Enabling Guaranteed Beacon and Data Slots in Multi-hop Mesh Sensor Networks for Home Health Monitoring

Juan Lu[1,2], Adrien Van Den Bossche[1,3] , Eric Campo[1,2]
[1]Université de Toulouse; UPS, INSA, INP, ISAE, UTM, F-31703 Blagnac, France
[2]CNRS; LAAS; 7 Avenue du Colonel Roche, F-31077 Toulouse, France
[3]CNRS; IRIT; 118 Route de Narbonne, F-31062 Toulouse, France
{lu, vandenbo, campo}@iut-blagnac.fr

Abstract—**The MAC (Medium Access Control) protocol has an important influence on network performance, especially in home health monitoring which constrains delivery of time-sensitive message and power consumption. In this paper, a multi-hop mesh sensor network is proposed based on a novel MAC protocol ADCF (Adaptive and Distributed Collision-Free). ADCF uses CFBS (Collision-Free Beacon Slot) and CFDS (Collision-Free Data Slot) mechanisms to guarantee QoS (Quality of Service) while reducing energy consumption in a mesh topology. The simulation results show better performances of ADCF compared with IEEE 802.15.4 MAC protocol in terms of energy and guaranteed medium access with the flexibility of mesh topology.**

Keywords-IEEE 802.15.4; mesh topology; QoS; energy saving, health monitoring application

I. INTRODUCTION

Our application scenario is focused on the monitoring of the elderly at home via a WSN (Wireless Sensor Network). ADCF sensor nodes are put on the ceiling, wall, furniture and the body of the person. For example, when the accelerometer detects a fall of the person, an alarm should be sent with some guaranties in terms of delay. In addition, the network should be self-organizing and could tolerate a link failure or a link establishment. Therefore, all ADCF nodes are expected to have the same role (both sensor and router) in a mesh topology.

Several projects have been investigated on the habitat monitoring [1-3]. There are generally two main constraints for this WSN: time-sensitive delivery of some urgent messages and power consumption. Many technologies exist at different layers to improve these two constraints [4]. Our work focuses on MAC layer. As the largest energy consumption of the nodes is due to the time spent in the idle state [5], so time slot allocation is an important task. The avoidance of collisions between 2-hop neighbors is another goal because there is scarcely interference at distance of more than 2 hops [6].

This paper aims to present a novel MAC protocol based on IEEE 802.15.4 to build a scalable and robust WSN for home health monitoring. The paper is organized as follows: section 2 investigates the current MAC protocol for this application. The proposed ADCF MAC is described gradually in section 3. Section 4 provides simulation results while the last section concludes the paper.

II. RELATED WORK

MAC protocols for WSN could be classified into two categories. The first category is based on conventional wireless protocols, especially IEEE 802.11(a/b/g/n/ac). These protocols typically provide a general mechanism that works reasonably well for a large set of traffic load. Therefore, these protocols don't meet our goals and will not be discussed in this paper. IEEE 802.11ah is an on-going work about energy efficient MAC for low traffic sensor network. However, some issues such as frame header compression are still open and there are now no available products for our future work. The second category based on IEEE 802.15.4 is being considered as a promising way for low-cost low-power WSN. In part A, IEEE 802.15.4 standard is briefly presented. Recent works based on this standard have been fully studied in part B.

A. IEEE 802.15.4 Standard

IEEE 802.15.4 [7] protocol supports beacon and non-beacon mode. More precisely, in beacon mode, it is possible to achieve variable duty cycles (from 100% down to 0.006%), which is particularly interesting for our application where energy constraint and network lifetime are main concerns. In addition, beacon mode has an attractive feature for time-sensitive applications as QoS properties are available with GTS (Guaranteed Time Slot) mechanism. On the other side, non-beacon mode, which has the advantage of lower complexity and more scalability as compared with beacon mode, does not provide any of those features.

Therefore, we focus on beacon mode which seems to be a promising way. However, several issues in the standard are still open. One of those issues is how to build a synchronized multi-hop mesh network for power efficient, scalable and robust networking. In fact, while the current standard supports multi-hop networking using peer-to-peer topology, it restricts its use to non-beacon mode. This contradiction makes urgent requirement of novel MAC protocols.

