A SPIN-based dynamic TDMA communication for an UWB-based infrastructure-free cooperative navigation

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Abstract—This letter presents a negotiation-based dynamic time division multiple access (DTDMA) medium access control (MAC) protocol for ultra-wideband (UWB) communication via DWM1000 transceivers for an infrastructure-free cooperative navigation (CN) system. DTDMA scheme is used to avoid packet collision by dividing the channel access into different time slots and dynamically changing the time schedule such that the time schedule of the agents accommodates the change of the network topology because of the agents' mobility. The negotiation-based rescheduling method motivated by the sensor protocols information via negotiation (SPIN) protocol is used to schedule CN updates selectively to reduce the communication cost while maintaining an acceptable level of localization performance. We demonstrate the effectiveness of our proposed communication protocol via experiments and complexity analysis.

Index Terms—UWB communication, MAC protocol, DTDMA, negotiation-based rescheduling, Cooperative navigation

I. INTRODUCTION

A loosely coupled CN is an aiding localization augmentation, which without the dependency on the infrastructure in the GPS and landmark challenged environments, is used to assist inertial navigation system (INS) or other dead-reckoning local localization filters of a group of communicating mobile agents; see [1]–[5] for examples. CN bounds the error accumulation in the INS or other dead-reckoning localization filters by processing the relative measurement feedbacks between the mobile agents. In a loosely coupled CN, there is no network-wide connectivity requirement; each agent opportunistically corrects its location estimation whenever it detects another agent and processes the relative measurement that it takes from that agent [5]. To process any relative inter-agent measurement, the agent taking the measurement needs to request the local location estimate and the corresponding error covariance (referred hereafter as local belief) of its landmark agent. The landmark agent is the agent that the relative measurement is taken from. We consider a CN method that the relative measurement between the agents is the relative range. Motivated by the high data rate and lower susceptibility of the UWB signals for interference with other radio frequency signals, we use the UWB as both the sensing technology to take inter-agent relative range measurements and the communication technology to exchange local beliefs without relying on the infrastructure. We recall that the range measurements between UWB transceivers are obtained by time-of-arrival (TOA) methods, which measure the propagation time of an UWB signal impulse that travels from the transmitter to the receiver. We use the DWM1000 UWB transceiver, which is one of the most popular UWB transceivers in the market.

The DWM1000 transceiver's default communication system is half-duplex, meaning that this transceiver *cannot* transmit (TX mode) and receive (RX mode) data packets at the same time. As a result, in a CN application if two agents happen to be in the same communication mode they cannot detect each other even if they are in each other's sensing range. Therefore, for the CN application, the channel access by the agents should be managed properly so that any two agents that are within the sensing range of each other can detect each other in most circumstances. Moreover, the protocol should be accommodating the dynamic nature of the network due to the agents' mobility and the possibility of mobile agents leaving or joining the network. Lastly, the protocol should be energy-efficient to prolong the battery life of the portable device used in CN.

Carrier sense multiple access with collision avoidance (CSMA/CA), slotted ALOHA random access control, and frequency division multiple access (FDMA) control are not appropriate for CN application. CSMA/CA and slotted ALOHA random access control are the two popular UWB MAC protocols used by IEEE 802.15.4-2011 [6]. 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 packet collision. Slotted ALOHA random access control [7]–[9] allows the transmission of a packet at the beginning of random slot and the packet will be re-sent if a collision is sensed. However, both CSMA/CA and ALOHA random access control have limited control over the access that each node can have to the channel, which makes the performance of these two protocols highly dependent on the air utilization rate. The performance of data transmission degrades quickly when the air utilization rate is high [10]. As such, these protocols are not suitable for CN where the agents are mobile and the agents should be able to communicate when they encounter each other opportunistically. Alternatively, FDMA 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 the TX mode due to the half-duplex nature of DWM1000.

To achieve a collision-free communication with optimal channel access via DWM1000 transceivers used for CN, we propose to use a TDMA MAC protocol to manage the channel access. In TDMA [11], [12], 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 the time schedule such that packet collision is avoided. We use dynamic scheduling to adapt to the change of 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

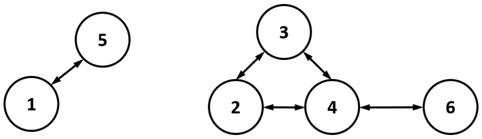


Fig. 1 – A group of networked agents with two connected subgraphs.

method. This negotiation-based rescheduling method is based on the observation that the benefit of the 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 from the update will be low. Inspired by the sensor protocols information via negotiation (SPIN) protocol [13], in our negotiation-based rescheduling method, a negotiation by sending a meta-data happens beforehand to rank the priority of the agents that should participate in the inter-agent communication and ranging. Only the high priority communication is scheduled a time-slot while the rest is ignored. By introducing this rescheduling method, the efficiency of energy and channel utilization is improved significantly.

