An UWB-based communication protocol design for an infrastructure-free cooperative navigation

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***Abstract*—In this paper, we design a practical medium access control (MAC) protocol for an infrastructure-free cooperative navigation method for a group of firefighters which utilizes an ultra-wideband (UWB) technology for inter-agent ranging and communication. Specifically, our focus in this paper is on developing a communication protocol for the DWM1000 UWB transceiver that works in a robust and energy-efficient manner for our cooperative navigation system. Our proposed solution is a dynamic time division multiple access (DTDMA) in conjunction with a novel negotiation-based rescheduling method. The negotiation-based rescheduling method is designed based on the characteristic features of our cooperative navigation algorithm of interest. We demonstrate our result using a field test and a complexity analysis.**

I. Introduction

In this paper, we design a practical medium access control (MAC) protocol for an infrastructure-free cooperative navigation method for a group of firefighters that utilizes an ultra-wideband (UWB) technology for inter-agent ranging and communication. The transceiver that we use is the DWM1000 UWB by DecaWave. Our focus in this paper is to develop a communication protocol for the DWM1000 UWB transceivers that works in a robust and energy efficient manner when used in our cooperative navigation system.

In a firefighter localization problem, the interest is in a fast deployable infrastructure-free localization. For this application, in the absence of GPS signals, the obvious infrastructure-free localization solution is the use of a shoe-mounted Inertial Navigation System (INS), which measures the acceleration and the rotation by inertial measurement unit (IMU) to continuously calculate the position, the altitude, and the velocity of the firefighter it is mounted on. However, due to the drifting because of the unbounded error accumulation, stand-alone free INS localization is inaccurate for operations with a long duration. The Zero Velocity Update (ZUPTing) [1], which detects the zero-velocity phase of mobile agents as a pseudo measurement to update the location estimation can be used to reduce the growth rate of the error. But ZUPTing still does not fully bound the error. In recent years, wireless signal assisted localization techniques [2] have emerged to improve the localization accuracy of the INS localization. In these techniques, measurements with respect to a pre-installed beacons with known locations are used to assist the INS localization. However, pre-installing beacons in predetermined locations are often infeasible especially in a priori inaccessible environments. A technique that has a promising prospect to assist INS localization for a group of mobile agents is cooperative navigation (CN) [3]. In CN, the mobile agents in a team use the inter-agent measurements as feedback to update local location estimates (based on INS) to achieve better localization accuracy without the dependency on the infrastructure in GPS and landmark challenged environments. Naive implementation of CN can result in all-to-all communication requirements in the network of mobile agents. By using a known uncorrelated upper bound on the joint covariance matrix of any two agents, in our previous work [4], we have proposed a loosely coupled CN algorithm that only requires communication between the two agents involved in relative measurements without any restrictive connectivity condition, see Fig 1. In this algorithm, each agent using a local filter localizes itself in a global coordinate frame. Then, whenever a relative measurement takes place between the agent and another team member, it opportunistically corrects its location estimation using this relative measurement. This algorithm is utilized to design a global localization augmentation system in this paper.

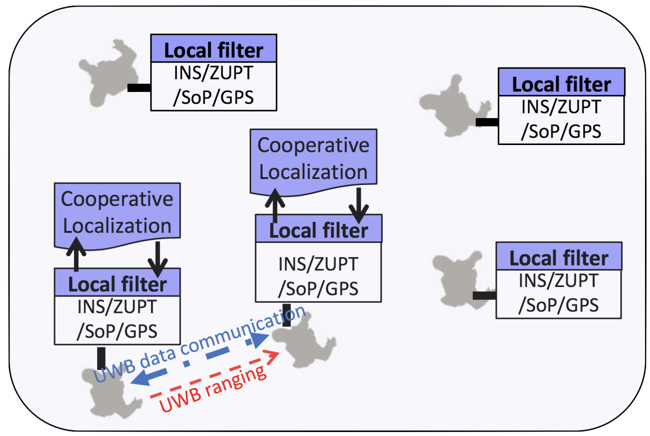

Fig. 1: The desired CN for firefighter localization application. CN becomes active only when there is a relative range measurement between two agents. UWB is used for both inter-agent ranging and inter-agent data communication.