 ISBN: 978-1-61208-203-5

B. MAC Protocols Based on IEEE 802.15.4

ZigBee specifications [8] clear the ambiguities of IEEE 802.15.4 in a cluster-tree topology. The centralized PAN (Personal Area Network) coordinator assigns a beacon transmission offset for each node when it wants to associate the PAN. Therefore, the communication range and the requirements of time-sensitive are both limited.

Anis Koubâa [9-10] continues the work in the domain of cluster-tree topology. However, the requirement of different BI (Beacon Interval) and SD (Superframe Duration) for each node is calculated in advance. These weaken the flexibility and robustness as well as restrict the scalability of network.

Another example has been proposed in OCARI project [11-12]. A PAN coordinator which receives all the association requests decides beacon slot for each node. The main drawback of this solution is the lack of flexibility, especially regarding the changing topology and the inconstancy of wireless medium.

P. S. Muthukumaran presented MeshMAC protocol [13]. This protocol enables mesh networking over beacon mode through a distributed SDS (Superframe Duration Scheduling) strategy in which each node calculates its schedule to transmit beacons based only on locally available information. The limitations of MeshMAC are: it imposes very low duty cycles; the beacon transmission offset is difficult to choose for the changing topology.

B. Carballido Villaverde proposed DBOP MAC protocol [14]. It creates a BOP (Beacon Only Period) where beacons are transmitted at different time slots among neighbors and neighbors' neighbors. However, DBOP introduces an overhead into the network. Another drawback is the inefficient management of BOP length. In addition, how to offer QoS for different application traffic is not discussed.

III. ADCF MAC PROTOCOL

The objective of ADCF is to build a beacon-enabled WSN over an IEEE 802.15.4 PHY which supports mesh topology and enables better energy efficiency. While a previous paper [15] only focused on beacon scheduling and network construction, in this paper we detail the mechanism of Collision-Free Data Slot (CFDS) in the mesh topology. Additionally, corresponding simulation results and the operation of ADCF are first presented.

Before showing the characteristics of ADCF, some assumptions should be highlighted: all the considered nodes have the capacity to be both sensor and router; nodes addresses have been preliminary set.

A. Overview of ADCF

As shown in Fig. 1, the superframe of ADCF is organized in three parts: BOP, active period and inactive period. BOP is organized by CFBS (Collision Free Beacon Slot). Each node has a 2-hop collision-free beacon slot in BOP. Similarly, ADCF nodes can access the medium by slotted CSMA or guaranteed mechanism CFDS (Collision Free Data Slot) in the active period. Inactive period is optional for energy saving.

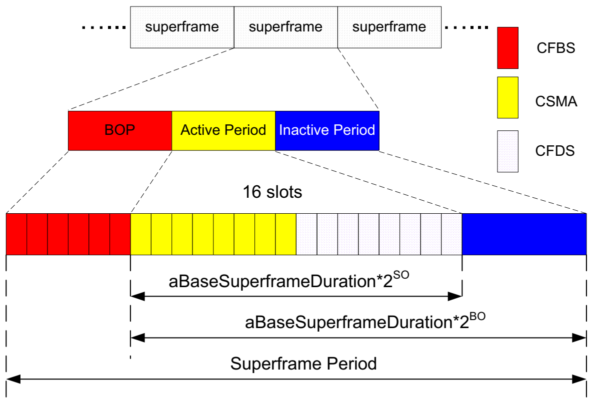

Figure 1. ADCF superframe structure.

The basic parameters are consistent with IEEE 802.15.4:

- Active period is divided into 16 slots.
- $0 \leq$ SO (Superframe Order) $\leq$ BO (Beacon Order) ≤ 14.
- aBaseSuperframeDuration denotes the number of symbols that form a superframe when SO is 0.

B. Operation of ADCF

ADCF includes several slight protocols: BEP (Beacon Exchange Protocol), ISP (Initiator Selection Protocol), BSAP (Beacon Slot Allocation Protocol), DSAP (Data Slot Allocation Protocol) and SRP (Smart Repair Protocol). In addition, SPA (Simple Priority Algorithm) is used repeatedly in ISP and BSAP.

