Towards Low-datarate Communications for Cooperative Mobile Robots

Gaetano Patti*, Giovanni Muscato*, Nunzio Abbate†, Lucia Lo Bello*

*Department of Electrical, Electronic and Computer Engineering, University of Catania, Catania, Italy
{gaetano.patti, lobello}@unict.it, giovanni.muscato@dieei.unict.it

†STMicroelectronics, Catania, Italy
nunzio.abbate@st.com

Abstract

Communication networks for cooperative mobile robot applications have to cope with some peculiar requirements that make them quite different from typical MANETs or WSNs. Recent cooperative robot applications envisage the support of low datarate communication technologies, as this choice is beneficial in terms of energy consumption, weight reduction and integration with WSNs. In this context, this paper discusses the design choices behind a novel protocol for cooperating mobile robot applications that operates on low datarate networks and is able to provide bounded latencies, mobility and reliability.

1. introduction

Current advances in robotic applications and in wireless communication systems are increasing the interest in cooperative mobile robot applications both in academia and in industry. In fact, cooperation enables robots to go beyond the limitations of individuals [1], providing the possibility to perform more complex tasks.

In this context, the communication system plays a major role, as robots need to share their status information with other robots in order to accomplish a task. Nowadays the commonly used communication technologies and protocols for cooperative robotics are based on the IEEE 802.11 standard (here, called WiFi) in various flavors [2], [3]. Recent works and recent applications [4]–[6] propose the view of cooperating robots as the mobile sensors of a Wireless Sensor Network (WSN) based on low datarate communication technologies (e.g., the IEEE 802.15.4 standard). WiFi protocols are not suitable to be implemented in low datarate devices as they are specifically devised to operate with high datarate. To cope with the multiple requirements of the considered applications, cooperating robots are generally equipped with multiple different communication devices. For instance, in [5] WiFi and Bluetooth devices support the communication between robots, while IEEE 802.15.4 devices enable the communication with the sensors in the WSN. However, such a design choice entails high costs and complexity. For this reason, a new approach is needed for cooperating robots, i.e., a protocol for low-datarate low-energy communications that can be integrated in WSNs.

The main requirements of Networks for Cooperative Mobile Robots (NCMRs) are the following.

Mobility. Mobility support is of outmost importance, as robots have to transmit and receive messages while on the move and regardless of their position.

Bounded delays. In cooperative mobile robot applications, the messages exchanged enable robots to share their status (e.g., position, sensor values, etc.) with the other robots in the network. As a result, these messages have to be consumed within a given time interval, that depends on both the robot speed and the required localization accuracy. Therefore, messages have deadlines (e.g., from tens of milliseconds up to one second), which communication protocols must cope with.

This work was partially funded by the University of Catania under the FIR 2014 project "Self-reconfigurable, flexible, multi-body, low-cost, modular robot systems for exploration of dynamical, hostile or unknown environments".

Multi-hop transmissions. Cooperative mobile robot applications generally require that data is transmitted both to all the robots of a network (or sub-network) and to a single robot (e.g., for jointly carrying a load, but also for joint sensory tasks, such as distributed exploration and map building). In some cases, a network managed by coordinators or access points is a suitable choice, while in other cases, due to the limited coverage of wireless devices, multi-hop transmissions are required. To comply with the requirement of bounded network delays, the routing protocols have to be deadline-aware and have to enable nodes to forward data messages in a predictable way.

High reliability. Mobility may affect the quality of the communication links between robots. This fact, in addition to possible interference, noise and fading on the wireless channel, entails a high potential for a large number of message losses. NCMRs cannot properly operate when a high number of messages is lost. For this reason, reliability is an important requirement that has to be met taking also into account that delay grows with the number of retransmissions. NCMRs have also to provide the capability to tolerate the interference due to external traffic.

This work discusses the desirable properties of a novel communication protocol for cooperative mobile robot applications which can be implemented on low datarate technologies to allow for integration with existing WSNs (e.g., on top of the IEEE 802.15.4 physical layer), and also to enable implementation in Sub-GigaHertz (Sub-Ghz) devices (i.e., devices operating on frequencies lower than 1 GHz). The major benefit of Sub-Ghz communications is that those frequencies are less crowded than other ones.

The paper is organized as follows. Sect. 2 presents related works. Sect. 3 describes the main concepts and approaches underpinning the protocol here envisaged and presents possible solutions, while Sect. 4 discusses the main design challenges. Finally, Sect. 5 concludes the paper and discusses ongoing work.

