TDMA-based MAC Protocols for Wireless Sensor Networks:
State of the Art and Important Research Issues

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Abstract – This paper gives a short overview of the state of the art of time-division multiple access (TDMA) based medium access control (MAC) protocols for wireless sensor networks (WSN). These sensor networks have special requirements on MAC protocols, which make it impossible to function efficiently with the help of ordinary wireless MAC protocols. Research challenges and state of the art are described and open research questions are pointed out.

Keywords – Medium Access Control (MAC) Protocols, Wireless Sensor Networks (WSN), Time Division Multiple Access (TDMA)

I. INTRODUCTION

Many of today’s applications for distributed computing need wireless connections in order for the nodes to be able to communicate their results and data. One special kind of node is a sensor, usually consisting of a sensing device and computation, data processing and communication components. Sensors are mostly battery-powered and have therefore a very limited amount of energy to spend. Wireless sensor networks (WSNs) are self-organizing multihop structures that work together in applications like localisation of vehicles, tracking goods or surveillance of areas.

Because of their special properties, which will be described more in section II, wireless sensor networks have to prioritise differently, compared to wire line networks, when it comes to performance. Where other network types aim at a high degree of fairness when it comes to medium access, and a low time delay for packets that cross the network, wireless sensor network have different performance requirements. One of the most important objectives is to conserve energy and use the very limited battery power in the most efficient way. Other highly prioritised questions are: How can we achieve a higher throughput in the network? How can we improve the scalability of the network? How can self-configuration be organised in the best way? [1]

This paper will give a short overview of a small area of research in the field of wireless sensor networks, namely medium access control (MAC) protocols. Efficient MAC protocols are crucial to wireless sensor networks as all sensor nodes compete for the commonly shared wireless medium. But because of the wireless sensor networks special needs, ordinary wireless MAC protocols like Bluetooth or the IEEE 802.11 standard for Wireless Local Area Networks (WLAN) are not suitable for them. They are simply not fitting these networks’ properties, like the constraints in energy resources, processing power, memory space and connection bandwidth, and can therefore not help them to work as efficiently as possible.

The area of MAC protocols is vast, so this paper will concentrate on one special type of protocol, namely those that are time division multiple access (TDMA) based. These protocols usually work by allocating different time slots for different sensor nodes, and require that the communicating nodes are synchronised. (Clock synchronisation in wireless sensor networks falls outside the limits of this paper. An exhaustive survey over the subject can be found in [2], while [3], [4], and [5] are examples on suggestions for improvement.)

The rest of the paper is organised as follows. Section II will explain the particular research challenges in the field of MAC protocols for wireless sensor networks. The State of the Art will be described in section III including an extensive survey on existing protocols with interesting proposed solutions for some of the problems. Section IV will identify a number of open research questions, before the paper is concluded in section V.

II. MEDIUM ACCESS CONTROL PROTOCOLS IN WSN

In Fig.1 [7], the communication architecture of a wireless sensor network, implemented by a protocol stack, is shown, built out of 5 layers and 3 cross-layer planes. Medium access protocols reside in the Data Link Layer, which itself not only is responsible for a fair distribution of resources, but also for providing data stream multiplexing, frame detection and error control. Parts of these goals are accomplished by MAC protocols.

The main duties of the medium access protocol are firstly to assist the construction of a network infrastructure, and secondly to control the medium access, so that all sensor nodes in the network have equal access to the resources and use them as efficiently as possible[7]. This paper will take a closer look at MAC protocols organising medium access by the means of time-division multiple access, TDMA. In order to be able to implement time-slotted MAC protocols, clock synchronisation between the sensor nodes in the wireless network is an important requirement. This task can be rendered possible by the Sensor Management Protocol on the Application Layer.