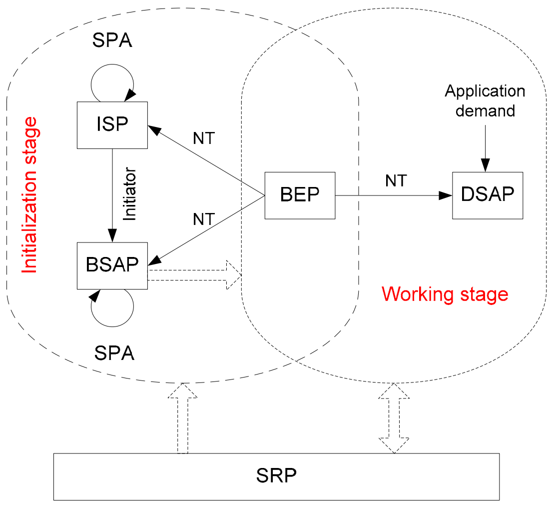

Figure 2. ADCF operation diagram.

Each ADCF node has a NT (Neighbor Table) and executes the following as shown in Fig. 2. SRP allows

ADCF nodes to switch between initialization stage and working stage depending on the changing topology of network. The beginning and core of ADCF is BEP which sets up NT and updates NT in both stages. BEP runs periodically according to the preset parameters such as BO. With the information of NT, ISP is executed. Then BSAP is triggered and so the node could synchronize with the initiator. DSAP will work when there are application requests from the higher layer.

- **BEP**: the main concern for BEP is collection of interesting information in a 2-hop neighborhood. Each new node will firstly listen to the channel for a fixed period when it is powered-up. Depending on the received beacons during listen, the new node will send its own beacon by different mechanisms. Each node broadcasts its beacon within 1-hop and records direct neighbors' in its NT. Therefore, all the 2-hop neighbors' information is obtained by this new node. The interesting information in a beacon includes NA (Neighbor Address), NE (Neighbor Energy) and ND (Neighbor Density). Here, ND is defined as the number of neighbors within 2-hop (including itself). The overhead incurred by BEP is studied and simulated in [15].
- **SPA**: SPA is implemented by comparing 3 parameters of the nodes. The comparison order is ND, NE and NA. At first, the node with maximum ND is selected. If the nodes have the same ND, SPA chooses the one with maximum NE. Finally, the node with minimum address has the highest priority if two other parameters are the same.
- **ISP**: the objective of this protocol is to select an initiator which has two functions: it specifies the beginning of BOP and measures the length of BOP in order to realize the network synchronization. This length is defined as the initiator ND. Each node selects an initiator candidate locally by SPA from its NT. If one initiator candidate is different from the neighbors', SPA is repeatedly used to decide a unique initiator. This initiator's information will be added to NT and be sent in the next beacon. Therefore, there may be several initiator candidates in the initialization stage but a unique initiator in the working stage.
- **BSAP**: this protocol makes each node choose a CFBS in BOP. The nodes execute SPA locally and the one has higher priority first to choose its beacon slot. It takes a slot which is not used by its 2-hop neighbors and stores the slot number in its NT. At last, the node which has its chosen slot will be deleted from SPA list and the other nodes in this list continue BSAP.
- **DSAP**: in the original IEEE 802.15.4, GTSs are requested via a GTS request command sent in Best-effort mode using CSMA/CA. In ADCF, each node can request CFDS using its beacon to all its neighbors without the need to send a dedicated frame. A bi-direction communication is possible. When a node receives neighbor's beacon and finds its address as CFDS destination, it checks it NT, allocates the first available data slot to the requesting node and announces this allocation in the next beacon. When the requesting node receives this beacon containing the slot number, it may use it to send the application traffic in the CFDS. CFDS request and CFDS indication subfields take only 2 bytes in the beacons.
- **SRP**: this protocol reduces the impact of changing topology as much as possible. For example, if link failure is detected, neighbors will simply delete this failure node from their NT. If the initiator fails, others re-select an initiator but keep their BOP with the original beacon slots. Therefore, the network will still work without disruption. As there are free slots in BOP, a new node may choose its beacon slot directly after a period of listening. If BOP length is not enough, a new node may send its beacon by CSMA until a new initiator is designed with updated ND.

