ON SUPPORTING REAL-TIME COMMUNICATION OVER THE IEEE 802.15.4 PROTOCOL

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Keywords: Real-time communication, wireless network, QoS.

Abstract: IEEE 802.15.4 is a new enabling technology for low data rate wireless personal networks. This standard was not specifically designed for wireless sensor networks, but it has shown to be a good match with necessary requirements on low data rate, low power consumption and low cost. Unlike the former 802.11 standard, the MAC protocol specified in IEEE 802.15.4 can operate in two different modes: beacon-enabled mode or non-beacon enable mode. In beacon-enabled mode, nodes can exclusively allocate a number of guaranteed time slots, similar to a resource reservation scheme. Hence, the IEEE 802.15.4 MAC protocol have sufficient capabilities for supporting real-time communication. This paper presents the key features of IEEE 802.15.4 which makes it an attractive standard to use for real-time wireless sensor networks. Two real-time protocols extending the IEEE 802.15.4 standard are reviewed. The purpose of this paper is to present the state of the art on real-time support over IEEE 802.15.4 for wireless sensor networks and to discuss the possibilities on improvements on both the standard and the real-time protocols extending the standard.

1 INTRODUCTION

Supporting real-time (RT) communication over Wireless Sensor Networks (WSNs) has attained an increasing interest from both industry and academia. During the recent decade, advances in WSN enabling technology has opened up for many proposals of new innovative applications. However, many of the proposed applications require support for RT communication; guarantees for data being delivered from a source node to a destination node within its given *end-to-end deadline*. For example, a surveillance system needs to alert the detection of an intruder within seconds for the authorities to be able to initiate pursuing actions in time (He et al., 2006). Depending on the specific application, different kinds of data have different deadline requirements due to its validity interval. Data registering the movement of a tank in a military surveillance system have shorter update intervals than data registering transport pallets being moved in and out from a goods storage. Similarly, the location registration of an intruder have a shorter validity interval than the temperature measurement in automatic room temperature control system (Lu et al., 2002). Thus, there is a need for WSNs to support time-sensitive communication by guaranteeing packets end-to-end deadlines or minimizing the deadline miss ratio, i.e., the number of packets that meet their end-to-end deadline.

Supporting RT communication in WSNs is a great challenge due to many reasons (Stankovic et al., 2003). The communication in WSN per se is less reliable and less predictable than in wired networks because of its wireless nature. Moreover, a WSN in general consists of an arbitrarily number of nodes equipped with highly limited resources; at the one hand batteries need to be small and at the other hand they need to be operable during a long time. Therefore a major factor that must be considered in the development of a communication protocol for WSNs is power-efficiency. Most of the earlier reported work on RT communication protocols for WSNs have to a large an extent been focused on the trade-off between energy efficiency and end-to-end delay guarantees (He et al., 2003; Chipara et al., 2006). Still it remains as one of the most important issues for research community. Other characteristics that complicates RT support is network topology. In many proposed applications, the topology is required to be highly dynamic: nodes can relocate, join or leave the network. Besides making routing more complicated, the workloads in such dynamic topologies become highly unpredictable. Clearly, there is a need for new scheduling methods which can adapt efficiently to such dy-

Hoang H. and Bengtsson J. (2008).
ON SUPPORTING REAL-TIME COMMUNICATION OVER THE IEEE 802.15.4 PROTOCOL.
In *Proceedings of the International Conference on Wireless Information Networks and Systems*, pages 82-87
DOI: 10.5220/0002023800820087

namic environments. A more detailed view of RT challenges in WSNs can found in (Stankovic et al., 2003; Li et al., 2007).

In December 2003, IEEE introduced the IEEE 802.15.4 standard (IEEE, 2003) - covering the Medium Access Control (MAC) layer and the physical layer - for Low-Rate Wireless Personal Area Networks (LR-WPAN). The IEEE 802.15.4 protocol is particularly suitable for WSNs because it is mainly specified for: low data rates, providing reliable data transfer, low cost and low power consumption. Especially interesting for RT applications is that the IEEE 802.15.4 MAC protocol has the capability of providing Guaranteed Time Slots (GTS) for time-sensitive data, similar to traditional TDMA allocation. The IEEE 802.15.4 protocol has been widely adopted as one of the more interesting candidates for developing RT communication protocols for WSNs. The GTS transmission scheme allows each node in the network to send data, using a certain number of time slots according to the first-come-first-served (FCFS) algorithm. However, due to its simplicity, only static schedules can be implemented using FCFS based scheduling. This problem has motivated a number of researchers to work on more efficient RT scheduling methods, enabling dynamic allocation of time slots.