2. Related Work

Research on protocols for mobile low datarate networks mainly focuses on monitoring and WSNs applications. For instance, in [7] a TDMA protocol (called M_TDMA) that supports mobility was proposed. In M_TDMA the network is partitioned into clusters, each one coordinated by a cluster-head node. As a node that joins a cluster requests a slot to the cluster head, a number of slots have to be reserved for this purpose. Moreover, slots have to be reserved to allow inter-cluster communication. However, this reservation entails high message latencies.

In [8] the MobiSense protocol is presented. It provides a hybrid network architecture made up of fixed and mobile nodes organized in a cluster-tree topology. In each cluster, nodes communicate on different channels. A superframe-based TDMA transmission scheme is adopted. Each superframe provides uplink and downlink slots for data transmission, discovery slots for beacon transmission, and admission mini-slots used for the nodes that want to join a cluster. Such a protocol provides high throughput thanks to multi-channel communication and the adoption of a fast cluster selection mechanism. However, MobiSense is not suitable for cooperative robot communications, as it requires fixed nodes, which may not be always available in these application scenarios.

Other WSNs protocols addressing mobility are presented in [9]. Some of them provide bounded delays, but none of them is able to cope with all the requirements addressed in this paper.

In [10] a protocol for real-time communications in mobile ad-hoc networks is proposed. This protocol provides a TDMA scheduling mechanism in which nodes periodically transmit messages according the Earliest Deadline First (EDF) algorithm. Each node maintains a Communication Requirements Table (CRT), which contains the properties of all the messages to be scheduled in the network. The CRT is updated with a consensus mechanism that enables the network to cope with changes in the message streams and allows nodes to dynamically join or leave the network. To support topology self-checking (i.e., online monitoring of topology changes), synchronization, and admission control, each node periodically broadcasts a message with its CRT, the Neighbor Node Matrix (NNM), the local clock value and other information relevant to the consensus procedure. The protocol in [10] requires one dedicated timeslot per round for the transmission of the CRT and NNM. This choice is suitable in the case of high datarate networks (at least 1-2 Mb/s), while in low datarate networks (up to 256 kb/s) with a high number of nodes (e.g., tens of nodes). This choice increases the NNM update time, the round period and the end-to-end message delay, as all the timeslots have to be sized so as to accommodate the transmission of large frames.

Several other works addressed protocols to support communications between mobile robots, however, most of them addressed the IEEE 802.11 technology. For instance, in [2], an adaptive TDMA protocol is proposed. Such a protocol partitions the time into cyclic temporal windows, in which robots are allowed to transmit following a TDMA mechanism. Synchronization is based on the reception time instants of the messages transmitted by the other nodes. This protocol performs better when communications go through an access point than in ad-hoc networks. However, the protocol requires a high bandwidth, so it is not suitable for low datarate communications. In [3], the latest version of a distributed protocol called RT-WMP is presented. The protocol operates on IEEE 802.11 networks and consists of three phases. In the first phase, a token circulates between nodes. Such a token contains information about the network topology (through a Link Quality Matrix) and information about the node that holds the highest priority message. The last node that receives the token starts the second phase transmitting an "authorization to transmit" to the node that has the highest priority message, so that it starts data transmission (third phase). The RT-WMP protocol [3] fulfils most of the requirements for cooperative robots applications, as it provides real-time transmissions, mobility support and routing based on the nodes position. However, the the token-passing mechanism, due to its overhead, does not make the RT-WMP protocol the best choice for low datarate networks.

In [11] and [12] an isochronous medium access (IsoMAC) for real-time wireless communications in industrial automation systems was presented as one of the outcomes of the flexWARE European project [13]. The protocol operates on top of the IEEE 802.11 physical layer and provides a scheduled phase for process data, in which nodes transmit according to a TDMA mechanism, and a contention phase for best-effort and management traffic. The protocol requires access points that transmit the beacon frames containing the schedule information for the nodes. In the flexWARE architecture mobility is enabled by suitable hand-off mechanisms. The IsoMAC protocol meets the real-time, mobility and reliability requirements of cooperative robots networks. However, IsoMAC needs access points to manage communications and this is a drawback in cooperative robot networks, as nodes may lose the network connectivity if they move away from the coverage area of the access points.

This paper investigates the main design issues of a protocol for cooperative mobile robot applications suitable for low datarate communication technologies and able to cope with all the requirements of the considered applications.