Given the challenging operating environments for firefighters, we use UWB ranging technology to obtain inter-agent relative range measurements between any two agents. The UWB

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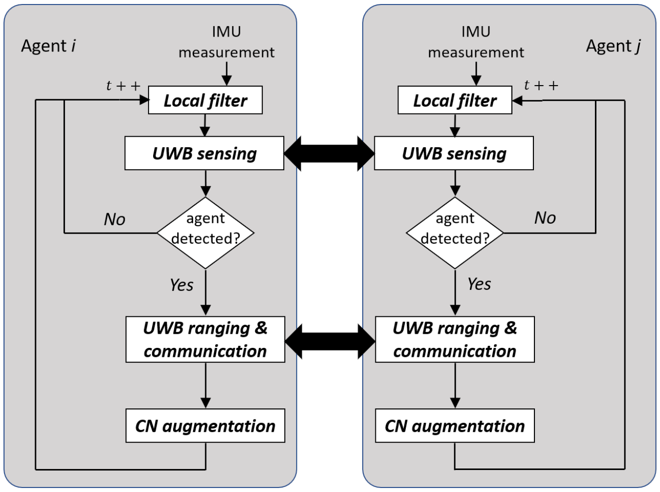

Fig. 2: The architecture of CN argumentation atop of INS based local filter based on UWB ranging and communication.

time-of-flight (ToF) based range measurement, which under appropriate conditions can reach decimeter level accuracy, has received attention in recent years as an effective ranging technology in complex environments. This is due to UWB's capability to take NLoS ranging measurements and its less susceptibility to interfere with coexisting radio signals or UWB signals from other paths. The UWB radio technology also provides a promising solution for wireless communication [5], which is important to realizing CN. We note that in our CN algorithm of interest, to perform any CN update, the two agents involved in a relative measurement need to exchange their local beliefs about their location.

Unlike the continuous waveform of the traditional narrow-band RF signals, the UWB signal has short-duration pulses (picosecond to nanosecond level) with a very low duty cycle (the proportion of the time pulse exists to the total time of a cycle). UWB communication also has a large data rate and resistance to jamming because of its wide bandwidth. The low power emission density makes also the UWB devices energetically efficient. All those characteristics make the UWB a suitable solution as the sensing and an infrastructure-free communication technology for our CN, see Fig. 2.

In our work, the specific UWB transceiver that we use is the DWM1000 UWB transceiver by the DecaWave Inc, which is one of the most popular UWB micro-chips in the market. DWM1000 transceiver is designed to be half-duplex. This means that this UWB transceiver cannot transmit (TX mode) and receive (RX mode) data packets at the same time. Therefore, in a cooperative navigation application when two agents are in the same mode they are not going to be able to detect each other even if they are in each other's sensing range. Therefore, to embed the UWB transceiver into our CN system, the shared channel access by different agents in the group should be managed properly.

Carrier sense multiple access with collision avoidance (CSMA/CA) and slotted ALOHA random access control have been used as two main options for UWB MAC protocol by IEEE 802.15.4-2011 [6]. CSMA/CA, which is the most popular MAC scheme in wireless networks, has been studied for UWB communication [7]–[9]. CSMA/CA assumes that each UWB transceiver in the network is able to monitor the status of the channel before transmitting the information. The transceiver is only allowed to transmit a packet when the channel is detected to be *idle*, otherwise the packet transmission is postponed. Strategies such as inter-frame space, contention window, and acknowledgments are used to reduce the rate of frame collision. Slotted ALOHA random access control [10]–[12] allows the transmission of packets at the beginning of each slot randomly. The packet will be re-sent if collision is sensed. However, both CSMA/CA and ALOHA random access control have limited control over the access each node can have to the channel, which makes the performance of these two protocols highly dependent on the air utilization rate and not suitable for CN where the agents are mobile and we need the agents to be able to communicate when they encounter each other opportunistically. The performance degrades quickly when the air utilization rate is high [13]. The alternative, frequency division multiple access (FDMA) control [14] divides the bandwidth of the whole channel into sub-channels separated by guard bands such that there is no interference between each sub-channel. However, the packet is still lost if the intended receiver happens to be in transmission mode due to the half-duplex nature of DWM1000.