This paper presents the most relevant characteristics of the IEEE 802.15.4 - the de facto standard for time-sensitive WSN applications - for RT scheduling methods. Two of the more interesting RT scheduling methods developed for this standard are reviewed (Koubaa et al., 2006b; Mishra et al., 2007). The rest of the paper is organized as follows: section 2 introduces to real-time concepts and the main requirements for developing a RT communication protocol. Section 3 provides a brief description of the IEEE 802.15.4 standard. In section 4, we discuss two related allocation methods: one method based on fix-priority scheduling and one based on dynamic-priority scheduling. Finally, we make a concluding remark of our review findings and discuss possibilities for future work in section 5.

2 REAL-TIME COMMUNICATION

The characteristics of RT communication differ from the characteristics of traditional best-effort communication. For example, in best-effort communication, the performance measurement of a communication protocol is the network throughput. In RT communication the performance of the protocol is measured by the number of messages successfully delivered before their deadlines. RT communication is usually divided into two main categories: hard RT and soft RT. In soft RT communication, some amount of packet loss can be tolerated, while in hard RT communication there is no toleration for any packet loss. In hard RT communication, all messages have strict timing constraints. For example, if any packet is delivered late, it is considered as being lost. In hard RT communication, an upper bound on end-to-end message delays or a *deterministic* bound is required. In contrast, for supporting soft RT communication over the network, a probabilistic end-to-end delay bound should be provided.

For WSNs, it is more realistic to offer a probabilistic end-to-end guarantees, due to facts that: the network conditions varies with time, the traffic is unpredictable and constraints on power-efficiency requires i.e., limited transmit power. A common approach taken for supporting end-to-end guarantees in multi-hop networks in general, and in WSNs specifically, is that the MAC protocol should provide a delay bound for a single-hop, and the network layer should take the responsibility for multi-hop delay bounds. Scheduling methods are commonly used in the MAC protocol (scheduled-based MAC protocols). Finding efficient scheduling algorithms for the MAC protocol is one of the most important issues for RT communication in WSN.

3 IEEE 802.15.4

The IEEE 802.15.4 protocol specifies the MAC layer and the physical layer for LR-WPANs. This protocol is often used in conjunction with ZigBee protocol (Zigbee Alliance, 2004) to provide a full protocol stack. This section presents the relevant features of the IEEE 802.15.4 standard related to RT communication over WSNs. Further details of the standard can be found in (IEEE, 2003; Koubaa et al., 2005).

3.1 Network Devices and Topologies

Network Devices. The IEEE 802.15.4 standard specifies two types of network devices that are supported: a Full Function Device (FFD) and a Reduced Function Device (RFD). An RFD is a simple device operating with a minimal implementation of the IEEE 802.1.5.4 protocol. An FFD is a device that has the capability of operating in two modes; either as a coordinator, providing a synchronization service through the transmission of beacons, or, as a simple device but implementing the complete protocol set. An FFD can act as both a simple coordinator and a PAN-coordinator. A Coordinator is a network device that provides synchronization services through the transmission of beacon frames. If a coordinator has the function of identifying and controlling the network, it is called the PAN coordinator. A network should include at least one FFD performing as PAN-coordinator.

Network Topologies. The IEEE 802.15.4 protocol supports networks organized in both star-topology peer-to-peer topology. In star topology, communication is established between network devices (FFD and RFD) and the PAN-coordinator. After an FFD is activated the first time, it may establish its own network and become the PAN coordinator acting as the network's controller. A PAN coordinator can allow other devices to join its network. The communication paradigm in star network topology is centralized. In peer-to-peer topology, any network device can communicate with any other devices within its radio range. There is also a PAN coordinator in the peer-to-peer topology. In contrast to the star topology, a device can be nominated as PAN coordinator by another device in the peer-to-peer topology. A network with peer-to-peer topology can be ad hoc, self-organizing, self-healing, and allows multiple hops to route data from any source node to any destination node.

3.2 IEEE 802.15.4 MAC Layer

The MAC protocol specified in IEEE 802.15.4 can operate in two different modes: *beacon-enabled* mode and *non beacon-enabled* mode.

