantly depending on the environment the system is operated at.

To compensate for those effects, we use the channel impulse response to obtain information on how the signal energy distributes over time. As we learn about the characteristic impacts of reflections and non-line-of-sight paths, we can characterize the quality and hence the accuracy of an obtained distance reading. For example, a prominent peak power in

the beginning of the reception with linearly decreasing energies for subsequent oscillations represent a typical LOS characteristic yielding an accurate distance measurement. As contrast, a smaller difference between peak energy and oscillations with spontaneously appearing oscillation peaks represent a characteristic multi-path environment which increases the possibility of inaccurate readings and the determination of wrong distances (e.g., sender to a wall and then to the receiver). Many more characteristics are considered and factor in to establish a more reliable determination of environmental effects on the obtained distance measurement. We therefore developed an algorithm to utilize various characteristics based on peak energy, energy distribution, oscillations, peak widths and relations between them to conjecture the surrounding environment. In additions, we implemented a neural network to learn typical signal energy distributions in known environments. The trained neural network can then be used to classify and conjecture environmental influences in percent by pattern matching with learned characteristics of known input data. Once we are able to classify the quality of the measurement, we add a weighting factor to the obtained distance to account for possible tolerances in the lateration process for the global mapping and the involved plausibility check.
The developed system including the multipoint-to-multipoint localization is going to be evaluated under different scenarios to refine the accuracy further. Also, we want to conjecture correction factors for the distance measurements based on the environment. This requires more testing and sufficient training data. Also the functionality of the neural network can be improved by increasing the amount of training and verification data.

6 Outlook

Another interesting topic is to enhance the system to cope with effects caused by moving objects. Such movement yields varying multi-path effects on the receiver which ultimately creates a more complex influence at the receiver to compensate for.
Further, it is to be mentioned that a cooperative localization approach, that uses the channel impulse response can be used for any communication technology available. As further work, the developed environmental awareness could be implemented as a protocol stack and provided as library. Such a library could then be used for different communication technologies to verify their potential use for distance measurements and to test their accuracy against UWB communications. This could potentially lead to more accurate distance estimations for currently used technologies and for range estimation, tracking or localization. This could potentially aid in the design of a sensor network to decide which technology to apply depending on QoS requirements and the environment the system is operated at. Further, the developed visualization tool is independent from our platform which enables the verification of distance estimations obtained from different technologies in one tool. Further developments of the visualization tool will improve its abilities such as the autonomous plotting of obtained distance variances obtained from the sensor network over time. Also, the effects of objects being introduced to the testbed and their implication on the sensor network's distance accuracy (i.e., the propagation of inaccurate distance estimation through the cooperative network) can be investigated and visualized. Further, the visualization tool is supposed to be developed to provide live localization and tracking of sensor nodes in a testbed. As a result, it will be used for demonstrating the

environmental effects in real time for different communication technologies. For example, two identical testbeds could be used, one employing UWB localization, and another using ZigBee communications for a localization task. By introducing the same obstacle at identical positions at both testbed, we are able to demonstrate (in real time) the accuracy of cooperative localization approaches for two different communication technologies and visualize the environmental impacts on the resulting distance accuracy and precision for both technologies. This could be very useful, especially when investigating mobility for individual environments. The dimensioning (number of fixed reference points) of the system and the design of the communication technology can be investigated based on the required accuracy (with respect to QoS demands of distance measurements) in regard to the environment the sensor network is operated at.

7 Research Timeline

The research stay with an overall duration of more than 6 months was divided into 5 main milestones that were completed in a subsequent order. The following enumeration lists those milestones:

1. Initialization and literature research
2. Implementation of localization approaches
3. Implementation of sounding approaches
4. Merging and development of an visualization tool
5. System verification

First we research the literature to evaluate the state-of-the-art to outline the research plan more specifically. Second, we implemented a double-sided [9] point-to-point localization approach to obtain distance measurements without prior synchronization. Further, we extended this work for an arbitrary number of sensors. The multipoint-to-multipoint localization procedure was implemented, and verified. Third, we implemented the sounding approach to obtain environmental properties and to retrieve the channel impulse response. The characterization of key features to determine different environments was performed and formulated. Also the neural network was developed, trained and tested for a number of scenarios. Fourth, we merged the localization concept with the sounding approach to obtain distance readings and environmental classifications of a network of sensors. This information can be transmitted to a computer to visualize the positions of nodes with respect to distances between all nodes. Reference points are utilized to create a globally valid coordinate system to visualize the positions. Therefore, plausibility checks are performed to map distances of all nodes to known reference points on a global scale. Fifth, we tested the system's behavior for various scenarios to test and verify the development on a system level. Below, the duration of the research stay is outlined:

Start Date: 5^{th} of February, 2018

End Date: 13^{th} of August, 2018

The milestones were spread over the 6 months starting at the 5th of February 2018 and ended at the 13th of August 2018. Subtasks were assigned and distributed to the main milestones accordingly. The additional buffer time of 1 week as noted in the research proposal was used to get the most out of the collaboration and to complete all tasks successfully.

7.1 Potential Conferences to Target

We aim to publish the work at a conference. Potential venues are enumerated below:

IEEE International Conference on Communications **(ICC)**
IEEE International Conference on Computer Communications **(INFOCOM)**
IEEE Wireless Communications and Networking Conference **(WCNC)**

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