II. RESEARCH CHALLENGES

A. General WSN research issues

Wireless sensor network suffer from a number of general research challenges. The need for efficient power management due to the extremely limited resources has already been indicated in this paper, but even the lack of processing speed, memory space and connection bandwidth must be taken into consideration. Another important factor when talking about the implementation of a wireless sensor network is cost, as these sensor networks typically consist of a large number of nodes, i.e. sensor devices. Real-time requirements are another...
challenge; a number of characteristics in sensor networks, like the large scale of the network, both in terms of number of nodes and the geographic extent, make it difficult to give any timing guarantees or guarantees for service differentiation. Also high levels of noise and the non-deterministic nature of the network are challenging problems for network developers. But as these sensor networks often operate in a context where timing constraints, i.e. both implicit (e.g. routing deadlines) and explicit (intrinsic in the application) timing requirements, are unavoidable, like e.g. in periodic velocity readings in a vehicular anti-crash system or in surveillance systems for biological/chemical/nuclear warnings, real-time considerations in the design of wireless sensor networks must not be forgotten. As a last general research challenge even the improvement of security in the net should be mentioned. Security is a factor often overlooked when designing protocols, as the attempt to minimise the cost and overhead part of the communication can result in unwelcome security holes. [6]

B. WSN MAC protocol design research issues

The development of protocols in general, and MAC protocols in particular, can be influenced by a number of different factors [7]: how power efficient and fault tolerant is the network, what the network topology look like, and which transmission medium and hardware equipment are used in the network; just to mention a few. Even scalability, i.e. being able to handle an extremely large number of sensor nodes in the network, must be taken into account when designing the medium access control protocol.

As the amount of power in a sensor node, i.e. how long its battery will last, is directly linked to the lifetime of the network, MAC protocols for wireless sensor networks should offer the alternative of accepting a longer transmission delay and a lower throughput in order to increase the time the power source will last. This trade-off can be defined explicitly by every application itself. Sensor nodes do perform a variety of tasks and one can see three groups of activities that consume power, namely the sensing function, the processing of data and lastly the task that drains the battery of power the fastest, data communication. MAC protocols have a direct influence on the power consumption by being able to decide on e.g. the size of the transmitted packets and how often transceivers on the sensor nodes should be turned on and off. Unfortunately there is no easy solution to the power saving problem, even the obvious possibility of turning the transceiver off when not in use, will add elevated power consumption when starting-up again. According to [7], the time spent in off-mode must exceed a certain threshold compared with the time the transceiver is active, in order to achieve a gain in power. Otherwise, turning off the transceiver could even increase the power consumption of the sensor node.

The task of organizing the sharing of common resources is common and characteristic for all MAC protocols. The special need in wireless sensor networks for the MAC protocol to help building the wireless infrastructure arises from the fact that sensors from the beginning are not ordered in a network, but must organise themselves in a multihop network. Therefore also the MAC protocol must be able to cope with this phenomenon by providing the possibility of channel access for the sensor nodes. [8]

The aforementioned capability of self-organisation is only one reason why “ordinary” wireless MAC protocols cannot be efficiently implemented in wireless sensor networks. Other reasons might be [7]: larger numbers of nodes in the network, lower transmission power and radio range of the sensor nodes, frequent topology changes, different degree of mobility (higher than e.g. Bluetooth-connected networks, but lower than the typical mobile ad hoc network (MANET)), and of course a different need of power management. Up to now, special demands on optimising latency behaviour or offering of differentiated services have not been in the foreground, but they will grow to become more and more important as the utilisation of wireless sensor networks will be more and more critical applications where real-time behaviour is essential.

III. STATE OF THE ART

There are two types of protocols for regular multihop wireless networks, those that are based on scheduling or resource allocation (also called contention free), and those that are contention based [6]. The first group of the mentioned protocols contains, amongst others, protocols using TDMA.

The principle of TDMA works like shown in Fig. 2. [9]: TDMA-based protocols divide the bandwidth between all the nodes by dividing each logical channel into time slots, and further combining J of these slots into one frame. In every frame, (usually) every node has access to one dedicated time slot in which it can send and/or receive data on the entire bandwidth of this channel. This in turn makes it possible for the sending node to transmit its data at the highest data rate as the bandwidth of the signal is as wide as the bandwidth of the current medium. This provides a big advantage compared to e.g. code division multiplexing, where all nodes have to share the bandwidth. Being able to use the complete signal bandwidth minimizes the transmitting time because of its inverse proportionality to the bandwidth [10].