In *beacon-enabled* mode, the coordinator generate beacons periodically in order to synchronize all nodes in the PAN and to identify the PAN. Data exchanged between all nodes and the PAN coordinator has a special format, which is defined by the PAN coordinator, called *superframe* structure. The length of a super frame is equal to the interval between two consecutive beacons, and it is divided into 16 equally sized time slots. Figure 1 illustrates some parameters embedded in a superframe.

A superframe can either include both an active- and an inactive period, or just an active period. During the inactive period, the coordinator do not have any interaction with other nodes and it stays in a low power-mode. The first slot in a superframe is used for the beacon frame.

- **CAP.** The contention access period (CAP) starts immediately after the beacon frame. Transmissions occurring during the CAP period must follow a slotted-CSMA/CA mechanism. Nodes wishing to transmit must compete for the communication medium based on CSMA/CA with some back-off period, aligned with superframe slot boundaries.
- **CFP.** In difference to other IEEE standards for wireless communication, such as the IEEE 802.11, the IEEE 802.15.4 do not only offer the CSMA/CA mechanism for the MAC protocol. The IEEE 802.15.4 MAC protocol may also include a contention free period (CFP) within the superframe. CFP is an optional field, which has been defined for QoS requirements on for example low-latency or a specific transmission bandwidth. A PAN coordinator can allocate a certain number of time slots called Guaranteed Time Slots (GTS), during the CFP upon on request. All transmissions occurring during the CFP do not follow the CSMA/CA mechanism. The PAN coordinator can assign up to 7 GTSs and can only be used for communication between a node and the PAN coordinator.
- **GTS.** A GTS scheme is a kind of resource reservation in WPANS. It is a portion of the superframe, which is allocated exclusively to a given node in the PAN. When a node have data with timing constraints to transmit, it sends a request frame to the PAN coordinator asking for GTSs. The PAN coordinator will do admission control to check whether the request can be accepted or not. The GTSs are allocated following the basic first-come-first-served (FCFS) rule. A node is assigned GTSs if there are resources available, i.e. if the number of requested slots are less than or equal to the number of free slots in the superframe duration. Node with allocated GTSs can access the communication medium without contention during the CFP. A node transmitting during a GTS must guarantee that its transmission end before the next GTS start. There are maximum seven GTSs that can be used at the same time.

In *non beacon-enabled* mode, there are neither beacons nor superframes. Nodes communicate with each other freely according to the unslotted CSMA mechanism. Both the *non beacon-enabled* and the *beacon-enabled* mode use the CSMA/CA with back-off periods, but in the former the back-off period for each node is independent from other nodes back-off periods.

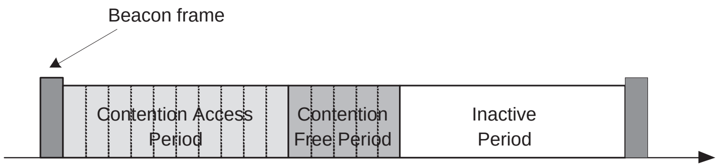

Figure 1: Structure of a supperframe.

4 REAL-TIME PROTOCOLS OVER IEEE 802.15.4

The GTS scheme in *beacon-enabled* mode is more interesting when it comes to supporting RT communication over the IEEE 802.15.4. However, there are still some limitations that might make it less efficient (Koubaa et al., 2006b). Firstly, since the GTS allocation is managed using simple FCFS, there is no priority support. All types of traffic are treated equally. Secondly, it might also happen that a node with low arrival rate will be assigned unnecessary high bandwidth and thereby reducing the network utilization. Moreover, the GTS allocation is made explicitly, which means that the number of nodes that can have access to GTSs is limited to the maximum number of GTSs.

During the last two years, there are few works reported on improving the GTS allocation scheme in order to provide a more efficient way of utilizing GTS to support RT communication. The most common way is to apply some kind of scheduling method, either static scheduling algorithms or dynamic scheduling algorithms. In this section, we review two of the more recent and interesting GTS allocation methods. One method uses static scheduling based on round-robin scheduling algorithm (called i-GAME) (Koubaa et al., 2006b) and the other applies dynamic scheduling based on the earliest deadline first (EDF) scheduling algorithm (Mishra et al., 2007) (called GSA).