To achieve collision-free communication with an optimal channel access when a group of mobile agents implement the CN of Fig. 2, we propose to use a TDMA MAC protocol to manage the channel access. In TDMA [15], [16], the access to the whole shared channel is divided into time-slots and only one agent is allowed to transmit a packet in one time-slot based on time schedule such that packet collision is avoided. We use a dynamic scheduling to adapt to the changes in the network topology over time due to the agents leaving and joining the network. Next, to mitigate the adverse effect of allowing only one agent to access the whole channel at any one time, we augment our DTDMA protocol with a novel negotiation-based rescheduling method. This negotiation-based rescheduling method is based on the observation that the benefit of CN update depends on the relative uncertainty of the two agents involved. If an agent performs CN update with an agent that has higher uncertainty, the localization improvement it will gain will be low. In our negotiation-based rescheduling method, a negotiation by sending a meta-data happens beforehand inspired by the sensor protocols information via negotiation (SPIN) protocol [17] and priority of communication is ranked. Only the high priority communication is scheduled for a time-slot while the rest is ignored. By introducing this rescheduling method, the efficiency is improved significantly.

The organization of the rest of this paper is as follows. Section II defines our problem setting and gives our objective statement. Section III introduces our negotiation-based

DTDMA protocol for our CN system of interest. Section IV reports on two experimental demonstration studies and complexity analysis that we used to validate our proposed algorithm. Finally, Section V presents our conclusions.

II. PROBLEM DEFINITION

Consider a localization problem for a team of N pedestrians (hereafter we occasionally refer to a pedestrian as an agent). Each agent has a self-contained INS based foot-mounted pedestrian localization filter that generates the agent's global location and attitude estimate. Let the local belief of agent i at time t about its location estimate and its corresponding error covariance obtained from the INS be $\text{bel}^{i\text{-}}(t) = (\hat{\mathbf{x}}^{i\text{-}}(t), \mathbf{P}^{i\text{-}}(t))$. Due to the accumulation of the inherent measurement errors without bound, the localization accuracy of INS downgrades and drifts over time even with ZUPTing. Occasional access to external signals (SoP) or GPS can help to bound the error but extra aiding is still needed due to the low accessibility of these aiding signals.

Our infrastructure-free CN augmentation system based on UWB technology as in Fig. 2 works atop of the local filter to help bound the error. Assume that each agent is equipped with an UWB transceiver. The idea of CN is that as agent i moves in the environment it may detect another agent (agent j) in an opportunistic manner if they are within the sensing range of each other. Then, agent i can take relative range measurement $\mathbf{z}^i_j(t)$ with respect to agent j and use it as a feedback to improve its localization accuracy, i.e.,

$$\hat{\mathbf{x}}^{l+} = \hat{\mathbf{x}}^{l\text{-}} + \mathbf{K}^l\,(z^i_j - \hat{z}^i_j), \quad l \in \{i, j\}, \tag{1}$$

where $\hat{z}^i_j = \mathbf{h}^i_j(\hat{\mathbf{x}}^{i\text{-}}, \hat{\mathbf{x}}^{j\text{-}})$ is the estimated measurement. Therefore, to perform CN, the local belief $\text{bel}^{l\text{-}}(t)$, $l \in \{i, j\}$ should be exchanged between the two agents. In implementation level, we use UWB as both sensing technology to take relative range measurements and communication technology to exchange local beliefs.

To implement the CN system, the access to the channel in the UWB network among the team of the agents should be set properly. In the physical layer (PHY), the specific UWB transceiver that we use in our system is the DWM1000 transceiver by DecaWave. DWM1000 is compliant with the IEEE 802.15.4-2011 standard for local and metropolitan area networks [6]. To manage the shared channel access, an UWB-based MAC protocol for our infrastructure-free CN system should be designed. To achieve timely communication with high efficiency, we identify the following properties for our desired communication protocol:

- Any two agents within the sensing range of each other should be able to detect each other in most circumstances so the localization improvement gained from CN is maximized.
- The protocol should work for a network with dynamic topology. That is agents should be free to leave or join the network.

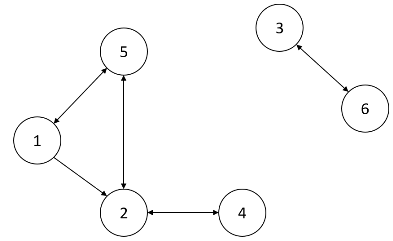

Fig. 3: A graph of a network with two connected subgraphs.