In conclusion, seldom MAC protocols for low-cost low-power network are in a mesh topology which has the advantages of scalability and robustness. ADCF aims to enable the efficient mechanisms and eliminate the difficulties, such as beacon collision, QoS and synchronization in a changing multi-hop mesh-link network.

IV. SIMULATION STUDY

To study the scope of our contribution, we use OPNET to establish a simulation model which implements the entire proposal. Two experiment examples are presented in this paper. The first one is the comparison of ADCF with IEEE 802.15.4. The second experiment is the ADCF performance with large scale and high neighbor density. The basic parameters are shown in the Table 1. We are now implementing ADCF on 13192-SARD board which has a total of 4Kb RAM for application data, variables, buffers etc. Therefore, the buffer for CSMA and CFDS could not be more than 2Kb in reality. This parameter configuration is useful for comparing the simulation results with prototype.

TABLE I. TABLE TYPE STYLES

Parameter	Value
Scene area	100*100 m^2
Transmission range	15 m
BO	7
SO	4
Traffic distribution	Constant
Application payload	100 bits
CSMA buffer	0.5 k octets
CFDS buffer	1.5 k octets
Simulation duration	30 min
Simulation times	20

A. Comparison of ADCF with IEEE 802.15.4

To our knowledge, there are two versions of IEEE 802.15.4 in OPNET. The version developed by Anis Koubâa [9-10] includes the GTS implementation and a fixed beacon scheduling mechanism. It is used in this experiment. 14 nodes join the network gradually in this experiment. A static routing mechanism is added above ADCF in order to simulate real traffics over the network. IEEE 802.15.4 applies ZigBee routing.

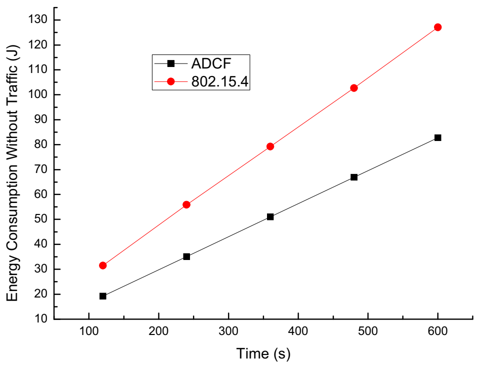

Figure 3. Energy consumption comparison.

In the energy consumption comparison, only beacons are delivered in order to compare the protocol cost. In addition, a more practical energy model [16] is used in our experiment. As shown in Fig. 3, ADCF consumes less energy, about 37%, than IEEE 802.15.4 as time goes by. This is because IEEE 802.15.4 nodes spend more time for idle listening.

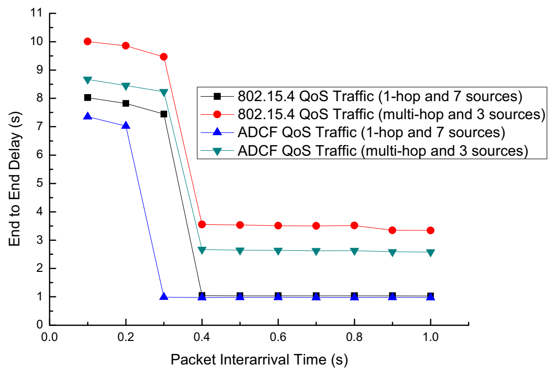

Figure 4. Delay comparison.

As shown in Fig. 4, there are 7 sources with 1-hop traffic or 3 sources with multi-hop traffic. When Packet Interarrival Time decreases from 1.0 to 0.1, the traffic load will increase. Therefore, End to End Delay becomes larger. When Packet Interarrival Time is about 0.4 s, there are radical changes caused by buffer overflow.

As the configured BO and SO, a superframe cycle is about 2 s. For 1-hop traffic, the difference between ADCF and IEEE 802.15.4 is tiny. This End to End Delay, about 1 s, includes the time from packet generation to the scheduled data slot. It also can be seen that ADCF saves about 25% End to End Delay for multi-hop traffic. Some multi-hop traffic may be transmitted in one superframe as the same active period in a mesh topology. IEEE 802.15.4 works in a cluster-tree topology which may take several superframes from the source to the final destination. The average hop count is 3, so this End to End Delay is about 2.7 s for ADCF and 3.5 s for IEEE 802.15.4.