II. UWB MAC PROTOCOL

Consider a team of N agents each with an UWB transceiver that has a unique MAC address. For simplicity we map the set of the unique MAC addresses of the agents to the unique identification (UID) set $\mathbf{V} = \{1, ..., N\}$. We consider an asymmetric two-way ranging (ATWR) [14] as the UWB ranging algorithm. ATWR requires a single-hop network. The wireless network topology of these agents is denoted by a bidirectional graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$ where $\mathbf{V}$ is the node set and $\mathbf{E} \subseteq \mathbf{V} \times \mathbf{V}$ is the edge set. Because of the agents' mobility, $\mathbf{G}$ is not necessarily fully connected at all times, see Fig. 1.

A. DTDMA

To avoid packet collision while implementing CN, we use a TDMA framework to design our communication protocol. Because of the mobility of the agents, the graph $\mathbf{G}$ may change with time, and it can break into multiple connected subgraphs. To accommodate the changes in the network connectivity, we implement a dynamic TDMA approach to optimally manage the communication time scheduling. In our design, the assumption is that each agent only has the prior knowledge of its UID, the total number of agents N in the network, and the length of time-slot δt. Given an agent i, let $\mathbf{S}_\mathrm{c}^i$ be the set of the agents in the sensing range (single-hop neighbors) of agent i and agent i itself. Next, let $\mathbf{S}_\mathrm{d}^i$ be the set of agents that are indirectly connected through shared neighbors. For example, in Fig. 1 we have $\mathbf{S}_\mathrm{c}^2 = \{2, 3, 4\}$ and $\mathbf{S}_\mathrm{d}^2 = \{6\}$ for agent 2. $\mathbf{S}_\mathrm{c}^i \cup \mathbf{S}_\mathrm{d}^i$ constitutes the connected subgraph that contains agent i. All the agents in the sub-network span by $\mathbf{S}_\mathrm{c}^i \cup \mathbf{S}_\mathrm{d}^i$ share the channel. Thus, their access to the channel should be controlled to avoid packet collision. Initially, agent i does not know the current connectivity status of the network, i.e., what agents are in the same sub-network as itself. Thus, $\mathbf{S}_\mathrm{c}^i$ 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.

Algorithm 1 DTDMA: initial time-slot synchronization for agent *i*

```
Initialization: $t_\mathrm{p} = 0$, is_synchronized ← false;
while is_synchronized == false do
    turn to RX mode;
    If received data$^j$:
        is_synchronized ← true;
        data$^i$ ← WriteToData($i$);
        If $i > j$:
            broadcast data$^i$ in $(i - j)\delta t$;
        else:
            broadcast data$^i$ in $(N + i - j)\delta t$;
        end if
        $t_\mathrm{p}$ = CurrentTime();
    else:
        data$^i$ ← WriteToData(i);
        broadcast data$^i$ in $N\,\delta t$;
        $t_\mathrm{p}$ = CurrentTime();
    end if
```

In our protocol, each agent is able to deduce its next assigned time-slot by adding the length of one cycle $n\delta t$ once it finds its initial time-slot, where $n \leq N$ is the number of agents in the same sub-network. Since there is no global clock available in distributed CN systems, an initial time-slot synchronization is needed such that each agent is able to find its first assigned time-slot. During the time-slot synchronization step, the channel access is divided into N time slots for one cycle and the ith time slot is intended for agent i such that every agent will be assigned a time slot without the knowledge of the initial connectivity condition. Once a time-slot is found by the corresponding agent, the ownership is declared and broadcast by sending a data packet containing its UID at that time slot. Following Algorithm 1, any agent i attempts to find its first assigned time slot by listening to the environment. By analyzing the UID of the current owner, agent i's time slot can be easily deduced. If nothing is heard from the channel, a data packet containing agent i's UID is sent in $N\delta t$ time as a reference to which the other agents are able to synchronize their time slots. In Algorithm 1, the *WriteToData*() function is used to write the data to a buffer in the memory for transmission. However, due to the conservativeness of the initial time schedule, the utilization of the channel is low and the protocol is not efficient. For example, for the case in Fig. 1, only two time-slots are utilized for the first sub-network containing agent 1 and 5. To improve the channel utilization and accommodate the change of network connectivity condition, handshaking is needed such that each agent will 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 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 2. 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.