- The ranging and communication should be able to finish within a short period of time such that all the relative measurement processing for CN is finished before the next time step.
- The protocol should also be energy-efficient due to the limited energy source for portable devices in cooperative navigation.
- The protocol should work with minimum pre-setting under different circumstances.

However, DecaWave's DWM1000 chip is designed to be half-duplex, which means it cannot transmit (TX mode) and receive (RX mode) data packet at the same time. Therefore, when two agents are in the same transmission mode, they cannot detect each other even though they are in each other's sensing range. Most UWB localization systems set the UWB transceivers in the network as either an anchor or a tag node with allowing only the tags to receive information from the anchor node. In this setting however, inter-anchor or inter-tag communication is not possible. To solve this problem and meet our design objectives, we implement a TDMA with dynamic scheduling. We augment this DTDMA with a negotiation-based rescheduling to improve the scalability, time-manageability, and energy-efficiency further. In the following section, the protocol is introduced in detail.

III. UWB MAC PROTOCOL

Consider a team of N agents equipped with UWB transceivers each with a UID $i \in \mathbf{V} = \{1, ..., N\}$. This setup is equivalent to a wireless network with N nodes represented by a communication graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$ with node set $\mathbf{V}$ and the edge $\mathbf{E} \subseteq \mathbf{V} \times \mathbf{V}$. The network does not have to be fully connected, see Fig. 3. We assume the communications between each pair of nodes are bidirectional. We use time-of-flight (ToF) based asymmetric two-way ranging (ATWR) [18] as the UWB ranging algorithm. Since one-hop data package transmission is necessary for UWB ATWR, we consider single-hop networks.

A. DTDMA

To avoid package collision, a TDMA framework is used to design our communication protocol. Assume a setting where each agent has only the prior knowledge of its UID i and

Algorithm 1 D-TDMA: time slot synchronization for agent *i*

```
Initialization: t_p = 0, isSynchronized ← false;
  while ! isSynchronized do
    turn to RX mode;
    if received data^j:
      isSynchronized ← true;
      data^i ← writeTodata(i);
      if i > j:
        broadcast data^i in (i - j)δt
      else:
        broadcast data^i in (N + i - j)δt
      end if
      t_p = currentTime();
    else:
      data^i ← writeTodata(i);
      broadcast data^i in Nδt
      t_p = currentTime();
    end if
```

Algorithm 2 D-TDMA: handshaking for agent *i*

```
Initialization: isHandshaked ← false;
  while ! isHandshaked do
    if currentTime() - t_p < Nδt:
      turn to RX mode;
      if received data^j:
        S_c^i ← appendTo(S_c^i, j);
        S_d^i ← combineWith(S_c^i, S_d^i, data^j);
      end if
    else:
      data^i ← writeTodata(i, S_c^i, S_d^i);
      turn to TX mode and broadcast data^i;
      t_p = currentTime();
      isHandshaked ← subnetworkDetected(S_c^i, S_d^i);
    end if
```

the total number of agents N in the network. Let the agents in the sensing range of agent i be $\mathbf{S}_\mathrm{c}^i$ and let the agents that are not in the sensing range of i but are in the same connected sub-network as i be $\mathbf{S}_\mathrm{d}^i$ (for example in Fig. 3 we have $\mathbf{S}_\mathrm{c}^1 = \{1, 2, 5\}$ and $\mathbf{S}_\mathrm{d}^1 = \{4\}$). Agent i initially does not know the current connectivity status of the network, i.e., what agents are in the sensing range of what other agents. Therefore, for every agent i, $\mathbf{S}_\mathrm{c}^i$ and $\mathbf{S}_\mathrm{d}^i$ are initialized as $\mathbf{S}_\mathrm{c}^i = \{i\}$ and $\mathbf{S}_\mathrm{d}^i = \emptyset$. A handshaking is necessary for each agent to detect the status of its sub-network. Initially, we divide the channel access into N time slots for one cycle. To find the assigned time slots for each agent so they can start communication, an initial time-slot synchronization is necessary by listening to the environment as in Algorithm 1. During the time-slot synchronization step, agent i starts listening to the environment and deduces its assigned slot by analyzing the owner of the current time slot. If nothing is heard, a data packet including its UID is sent in $N\delta t$ time. In Algorithm 1, the $writeTodata()$ function writes the passed data to the packet in a buffer for transmission. The $currentTime()$ returns the current time and $\mathrm{t_p}$ stands for the nearest previous time slot assigned to agent i.