4.1 i-GAME

Motivated by having a more efficient GTS allocation in IEEE 802.15.4, A. Koubaa et. al proposed an *implicit* GTS Allocation Mechanism (i-GAME) for time-sensitive wireless sensor networks (Koubaa et al., 2006b), instead of using *explicit* GTS allocation. The i-GAME method allows several nodes in the network to share the same GTS under the round-robin scheduling algorithm. The node that wants to have a guaranteed time slot, sends its traffic specification and its delay requirement to the PAN coordinator. The PAN coordinator will do the admission control to check whether the amount of available GTSs satisfy the communication requirements. The authors in (Koubaa et al., 2006b) have adopted the (b,r) traffic model, in which b denotes the maximum burst size, r denotes the average arrival rate. The network is a star topology network with a unique PAN coordinator. Each node i in the network generates a flow F_i represented by three parameters (b_i, r_i, D_i), where D_i is the delay requirement of flow F_i. It has been addressed in (Koubaa et al., 2006a; Koubaa et al., 2006b) that, N flows F_i, $i = 1, 2, .., N$ are allowed to share a GTS allocation consisting of k slots if

- the sum of all arrival rates is less than or equal to the bandwidth of k time slots: $\sum_{i=1}^{N} r_i \leq k \times R_{TS}$, where R_{TS} is bandwidth guaranteed per time slot
- the delay bound guaranteed by the allocation, $D_{i,max}$, does not exceed the delay requirement: $D_{i,\max} \leq D_i, \forall 1 \leq i \leq N$

The calculation of guaranteed delay bounds per time slot for original explicit GTS allocation and for the implicit method has been presented in (Koubaa et al., 2006a) and (Koubaa et al., 2006b) respectively. Network calculus have been used in both cases. By applying a round-robin scheduling algorithm, i-GAME allows each flow to equally share the bandwidth of k time slots in GTS.

Although the round-robin algorithm provides a fair GTS allocation scheme, it is not effective when different traffic flows have different arrival rates. Thus, it would be even more interesting to find a more flexible allocation scheme that can support different classes of traffic.

4.2 GTS Allocation with On-line Scheduling Algorithm - GSA

A. Mishra et. al (Mishra et al., 2007) recently presented a new GTS allocation scheme in IEEE 802.15.4, with an on-line scheduling algorithm supporting both periodic and aperiodic real-time traffic (named GSA). GSA is applied in the same network configuration as i-GAME, in beacon-enabled mode, but a different traffic model has been used. Each node i in the network generates its traffic flow F_i, which is represented by three parameters: time constraint d_i, total payload p_i and the number of requested slots r_i.

For the GSA method, the authors have presented a formula to calculate the estimated end-to-end delay required for each node to send one frame to the PAN coordinator. Base on this delay estimate, the PAN coordinator will find the minimum GTSs needed to be assigned for each node, in such way that the estimated delay must be less than or equal to the its requested delay. All the traffic flows in the network will be sorted according to the order of increasing deadlines (EDF scheduling). A set of traffic flows is schedulable with the GSA method, if for each flow, the cumulative transmission delay is less than or equal to its upper bound. The GSA can be described as follows:

1. Input: $S = F_i(d_i, p_i, r_i)$
2. Calculate estimated delay ED_i
3. Assign minimum number of GTSs s_i for each flow F_i
4. Do a feasibility analysis of the set S
5. If not feasible the last flow will be rejected

The biggest advantages of GSA is that it applies an on-line scheduling algorithm, providing a better support for different traffic classes. However, GSA is composed of a complicated analysis which cause overhead for the PAN coordinator. It is obvious that the analysis used in GSA could be improved. One of the very well known techniques used for EDF feasibility analysis - that have been widely adopted in the research community, *processor demand test* (Baruah et al., 1990), could be applied in GSA. The authors in (Mishra et al., 2007) also showed the improvement of GSA in comparison with basic FCFS scheduling. However, the complexity of the algorithm has been overlooked. Another drawback of GSA is that it may waste a portion of the GTSs since it always allocates the GTSs from the first slot of the CFP.