TDMA based protocols today are used by different kinds of wireless networks, e.g. the cellular GSM (Global System for Mobile communications) network. In order to make the implementation of a time-multiplexed protocol possible, the need of a central “master node” is apparent, as time synchronisation often is administered in a centralized fashion. This “master node” will periodically send out synchronisation messages on a downlink to all connected nodes, so that they can adjust their internal reference clocks. Protocols like TDMA which need some kind of synchronisation amongst nodes are easily used in networks that consist of cells (like e.g. the GSM net) or clusters, with one administrative centre (an equivalent to the base station in the GSM net) making time based scheduling possible. Unfortunately this fact does not fit the need for peer-
to-peer communication and self-organisation in wireless sensor networks very well. Communication amongst these cells or clusters today has still the need for protocols that implement a different kind of resource sharing, like e.g. code division multiple access (CDMA) or frequency division multiple access (FDMA).

MAC-protocols in general and therefore even TDMA-based MAC-protocols for wireless sensor networks can be categorized according to different properties. A possible characterization could be done according to this classification:

- Pure TDMA vs. hybrid solutions
- Distributed vs. centralized scheduling
- Clustering vs. flat topology
- Mobility vs. static nodes
- Synchronization vs. no synchronization
- Multihop vs. single hop networks
- Collision free vs. channel interference
- Energy efficient vs. energy unaware protocols

For a summary of the individual characteristics of the protocols mentioned in the next section, see Table I at the end of the following section.

A. Some examples on TDMA based MAC protocols

According to [7] there have been numerous design suggestions for wireless MAC protocols involving time division multiplexing (an extensive list is provided in the article), but as the majority of them is centralised and therefore involve global knowledge about the network topology and similar characteristics, these protocols are not easily applicable to wireless sensor networks. In the following, a short survey over TDMA-based MAC protocols that are explicitly targeted towards wireless sensor networks will be given. (The protocols are listed chronologically.)

1) SMACS

[11] develop in their paper a peer-to-peer transmission scheduling protocol which has the capacity of being self-organising and which draws on the idea of “super frames”, clearly inspired by the TDMA principle. As there is no clock synchronisation in the network and no requirement for administrative master nodes, no coordinated time schedule can be implemented though. In order to avoid interference (which can arise due to the lack of centralized control) they assign an extensive number of code-multiplexed or frequency-multiplexed channels to interfering links and so create the possibility of concurrent transmissions. Unfortunately, this method results in lower channel utilization [12].

In the following year, this protocol was further developed into the SMACS protocol [8], short for Self-Organizing Medium Access Control for Sensor Networks, and published together with several algorithms for the forming of an infrastructure, for performing routing tasks and for the mobility management, i.e. maintaining the network organization. SMACS is working together with the EAR (Eavesdrop-And-Register) algorithm to start up the network and connect the nodes. SMACS creates the infrastructure by discovering neighbouring nodes and establishing the schedule for resource sharing. This schedule is time multiplexed, so the logical channel, i.e. the communication link, is composed of time slots. In SMACS the idea of “slots” is implemented by defining one communication channel between two nodes as a pair of time slots. Even in SMACS, the principle of the superframe still exists. The length of this superframe, denoted $T_{frame}$, is fixed for all nodes. As soon as a node discovers a new neighbour, a new connection will be formed by assigning one slot (the same) of the superframe to both nodes during which they can send and receive. In order to decrease the probability of collision, which still can occur due to the lack of global synchronisation between nodes, each communication link is intended to occupy a different, randomly chosen frequency. New links can be initiated between nodes that have enough overlap in not-assigned time slots for an additional connection. As the superframes fill up, there will be times when two nodes cannot find common time slots. In this case, both nodes will try to connect with other nodes instead. This obviously indicates that $T_{frame}$ is one of the limiting factors when it comes to scalability.

The need for time synchronisation is reduced to synchronisation between nodes in the same subnet, i.e. nodes with overlapping superframes. These subnets are not physical clusters with a central master node, but temporary groups of nodes during the start-up phase. As these groups grow larger as more and more nodes are connected, the subnets will eventually link up with each other and finally create one common network.

Power consumption is managed efficiently by turning off nodes during those time slots where they are neither scheduled to send or to receive any packets. The main task of the EAR algorithm is to maintain guaranteed service to all mobile sensor nodes in the network. According to [7], this protocol is especially suitable for wireless sensor networks as it efficiently uses the large amounts of bandwidth inherent in those nets when seen against the considerable lower data rates expected when talking about sensor data. One obvious risk pointed out by [7] is that this particular implementation of the time multiplexed access scheme gives way for the possibility that sensor nodes that are already connected to other, different subnets never could be connected with each other due to e.g. problems with the synchronisation of the superframes.