After the initial time-slot synchronization, all the nodes find their assigned time slots and broadcast a data packet every $N\delta t$ time. Each agent starts handshaking to get aware of all the other nodes in its sub-network as in Algorithm 2. They broadcast one data packet each cycle at their assigned time slot and listen to the other nodes in the environment for the rest of the time. Once the data packet $\mathbf{data}^j$ of agent j containing $\mathbf{S}_\mathrm{c}^j$ and $\mathbf{S}_\mathrm{d}^j$ is received, $appendTo()$ function is used to append the agent number j that agent t directly receives data from to $\mathbf{S}_\mathrm{c}^i$, sorts the set and remove the repeats ones. The $combineTo()$ function is used to combine the received $\mathbf{data}^j$ with $\mathbf{S}_\mathrm{d}^i$, sort the set, remove the repeated ones and remove the ones already exist in $\mathbf{S}_\mathrm{c}^i$. The handshaking is repeated until all the received $\mathbf{data}^j$ overlaps $\mathbf{S}_\mathrm{c}^i \cup \mathbf{S}_\mathrm{d}^i$ which means all the agents in the local

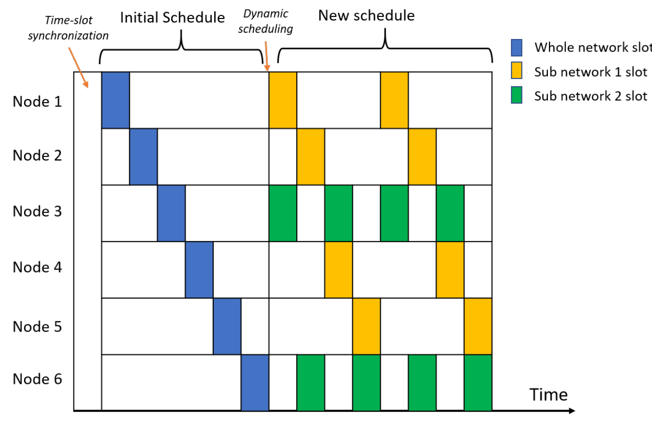

Fig. 4: The dynamic scheduling of DTDMA from the initial schedule over the whole network to the condensed schedule over the sub-networks.

sub-network has been detected. The dynamic rescheduling is finished in a decentralized way based on $\mathbf{S}_\mathrm{c}^i \cup \mathbf{S}_\mathrm{d}^i$ as in Fig 4. The new schedule is made based on the agents in the local sub-network such that the total number of time slot is reduced from N to N_s where N_s is the number of nodes in the sub-network.

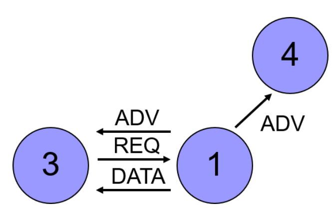

Fig. 5: The mechanism of data-driven SPIN protocol. A mega-data (ADV) is broadcast first to show the characteristic of the real data (DATA) and the real data is only sent upon request (REQ).

B. Negotiation-based rescheduling

The dynamic scheduling condenses the initial TDMA schedule over the whole network into sub-networks. Motivated by SPIN protocol– see Fig. 5–which is a data-driven protocol to maximize the efficiency, we propose to augment the DTDMA communication protocol with a negotiation-based rescheduling as we discuss next.