3. Design choices

In this section the foundations of a low datarate protocol for cooperative mobile robot applications are addressed.

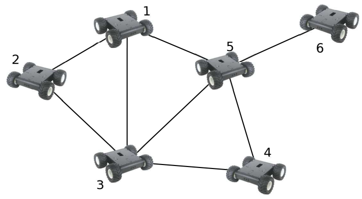

Figure 1. Example of a network topology of cooperating robots.

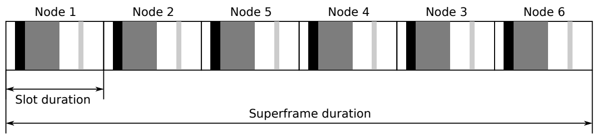

Figure 2. Example of a superframe for the network in Fig. 1.

A typical network topology for these applications consists of nodes that are not fully-linked (i.e., the radio coverage of a node does not reach all the network nodes), as shown in Fig. 1. For instance, node 6 is able to receive or transmit messages only from node 5, so if node 6 moves away from node 5, the latter will lose the connection with the entire network.

3.1. Distributed TDMA

To ensure connectivity in a scenario like the one in Fig. 1 a distributed network management approach represents the most suitable choice. In order to achieve predicable delays, a TDMA-based access mechanism is recommended, as other approaches (like the one proposed in [3]) require high datarate due to the overhead introduced by the network management messages. The approach here proposed is therefore distributed and TDMA-based, and provides a superframe partitioned in slots (as shown in Fig. 2). Each slot is statically assigned to a node for the transmission of data and control messages[1].

Unlike other TDMA approaches (e.g., those in [7], [10]) which provide slots dedicated to the network management messages, here a node is allowed to transmit control information together with data, in the same slot assigned for data transmission. Moreover, to check the neighbor availability and to allow node synchronization, control data is always transmitted regardless of whether a node has data to transmit or

1. Note that self-configuration mechanisms are not addressed in this paper, as they will be investigated in future works.

not. In this way the number of slots in the superframe is significantly reduced, thus allowing for shorter cycle times and, hence, lower message latencies.

3.2.Topology-aware behaviors

Cooperative mobile robots typically provide relative or absolute localization mechanisms, based, for instance, on the Received Signal Strength Indicator (RSSI), Time-of-Flight, Global Positioning System, etc. The robot position is shared with the other robots and such an information is exploited by several network mechanisms and procedures. For instance, a routing approach based on the node position avoids the need for a network topology discovery mechanism, thus reducing the network overhead. In addition, looking at the example in Fig. 1, it is possible to see that node 6 is three hops away from node 2. This means that, if node 2 and node 6 transmit at the same time, very likely there will be no collisions, as nodes 1 and 3 (which have a link with node 2) are not within the coverage area of node 6. The same holds for node 5 that will receive the message from node 6. Hence, if nodes are aware of their own position and of the position of the others, the slot assigned to the nodes that are located at least 3 hops away from each other can be re-used for the transmission of non-critical messages (i.e., those for which reliability and timing are not an issue).

In the case robots are not provided with a localization mechanism, the approach here envisaged foresees that they share a bitmap, here called Network Link Matrix (NLM), that holds the link relations between the nodes. In this way the nodes are aware of the network topology. The NLM is maintained by each node of the network and is updated in two cases:

- When a node receives a message from the node that holds the current slot. In this case the node marks it as a neighbor node.
- When a node receives the NLM of the neighbor nodes. In this case a suitable algorithm to update the NLM has to be adopted.

Note that, the transmission of RSSI values in the NLM provides better routing support. However, in low datarate networks, such a choice entails a large overhead that increases with the number of nodes.

The size (in bytes) of the NLM varies with the number of network nodes and can be calculated as in Formula (1)

$$NLM_{size} = \left\lceil \frac{NumNodes^2}{8} \right\rceil . \quad (1)$$

If nodes do not share their position information, each node transmits its NLR in the control portion of the slot (which in Fig. 2 is drawn as the black slot region). The transmission of the Network Link Matrix entails that longer messages have to be transmitted within a slot, thus increasing the slot size, and in turn the message latencies. However, the need to transmit the information in a separated data message is avoided.