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. 3), which is a data-driven protocol, to maximize the efficiency

Algorithm 2 DTDMA: handshaking for agent i

```
**Initialization**: is_handshaked ← *false*;
**while** is_handshaked == *false* **do**
    **if** $CurrentTime()$ - $t_p < N\,\delta t$:
        turn to RX mode;
        **If** received $\mathbf{data}^j$:
            $\mathbf{S}_c^i \leftarrow AppendTo(\mathbf{S}_c^i, j)$;
            $\mathbf{S}_d^i \leftarrow CombineWith(\mathbf{S}_c^i, \mathbf{S}_d^i, \mathbf{data}^j)$;
        **end if**
    **else**:
        $\mathbf{data}^i \leftarrow WriteToData(i, \mathbf{S}_c^i, \mathbf{S}_d^i)$;
        turn to TX mode and broadcast $\mathbf{data}^i$;
        $t_p$ = $CurrentTime()$;
        is_handshaked ← $IsSubnetworkDetected(\mathbf{S}_c^i, \mathbf{S}_d^i)$;
    **end if**
```

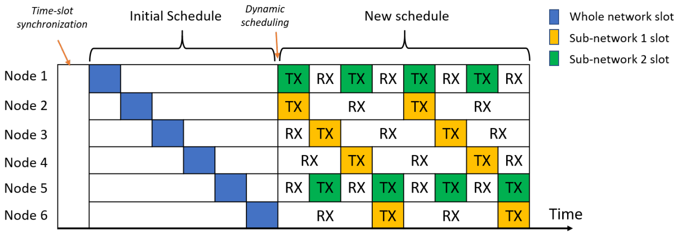


Fig. 2 – For the network in Fig. 1, DTDMA condenses the schedule over the whole network to schedules over the connected sub-networks.

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 $\theta^{ij} = \frac{\text{trace}(\mathbf{P}^{i-})}{\text{trace}(\mathbf{P}^{j-})}$ be the measure that determines the relative accuracy of agent j in comparison to agent i. Recall that $\text{trace}(\mathbf{P}^{i-})$ is a 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 $\text{trace}(\mathbf{P}^{i-})$ as the ADV message in the 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, 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 that is its 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. 4. Given the constraints on time and energy, only a certain number of CN updates, say N_{CN}, is allowed to happen at each time step. Then we only allow the top N_{CN} agents in the priority list to 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 that 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 scenario is shown in Fig. 4.

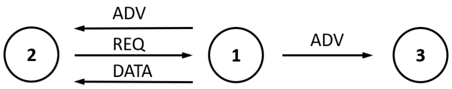
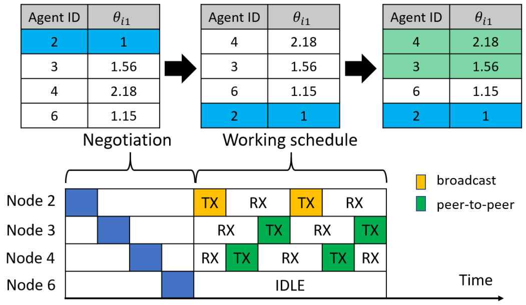


Fig. 3 – In a data-driven SPIN protocol first a meta-data (ADV) is broadcast to announce the characteristic of the real data (DATA). Then, DATA is only sent upon request (REQ).



Agent ID	θ_{i1}
2	1
3	1.56
4	2.18
6	1.15

Agent ID	θ_{i1}
4	2.18
3	1.56
6	1.15
2	1

Agent ID	θ_{i1}
4	2.18
3	1.56
6	1.15
2	1

Fig. 4 – An example of the negotiation-based rescheduling process (top) and the corresponding time-slot schedule over the whole process (bottom).