2) PACT

The PACT protocol (Power Aware Clustered TDMA) [13] was the first TDMA MAC protocol for large sensor networks that used passive clustering in order to take advantage of a dense topology to prolong both battery and network lifetime. The principle of passive clustering takes into consideration the individual energy level of every node, and appoints so called “cluster heads” depending on how long battery lifetime is left. The task of being cluster head is allotted to the nodes with the biggest energy reserves, but is rotated as soon as this ratio changes, in order to preserve a minimum of energy in all sensor nodes. The subset of cluster heads and certain gateway nodes which are responsible for traffic between neighbouring clusters, have priority in allocating time slots. Only after they have received their demanded bandwidth, the ordinary sensor nodes are granted the possibility to choose between the remaining time slots. Energy consumption is further minimized by
adjusting the active times of the nodes to the data traffic present in the network at a certain time, i.e. nodes are shut down when there is no transmission concerning them. [13] proved through simulation that their protocol could prolong network lifetime up to five times compared to the IEEE 802.11 wireless standard due to a more efficient power management. Through the use of passive clustering, network lifetime can also be improved by increasing the sensor node density in the network. Their simulation results point to a doubling of network lifetime when increasing the density by a factor 1.5.

3) MAC using EDF

This MAC protocol is aimed towards a cellular network structure [14], assuming periodic traffic with bounded delay. Messages are categorized depending on their destination; messages within the same cell (intra-cell messages) are scheduled by Earliest Deadline First (EDF), using TDMA, messages to any other cell (inter-cell messages) are sent via dedicated router nodes, using FDMA. Network utilization is increased by using FRASH, a frame sharing technique, where frames unused by the scheduled messages can instead be claimed by other nodes. According to the authors, the use of prioritization by the means of EDF extinguished the need for control packets and by that also reduces the overhead introduced by control traffic. Their simulations show a lower latency and a higher throughput than comparable TDMA or contention based protocols in the case of high traffic and a dense network topology.

4) DE-MAC/ER-MAC

[15] introduce a Distributed Energy aware MAC protocol (DE-MAC), which tries to look at the energy consumption from a network perspective and optimize energy savings by treating sensor nodes individually, depending on their energy remains. This is implemented in a local election scheme, where sensor nodes with an energy level under a certain threshold value can initiate a so called “local leader-election” (which is completely integrated with the TDMA schedule and therefore not influencing throughput performance). In this phase, the node(s) with the lowest energy remains will become the leader(s). This will result in a reduction of time slots for the loosing nodes, and an increase of time slots for the winning node(s). (At start-up all nodes have an equal amount of time slots.) According to [15], re-allotting slots in this manner will lead to less idle listening time of the critical nodes, i.e. the nodes with the lowest energy levels. This depends also on the introduction of periodic listen and sleep phases, where nodes will enter the sleep mode only during times when it is allotted time slots, but has no more messages to transmit. During the remaining time slots it has to stay awake listening in case other nodes is trying to reach it. Simulations indicated an improvement in energy savings compared to similar protocols.

Approximately the same protocol, introducing the additional term of “energy criticality” as a measure of node lifetime, was presented as ER-MAC (Energy and Rate based MAC) in [16].

5) TRAMA

TRAMA [17] is a traffic-adaptive MAC protocol which tries to achieve efficient energy management by avoiding receiver collisions at the packet level through the usage of TDMA scheduling, and by employing a low power mode for nodes which are neither expected to send nor receive. The usage of this low power mode is dynamically determined and adapted according to the current traffic pattern. Furthermore, TRAMA supports unicast, broadcast and multicast traffic, setting it apart from other TDMA schedules which usually are design for one of those alternatives (for the most parts unicast). TRAMA consists of three different sets of constituents which are responsible for different areas of the medium access control: the Neighbour Protocol and the Schedule Exchange Protocol (in charge of organizing the exchange of two-hop neighbour information and schedules), and AEA, the Adaptive Election Algorithm, which uses this information to schedule transmissions for the next time slot, making it possible for idle nodes to enter their low-power mode. Extensive simulation results prove an increase in throughput for TRAMA compared to well-known contention-based protocols, mostly based on the effective collision avoidance mechanism. However, the authors point out that the poor delay behaviour makes this protocol unfeasible for sensor networks that are delay sensitive.

There are numerous other MAC protocols, concentrating on different problems.