As far as the message routing is concerned, the nodes position or NLM information held by each node can be exploited to adopt position-based routing. For instance, in the case nodes share their position the Geographic Routing [14], a modified version of the Greedy Perimeter Stateless Routing (GPSR) [15] is an option. Otherwise, in the case nodes shares the NLM, a routing approach based on the lowest number of hops can be adopted. In both cases, the network allows messages transmission in a predictable time and without the need for additional routing messages. Conversely, if a message has to be shared among all the network nodes, a flooding approach can be adopted.

3.3.Multiple acknowledge mechanisms

Due to the probability of errors on the wireless channel, critical messages require suitable acknowledgment mechanisms and message retransmissions are also an option. In the case of a message transmitted to a specific node, a suitable choice is to acknowledge the message hop-by-hop within the same slot in which it is transmitted (in Fig. 2 the ack is represented by the light gray region of a slot). The node that correctly receives a message, after a guard interval, transmits an ACK message if it is able to handle the message, or a NACK message otherwise (e.g., in the case its transmission queue is full). In this way the transmitter node, according to a suitable policy, may or may not choose retransmission and, if so, either on the same or another route.

Conversely, in the case of message flooding, the above approach cannot be adopted, as all the nodes that received the message would transmit the relevant ACK, thus creating collisions. A solution to this problem is that each node transmits a group acknowledgment (GroupACK) in the control portion of the slot, to acknowledge the flooding messages received in the time interval between two consecutive slots assigned to the node. In this way nodes are aware of the messages that were correctly received.

Moreover, implicit acknowledgement mechanisms, such that adopted in [3], will be considered.

3.4. Advantages of the proposed approach

The addressed approach offers several advantages to cooperative mobile robot applications, as follows.

Predictable and low delays. The TDMA mechanism not only provides deterministic medium access time, but also enables to adopt real-time algorithms to prioritize the messages using either static or dynamic priorities.

Seamless mobility. Thanks to the knowledge of the positions of the nodes or of the link relations between them, messages can be transmitted by mobile robots regardless they are moving or not. No hand-off or discovery mechanisms are therefore needed.

Improved scalability. TDMA mechanisms generally suffer from scalability problems (as the number of slots grows with the number of nodes and so the message delays). To solve this issue, no slots are dedicated to network management and the nodes are allowed to reuse the assigned slots for transmitting non-critical messages. In this way the overall number of slots is reduced and the cycle times too.

Flexible reliability mechanisms. The acknowledgment mechanisms for both broadcast/multicast and unicast messages enable suitable retransmissions policies. In addition, the proposed approach can be implemented in low datarate Sub-GHz devices, that offer the appealing property of operating on less crowded frequencies than the 2.4GHz one.

Energy saving. The proposed approach allows the nodes to know when they can turn-off the transceiver, thus reducing energy consumption.

4. Open design issues

To develop in real scenarios a distributed TDMA protocol with the characteristics described in the previous Section, the following design challenges have to be addressed.

Nodes synchronization. To make the network work in a TDMA way, the network nodes have to be synchronized. Several distributed synchronization mechanisms were proposed [2], [10]. Such approaches are based on the expected arrival time of messages. In particular, in [2], a node synchronizes itself when a message is received in a bounded window within a slot and does not require clock synchronization mechanism. A way to enhance the synchronization accuracy is to perform synchronization at the beginning of the superframe, using the time offsets collected by all the neighbors nodes in the previous cycle. For applications that require a more precise synchronization, clock synchronization mechanisms can be considered, for instance those based on the Precision Time Protocol [16].

Updating the Network Link Matrix (NLM). As described in Sect. 3, when the robots do not implement any localization mechanism, the NLM has to be transmitted in the control portion of each slot. Due to node mobility, sometimes the NLM transmitted by a node may be inconsistent with the real status of the links. For instance, a node may receive a NLM from another node that does not have an updated NLM just before it has to transmit. Hence, an algorithm able to detect the inconsistent values has to be designed.

5. Conclusions and on-going work

This paper discussed the design choices behind a novel protocol for cooperating mobile robot applications. The novel contribution lies in the design choices, which were specifically made to fulfill the requirements of the targeted applications and to enable the implementation of the envisaged approach on low datarate devices.

Ongoing work is dealing with the definition of the full-fledged protocol, which will be followed by comparative simulations with other solutions. Furthermore, the protocol implementation on real devices, i.e., the STMicroelectronics SPIRIT1 Sub-GHz devices [17] will be also addressed. Mechanisms to support the dynamic addition and removal of nodes, admission control, and channel hopping or channel agility to further enhance the protocol flexibility and reliability will be also studied.