The Packet Success Ratios always keep 100% for both protocols when the CFDS buffers are available.

B. ADCF Performance in Large Scale and High Density

In this experiment, we focus on Packet Success Ratio of ADCF in large scale and high density in order to study the protocol performance in a variety of scenarios.

Firstly 14, 30 and 50 nodes are configured in the network. Then the 50 nodes with different neighbor density are simulated. For all the scenarios, there are 7 sources with QoS traffic and 7 sources with best-effort traffic at the same time. All traffics are generated for a 1-hop destination.

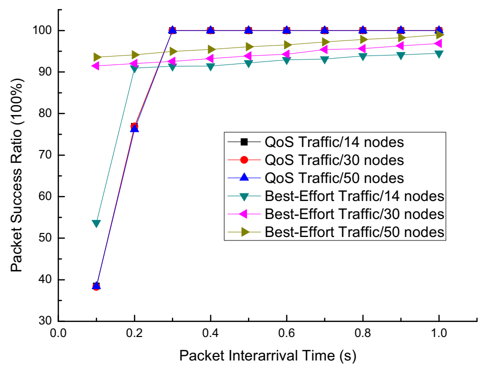

Figure 5. Packet success ratio for different scale.

As shown in Fig. 5, it can be seen that Packet Success Ratios always keep 100% for QoS traffic when the CFDS buffers are available. Packet Success Ratios become higher with the larger network scale for Best-Effort traffic. This is because of the risks of collisions are lower. When Packet Interarrival Time is 0.1, this traffic load is relatively light for the network of 30 and 50 nodes. However, the contention for Best-Effort traffic is intense in the network of 14 nodes.

Neighbor densities are average values obtained by simulations. As shown in Fig. 6, network density also has no much influence on QoS traffic. While for Best-Effort traffic, Packet Success Ratio is higher with the lower density as there is less collisions. When neighbor density is 8.76, the risk of collision is low. Therefore, the difference between 8.76 and 5.13 is tiny. When neighbor density is 15.24, there are a lot of nodes in the communication range of neighbors. Thus its Packet Success Ratio is the lowest of these 3 scenarios.

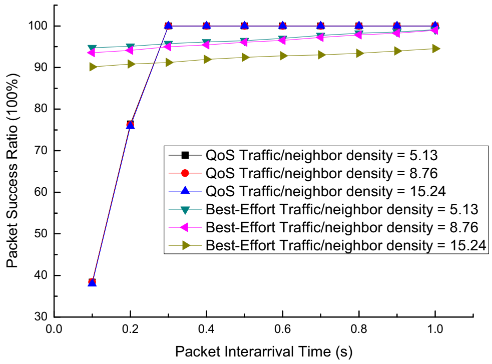

Figure 6. Packet success ratio for different density.

V. CONCLUSION AND PERSPECTIVES

This paper presents an original MAC protocol named as ADCF, which is based on IEEE 802.15.4 standard to build a mesh WSN. The 2-hop CFBS and CFDS mechanisms were described and implemented by a set of protocols which are explained. The simulation results show that ADCF consumes less energy (about 37%) while End to End Delay and Packet Success Ratio perform no much worse than IEEE 802.15.4. The simulation results also confirm that ADCF works well in the condition of large scale and high density. Therefore, ADCF satisfies the application request of delivering QoS message with low energy consumption. In addition, when a new node joins the network or a key node fails in the process of surveillance, the own functioning of other nodes is quite important for home health monitoring. Fortunately, the mesh topology of ADCF strengthens network flexibility to the changing link states. A perspective is the re-exploitation of the information gathered by ADCF in order to make them available for upper layers, such as routing layer, to reduce upper protocol overhead.

Now, the current work is focused on ADCF hardware implementation. The next step is its deployment in real conditions in “Smart Home” of Blagnac University Technological Institute.

ACKNOWLEDGMENT

This work is partly supported by the Academic OPNET Research and Educational Projects. Authors promptly acknowledge the support.

REFERENCES

[1] S. Nourizadeh, C. Deroussent, Y. Q. Song, J. P. Thomesse, “Medical and Home Automation Sensor Networks for Senior Citizens Telehomecare”, IEEE International Conference on Communications (ICC Workshops 09), Jun. 2009, pp. 1-5.