5 CONCLUDING REMARKS

In this paper, we have presented the most relevant characteristics of the IEEE 802.15.4 standard for supporting RT communication in WSNs. We have chosen to review two of the more interesting RT protocols that have been proposed for IEEE 802.15.4: one protocol applying a static scheduling method (i-GAME) and the other applying a dynamic scheduling method (GSA). The i-GAME protocol has low complexity, is easy to implement and introduces fairly small overhead for the PAN coordinator. Moreover, iGAME provides a fair allocation for all nodes in the network, which is very efficient in the specific case where all traffic flows have a similar arrive rate. On the other hand, the GSA protocol has significant advantages compared to iGAME since scheduling is dynamic and performed on-line. Thus, a broader range of traffic classes are supported, such as for applications requiring communication with unbalanced arrival rates. The trade-off in the GSA compared to iGAME, is the higher complexity of the scheduling algorithm and a higher overhead for the PAN coordinator. It should also be mentioned that iGAME has been implemented in a real sensor network while GSA has been evaluated by a simulation study.

As future work, we aim to investigate improved scheduling methods to be applied for the IEEE 802.15.4. We are in favor of dynamic scheduling methods, such as in the GSA, and we believe that scheduling complexity can be reduced, for example by applying a more simple feasibility analysis such as the processor demand function. We are also interested in investigating some specific application such as voice or media over WSNs, where QoS is highly important.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Anis Koubaa and Dr. Elisabeth Uhlemann for valuable input to this paper. This work has been funded by the CERES research profile grant from The Knowledge Foundation.

REFERENCES

T. He, P. A. Vicaire, T. Yan, L. Gu, G. Zhou, R. Stoleru, Q. Cao, J. A. Stankovic, and T. Abdelzaher "Achivieing Real-time Target Tracking Using Wireless Sensor Networks, " *Proc of the 12th IEEE Real-Time and Embedded Technology and Applications Symposium*, 2006.

C. Lu, B. M. Blum, T. F. Abdelzaher, J. A. Stankovic, and T. He. "RAP: A Real-Time Communication Architecture for Large-Scale Wireless Sensor Networks", *Proc. of the 8th IEEE Real-Timeand Embedded Technology and Applications Symposium*, 2002.

J. A. Stankovic, T. Abdelzaher, C. Lu, L. Sha, and J. Hou. "Real-Time Communication and Coordination in Embedded Sensor Networks", *Proc. of the IEEE*, 2003.

T. He, J. A. Stankovic, C. Lu, and T. F. Abdelzaher. "SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks", *Proc. of the International Conference on Distributed Computing Systems*, 2003.

O. Chipara, Z. He, G. Xing, Q. Chen, X. Wang, C. Lu, J. A. Stankovic and T. Abdelzaher. "Real-Time Power-Aware Routing in Sensor Networks", *Proc of the 14th Workshop on QoS*, 2006.

Y. Li, C. Chen and Y-Q. Song, "Real-Time QoS Support in Wireless sensor Networks: A survey," *Proc. of 7th IFAC International Conference on Fieldbuses and Networks in Industrial and Embedded Systems*, 2007.

IEEE 802.15.4 Standard-2003 "Part 15.4: Wireless medium Access Control (MAC) and Physical Layer (PHY) Specification for Low-Rate Wireless Personal Area Networks (LR-WPANs)", IEEE-SA Standards Board, 2003.

Zigbee Alliance, Zigbee Specification, December 2004: www.zigbee.org.

A. Koubaa, M. Alves and E. Tovar. "IEEE 802.15.4 for Wireless Sensor networks: A Technical Overview", IPP-HURRAY Technical Report (TR-050702), 2005.

A. Koubaa, M. Alves, and E. Tovard. "GTS Allocation Analysis in IEEE 802.15.4", *Proc. of the 20th International Parallel and Distributed Processing Symposium*, 2006.

A. Koubaa, M. Alves, and E. Tovard. "i-GAME: An Implicit Allocation mechanism in IEEE 802.15.4 for Time-Sensitive Wireless Sensor Networks", *Proc. of the 18th Euromicro conference on Real-Time Systems*, 2006.

A. Mishra, C. Na, and D. Rosenburgh. "On Scheduling Guaranteed Time Slots for Time Sensitive Transactions in IEEE 802.15.4 Networks", *Proc. of the IEEE Military Communication Conference (MILCOM07)*, 2007.

S. K. Baruah, R. R. Howell, and L. E. Rosier. "Algorithms and Complexity Concerning the Preemptive Scheduling of Periodic Real-Time Tasks on One Processor", *Real-Time Systems*, 1990.