- TRACE (Time Reservation using Adaptive Control for Energy efficiency) [18] is explicitly developed for real-time data broadcasting.
- [19] present a MAC protocol with a contention-free periodic message scheduler which emphasize on optimal scaling behaviour.
- EMACS is introduced shortly in [20] as a distributed and self-organizing TDMA scheme which is easy to integrate with higher layer protocols.
- The GANNS protocol [21] is based on a cluster topology, where dedicated cluster heads form the sensor net backbone. TDMA is only used for the traffic amongst cluster heads, while the sensor nodes communicate with the head of their cluster by means of a contention-based scheme.
- BMA (Bit-Map-Assisted) MAC [22] is intended for event-driven applications in large-scale cluster-based wireless sensor networks, offering another option for intra-cluster communication.
- BTODS/ODS, short for Busy-Tone On-Demand Scheduling and On-Demand Scheduling respectively, is presented in [23] and is targeted at sensor networks which use dedicated “sink” nodes where data from a large number of ordinary sensor nodes is aggregated. Their goal is to schedule additional transmissions to these sinks without disrupting the existing data flows between the remaining nodes.
- TDMA-W [24] (TDMA-Wakeup) uses a special “wake-up” slot in order to minimize the idle listening time of a node. By introducing this dedicated time slot, nodes only have to be awake during their allocated slots for transmission and reception, and the wake-up slot where they get information if and when they can expect transmissions from any other nodes.
IV. OPEN RESEARCH QUESTIONS

Although a number of research papers have been published on the particular area of scheduling-based MAC protocols for wireless sensor networks using TDMA, there are still a lot of unanswered questions and open research issues. Most of the suggested solutions only work in networks with exactly defined properties, which makes their application areas very small. Especially mobility and topology factors still need more intensive research. [7]

[6] identifies a number of areas where research has to be concentrated more on the special requirements of wireless sensor networks due to their differences from other wireless networks regarding e.g. infrastructure (both for communication and computation), physical characteristics (like small processing power, limited power resources and vast geographic dissemination) and unusual application areas, as e.g. the detection of substances and the tracking of vehicles.

A. Demand for real-time behaviour

The real-time demand for the possibility of service differentiation, so that a certain Quality of Service (QoS) can be guaranteed, is born from the fact that the actual applications are time-sensitive and need the sensor information to be processed in a timely manor. In that case, also the network, transport and application layer need to support real-time behaviour.

B. Decentralisation

As it is not possible to have one central node in a typical wireless sensor network (due to the vulnerability of every node and the sheer size of the network), all algorithms involved in the medium access control (e.g. to help scheduling) have to be decentralised.

C. Efficient power usage

The scarceness of power in these kinds of networks has been emphasised several times already in this paper. For the MAC protocol that means several of the scheduling of medium access should try to preclude events that are high in power consumption, like e.g. collisions (which result in resending of packets) or unnecessary listening to the medium. But also, these power issues result in an ever-changing topology where sensor nodes can disappear from the net due to them running out of power or being put into OFF-mode to save the remaining power. A MAC protocol must be able to cope with these topology changes.

D. Flexibility

Flexibility in this context means the ability of being able to adapt to different characteristics in the sensor network, e.g. concerning the traffic properties.

E. Consideration of multiple metrics

A balance among multiple metrics should be strived for to optimise the performance of the network not only regarding one aspect, but taking into consideration all the properties and demands of the sensor network, i.e. not accepting the improvement of one metric by degrading another. (Optimal power management might not compensate for low security levels or poor performance.)

V. CONCLUSION

This paper gives a short overview of the research in the field of time division multiple access based medium access control protocols for the special field of wireless sensor networks. There are both advantages and disadvantages that come along with the choice of a time multiplexed scheduling. While the protocol divides the shared medium evenly in a fair way and the scheduling algorithm attached to the protocol avoids (most) packet collisions and thereby power consuming retransmitting of packets, most of the current TDMA based MAC protocol suggestions are nevertheless still impractical for usage in real world wireless sensor networks. The lack of distributed scheduling algorithms results in the frequent requirement of global information in all nodes about all the other nodes, a demand simple unrealistic to meet in the highly changeable
sensor nets. The focus of future research should be on trying to find the balance between being able to predict delay, guarantee some kind of QoS, minimising communication overhead and lastly, optimise power usage; a combination of requirements characteristic for wireless sensor networks.

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