[2] Hongwei Huo, Youzhi Xu, Hairong Yan, Saad Mubeen, Hongke Zhang, “An Elderly Health Care System Using Wireless Sensor Networks at Home”, Third International Conference on Sensor Technologies and Applications (SENSORCOMM 09), Jun. 2009, pp. 158-163.

[3] Y. Zatout, E. Campo, J. P. Llibre, “WSN-HM: Energy-Efficient Wireless Sensor Network for Home Monitoring”, Fifth International Conference on Intelligent Sensors Sensor Network and Information Processing (ISSNIP 09), Dec. 2009, pp. 367-372.

[4] A. H. Salem, A. Kumar, A. S. Elmaghraby, “A Survey for QoS and Power Management Algorithms in Wireless Transmission”, IEEE International Symposium on Signal Processing and Information Technology (ISSPIT 06), Aug. 2006, pp. 720-727.

[5] S. Mahfoudh, P. Minet, “Maximization of Energy Efficiency in Wireless Ad hoc and Sensor Networks with SERENA”, Mobile Information Systems, Advances in Wireless Networks, Volume 5 Issue 1, Apr. 2009, pp. 33-52.

[6] A. van den Bossche, T. Val, E. Campo, “Prototyping and performance analysis of a QoS MAC layer for industrial wireless network”, 7th International Conference on Fieldbuses and nETworks in industrial and embedded systems (IFAC 07), Nov. 2007, Volume 7 Part 1.

[7] IEEE 802.15.4 Standard (2006) Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE Standard for Information Technology, IEEE-SA Standards Board.

[8] ZigBee-Alliance,http://www.zinbee.org.

[9] Anis Koubaa, André Cunha, Mário Alves, “A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks”, 19th Euromicro Conference on Real-Time Systems (ECRTS 07), Jul. 2007, pp. 125-135.

[10] A. Koubâa, M. Alves, M. Attia, A. Van Nieuwenhuyse, “Collision-Free Beacon Scheduling Mechanisms for IEEE 802.15.4/Zigbee Cluster-Tree Wireless Sensor Networks”, 7th International Workshop on Applications and Services in Wireless Networks (ASWN 07), May 2007.

[11] T. Dang, C. Devic, E. Livolant, A. Van Den Bossche, T. Val, “OCARI: Optimization of Communication for Ad Hoc Reliable Industrial Networks”, 6th IEEE International Conference on Industrial Informatics (INDIN 08), Jul. 2008, pp. 688-693.

[12] K. Alagha, G. Chalhoub, A. Guitton, E. Livolant, S. Mahfoudh, P. Minet, M. Misson, J. Rahme, T. Val, A. van den Bossche, “Cross-Layering in an Industrial Wireless Sensor Network: Case Study of OCARI”, Journal of Networks, Vol.4 issue 6, Aug. 2009, pp. 411-420.

[13] P. S. Muthukumaran, R. de Paz, R. Špinar, and D. Pesch, “MeshMAC: Enabling Mesh Networking over IEEE802.15.4 through Distributed Beacon Scheduling”, AD HOC Networks, Vol. 28 Part 1, Jan. 2010. pp. 561–575.

[14] B. Carballido Villaverde, R. De Paz Alberola, S. Rea, D. Pesch, “Experimental Evaluation of Beacon Scheduling Mechanisms for Multihop IEEE 802.15.4 Wireless Sensor Networks”, 4th Conference on Sensor Technologies and Applications (SENSORCOMM 10), Jul. 2010, pp. 226-231.

[15] J. Lu, A. van den Bossche, E. Campo, “An Adaptive and Distributed Collision-Free MAC Protocol for Wireless Personal Area Networks”, 6th International Symposium on Intelligent Systems Techniques for Ad hoc and Wireless Sensor Networks (IST-AWSN 11), Sep. 2011, pp. 798-803.

[16] N. Fourty, A. van den Bossche, T. Val, “Etude de l'impact énergétique de l'algorithme d'accès au médium pour un réseau de capteurs sans fil industriel”, Sixième Conférence Internationale Francophone d’Automatique (CIFA 10), Jun. 2010.