In CN an agent i benefits more from processing a relative range measurement with respect to a team member that has a lower localization uncertainty. We let $\theta^{ij} = \frac{\det(\mathbf{P}^{i-})}{\det(\mathbf{P}^{j-})}$ be the measure that determines the relative accuracy of agent j in comparison to agent i. Here, $\det(\mathbf{P}^{i-})$ is used as the scalar measure of the total uncertainty of agent i. To improve its localization, agent i prefers to take relative measurement with respect to an agent j that corresponds to a higher value for θ^{ij}. Based on this observation, we modify our DTDMA protocol as follows. First, each agent in the sub-network broadcasts its local estimation uncertainty measured by $\det(\mathbf{P}^{i-})$ as the ADV message in SPIN protocol. Note here that the data size of the ADV message, which is a scalar, is much smaller than the belief $\text{bel}^{i-}(t) = (\hat{\mathbf{x}}^{i-}(t), \mathbf{P}^{i-}(t))$ that is needed to perform a CN update. After broadcasting the ADVs, the agent with the lowest total uncertainty, lets say agent k then becomes the coordinator to reschedule the channel access. The coordinator not only reschedules the channel access but also acts as the landmark for the other agents to take relative range measurements from due to its high accuracy. As the coordinator, agent k calculates the θ^{ik} for each agent i which is his on-hop neighbor in its corresponding sub-network. The calculated θ^{ik} with the corresponding UID i are stored in a descending table as in Fig. 6. Given the constraints on time and energy, only certain number of CN updates, say N_{CN}, is allowed to happen at each time step. Then we only allow the top $N_C N$ agents in the priority list participate in a CN update by taking measurements from agent k. The working schedule is broadcast by agent k to the sub-network. The communication to perform ATWR and to exchange local beliefs then is performed according to the schedule broadcast by agent k. Note here, any agent in the sub-network that is not the one-hop neighbor of coordinator k will not be doing any CN update. An example of the protocol mechanism is shown in Fig. 6.

IV. Experimental Evaluations

We conducted two field tests to demonstrate the effectiveness of our MAC protocol for our CN operation of interest in a real-world scenario. In the field-tests, an UWB network with 6 nodes that represent agents in CN system as in Fig. 7 was set up in the Engineering Gateway Building at the University of California Irvine (UCI) campus. Each node in the network has a designated MAC address that works as UID in the communication protocol. We mimicked the real dynamic CN scenario that agents leave or join the network over time. The sensor nodes leaving or joining the network was accomplished by plugging or unplugging the power to the nodes.

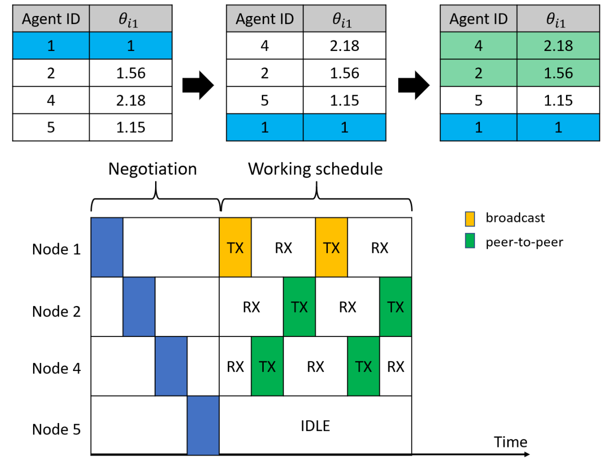

Fig. 6: An example of the negotiation-based rescheduling process (top) and the corresponding time slots schedule over the whole process (bottom).

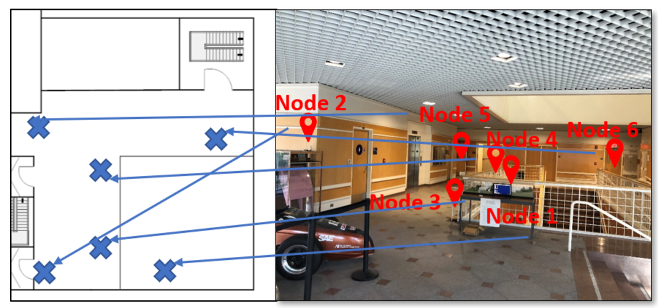

Fig. 7: The experimental setup of the proposed UWB communication protocol for CN. The field test was conducted with 6 UWB nodes spread in the lobby of Engineering Gateway Building at UCI campus.

First experiment: In the first experiment, the packet loss rate, defined as the rate of the packets failed to arrive at the destination node over the whole network, was used as the measure of communication performance. The packet loss rate was measured in real-time. In practice, packet loss is expected especially during the handshaking process when the nodes are trying to establish connections with the others. However, we are expecting that this packet loss should be low for an effective communication protocol. To test the performance under difference circumstances, 6 cases with different network topology as described in Table I were tested. The communication band selected for the system spans from 3.2 GHz to 3.7 GHz. We select the hardware features of DWM1000 as data transmission rate at 850 kbps, preamble length at 1024 octets, and pulse frequency at 64 MHz. The packet loss rate increases as the topology becomes more complicated but the packet loss is successfully bounded within 10% as shown in Fig. 8, which indicates that our protocol works effectively even for a highly dynamic network.