References

[1] Z. Yan, N. Jouandeau1, and A. A. Cherif, "A Survey and Analysis of Multi-Robot Coordination," *International Journal of Advanced Robotic Systems*, vol. 10, no. 339, pp. 1–18, 2013.

[2] F. Santos, L. Almeida, and L. S. Lopes, "Self-configuration of an adaptive TDMA wireless communication protocol for teams of mobile robots," in *Proc. of the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Barcelona, Spain, 15-18 Sept. 2008, pp. 1197–1204.

[3] D. Tardioli, D. Sicignano, and J. L. Villarroel, "A wireless multi-hop protocol for real-time applications," *Computer Communications*, vol. 55, pp. 4–21, 2015.

[4] A. Koubaa and K. Abdelmajid, Eds., *Cooperative Robots and Sensor Networks 2014*, ser. 554. Springer, 2014.

[5] A. M. Derbas, K. M. Al-Aubidy, M. M. Ali, and A. W. Al-Mutairi, “Multi-Robot System for Real-Time Sensing and Monitoring,” in *Proc. of the International Workshop on Research and Education in Mechatronics (REM)*, Elgouna, Egypt, 9-11 Sept. 2014.

[6] A. Wichmann, B. D. Okkalioglu, and T. Korkmaz, “The integration of mobile (tele) robotics and wireless sensor networks: A survey,” *Computer Communications*, vol. 51, p. 21–35, 2014.

[7] A. Jhumka and S. Kulkarni, “On the Design of Mobility-tolerant TDMA-based Media Access Control (MAC) Protocol for Mobile Sensor Networks,” in *Proc. of the 4th International Conference on Distributed Computing and Internet Technology (ICDCIT)*. Bangalore, India: Springer-Verlag, 2007, pp. 42–53.

[8] A. Gonga, O. Landsiedel, and M. Johansson, “MobiSense: Power-efficient micro-mobility in wireless sensor networks,” in *Proc. of the International Conference on Distributed Computing in Sensor Systems and Workshops (DCOSS)*, Barcelona, Spain, 27-29 June 2011.

[9] Q. Dong and W. Dargie, “A Survey on Mobility and Mobility-Aware MAC Protocols in Wireless Sensor Networks,” *IEEE Communications Surveys and Tutorials*, vol. 15, no. 1, pp. 88–100, 2013.

[10] T. Facchinetti, L. Almeida, G. C. Buttazzo, and C. Marchini, “Real-Time Resource Reservation Protocol for Wireless Mobile Ad Hoc Networks,” in *Proc. of the IEEE International Real-Time Systems Symposium (RTSS)*, Lisbon, Portugal, 5-8 Dec. 2004, pp. 382–391.

[11] H. Trsek and J. Jasperneite, “An isochronous medium access for real-time wireless communications in industrial automation systems - A use case for wireless clock synchronization,” in *Proc. of International IEEE Symposium on Precision Clock Synchronization for Measurement Control and Communication (ISPCS)*, Munich, Germany, 12-16 Sept. 2011, pp. 81–86.

[12] H. Trsek, L. Wisniewski, E. Toscano, and L. Lo Bello, “A flexible approach for real-time wireless communications in adaptable industrial automation systems,” in *Proc. of IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Toulouse, France, 5-9 Sept. 2011.

[13] “flexWARE European project,” available on: http://www.flexware.at/.

[14] F. Cadger, K. Curran, J. Santos, and S. Moffet, “A Survey of Geographical Routing in Wireless Ad-Hoc Networks,” *IEEE Communications Surveys and Tutorials*, vol. 15, no. 10, pp. 621–653, 2013.

[15] B. Karp and H. T. Kung, “Gpsr: greedy perimeter stateless routing for wireless networks,” in *Proc. Annual International Conference on Mobile Computing and Networking (MobiCom)*. New York, NY, USA: ACM, 2000, p. 243–254.

[16] A. Mahmood, G. Gaderer, H. Trsek, S. Schwalowsky, and N. Kero, “Towards high accuracy in IEEE 802.11 based clock synchronization using PTP,” in *Proc. of International IEEE Symposium on Precision Clock Synchronization for Measurement Control and Communication (ISPCS)*, Munich, Germany, 12-16 Sept. 2011, pp. 13–18.

[17] *SPIRIT1 - Low data rate, low power sub-1GHz transceiver*, STMicroelectronics, online available: http://www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/DM00047607.p