III. EXPERIMENTAL EVALUATIONS

We evaluate the performance of our proposed MAC protocol through two experiments. In the first experiment, we consider a group of 6 pedestrians, each carrying a portable DecaWave DWM1000 UWB transceiver, performing a random walk under four different network connectivity cases that are explained below in the Cooperative Systems Laboratory of UCI in an area of approximately 50 m^2. We set the communication band for the system spanning from 3.2 GHz to 3.7 GHz with a data transmission rate of 850 kbps. We use the packet loss rate, defined as the ratio of packets failed to be received by the intended receiver, as our performance measure. The four test scenarios considered are: (1) 6 pedestrians were walking in the room. All the agents are in the communication range of each other. (2) Initially, 4 pedestrians are walking in the room in the communication range of each other. Then, 2 agents enter the room and join the network to create a group of 6 mobile agents that are in the communication range of each other. (3) Initially, 6 agents are in the room. Then, two agents leave the room and get disconnected. (4) Initially, 5 agents are in the room. Then one agent leaves the room and gets disconnected, and shortly after a new agent enters the room and joins the network. The duration of each test is 60 seconds. These four cases have different levels of network dynamics. As the network gets more dynamic, it is more challenging for the communication system to work effectively. Figure 6 shows the packet loss rate of each case. It can be seen that the packet loss rate gets higher as the network gets more dynamic. But the packet loss rate is well-bounded below 6% even for the most dynamic case, showing our proposed communication protocol's ability to accommodate the change of network connection responsively. A video of this experiment is available at [15].

In our negotiation-based rescheduling, instead of performing CN updates between every pair of inter-connected agents, only the CN updates that bring a good amount of localization accuracy improvement are selected to be performed. The loss of localization accuracy is expected, but if the measurement scheduling is done carefully this loss can be an acceptable trade off for a reduced

Fig. 5 – The first experiment was performed by 6 pedestrians, each carrying an UWB transceiver (left-top).

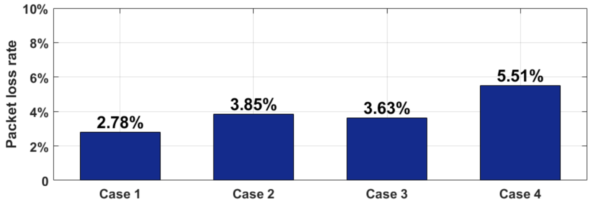


Fig. 6 – The packet loss rate for the four test cases with different level of network dynamics. The packet loss rate is well-bounded below 6%.

communication cost. As a demonstration experiment we considered a team of 6 UWB transceiver nodes, each with a simulated local belief stored on its embedded board. These nodes were deployed, evenly spaced, over an area about 100 m^2 in the second floor lobby of the Engineering Gateway building of UCI. The CN among these nodes was implemented using our proposed DTDMA communication protocol with and without negotiation-based rescheduling. We considered $M = 1038$ Monte Carlo runs. The normalized average error reduction and the normalized average uncertainty reduction (using the trace of covariance as the measure of uncertainty) 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 $\rho = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M}(1-\frac{\text{trace}(\mathbf{P}_j^{i+})}{\text{trace}(\mathbf{P}_j^{i-})})$ are used as the measure for the improvement of localization accuracy. The CN update was performed for only one single step for each set of data. Table 1 shows that in the negotiation-based communication the improvement of localization accuracy drops only about 2% while the number of communication is reduced by more than half. This result demonstrates that applying negotiation strategy reduces the communication complexity significantly and still maintains the localization accuracy. For a single step CN update, the communication complexity is reduced from $O(N^2)$ to $O(N)$ by applying a negotiation-based method.

IV. CONCLUSION

We designed a practical MAC protocol for an infrastructure-free CN method for a group of mobile agents that use DWM1000 UWB transceivers for inter-agent ranging and communication. The focus was on designing a robust and energy-efficient MAC protocol for this CN application. Our proposed solution was a DTDMA augmented by a SPIN protocol. The SPIN component of our protocol was designed to prioritize channel utilization based on the feedback on the position accuracy of the agents and the prospective localization improvement others can obtain by engaging in CN using relative measurements from an agent. Our experimental results showed that the negotiation-based rescheduling method reduced the communication complexity from $O(N^2)$ to $O(N)$ (N is the number of agents in the network) with only a little loss of localization accuracy.

Table 1 – Result of the second experiment.

Strategy	ϵ (%)	ρ (%)	Number of communication
Negotiation	22.14%	33.62%	16623
Without negotiation	24.37%	35.59%	37368

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