TABLE I: Network topology for 6 cases tested in the first experiment.

Case	Network topology
1	6 nodes in the network from begin to the end
2	5 nodes in the network, then Node 3 joins
3	6 nodes in the network, then Node 4 leaves
4	5 nodes in the network, then Node 3 joins Node 4 leaves
5	4 nodes in the network, then Node 2 Node 3 join Node 5 Node 6 leave
6	2 nodes in the network, then Node 3 to 6 join and Node 2 leaves

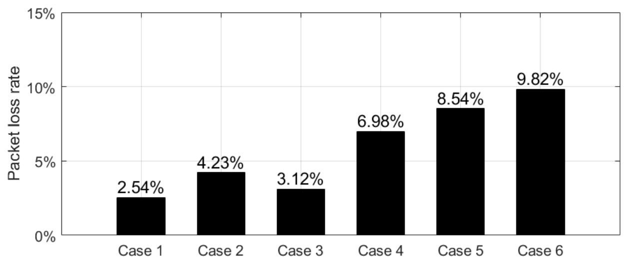

Fig. 8: The packet loss rate for the 6 different cases that are described in Table I. The packet loss rate is well-bounded below 10%.

Second experiment: In our second experiment, we considered a virtual CN scenario over our network of 6 nodes using simulated local beliefs stored at our UWB transceiver nodes. To condense the time schedule and improve the efficiency, instead of performing CN between all the inter-connected agents, the CN update is scheduled selectively according to our proposed novel negotiation-based rescheduling method. Our focus in this study was on the trade-off between the loss of localization accuracy due to selective CN update and the communication cost. . A Monte Carlo test was conducted with $M = 1038$ sets of prior beliefs generated randomly and relative range measurements corrupted by random noise for 6 agents represented by the UWB nodes under the same environment as in the first experiment, see Fig 7. Two strategies are applied: with the negotiation-based rescheduling such that only the CN updates that will bring large benefits are scheduled or without the negotiation-based rescheduling in which the CN updates are performed between every connected pair of the agents. We use the average error reduction percentage and the average uncertainty reduction percentage given by, respectively, $\epsilon = \frac{1}{NM}\sum_{i=1}^{N}\sum_{m=1}^{M}(1 - \frac{\|\hat{\mathbf{x}}_m^{i+} - \mathbf{x}_m^i\|}{\|\hat{\mathbf{x}}_m^{i-} - \mathbf{x}_m^i\|})$, and $\rho = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M}(1 - \frac{\det(\mathbf{P}_j^{i+})}{\det(\mathbf{P}_j^{i-})})$ as the measure for localization accuracy. The indicator for the communication cost is the number of the communications counted during the Monte Carlo test for each strategy. The CN update was performed for only one single step for each set of data. The result is shown in Table II. Comparing to the case without negotiation, when negotiation is used, the reduction of error and uncertainty from CN update drops only about 2% and 3% respectively while the number of communication needed reduces significantly from 37368 and 16623. This result demonstrates the reduction of communication cost is significant with only a little loss of localization accuracy after applying negotiation strategy. From

TABLE II: The result of the second experiment demonstrates the negotiation-based rescheduling method reduces the communication cost significantly without much loss of localization accuracy.

Strategy	$\epsilon(\%)$	$\rho(\%)$	Number of communication
Negotiation	22.14%	34.19%	16623
Without negotiation	24.37%	37.27%	37368

a theoretical perspective, by applying the negotiation-based method, the communication cost is reduced from $O(N^2)$ to $O(N)$ for a single step CN update.

V. CONCLUSION

In this paper, we proposed a negotiation-based DTDMA MAC protocol for UWB communication for a cooperative navigation system. The protocol utilized a TDMA scheme to avoid packet collision in a dynamic way such that the time schedule accommodates the changes in the network topology. The negotiation-based rescheduling method motivated by SPIN protocol was used to schedule CN updates selectively to reduce the communication cost while maintaining an acceptable level of localization performance. Our experimental results showed that in a network of size N, the negotiation-based rescheduling method reduced the communication complexity from $O(N^2)$ to $O(N)$ with only little loss of localization accuracy.

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