Guaranteeing Reliable Communications in Mesh Beacon-Enabled IEEE802.15.4 WSN for Industrial Monitoring Applications

Berta Carballido Villaverde, Susan Rea, and Dirk Pesch

Nimbus Centre for Embedded Systems Research
Cork Institute of Technology
Rossa Avenue, Cork, Ireland
{berta.carballido,susan.rea,dirk.pesch}@cit.ie

Abstract. Wireless Sensor Networks (WSN) are a very promising solution for industrial monitoring applications in terms of safety, costs, efficiency and productivity. However, in order to move from the adopted manual/wired designs to wireless designs, certain guarantees must be assured, especially in terms of reliability, bandwidth and message transmission delays. Although quality of service (QoS) requirements can be satisfied in star based topologies using the Guaranteed Time Slots (GTS) feature of the IEEE802.15.4 standard, GTS communications in multihop scenarios are currently limited by IEEE802.15.4 beacon scheduling designs and peer-to-peer GTS allocation methods. This restricts applications to run over sensors that are within radio range of the network coordinator. In this work, we propose a distributed IEEE802.15.4 MAC modification to improve GTS usability and scalability in mesh networks. Also, we propose a reactive multihop GTS allocation technique based on our MAC modification to ensure reliable and latency aware end-to-end communications. Results show that our techniques improve greatly the reliability of multihop GTS communications.

Keywords: Wireless Sensor Networks, IEEE 802.15.4, Mesh, GTS, Beacon Scheduling.

1 Introduction

Condition monitoring is recognized to benefit engineers by providing an evaluation of current equipment health, enabling optimized maintenance schedules to be made, and ensuring plant uptime [1]. This can be very critical because shutting down a factory to repair defective equipment can be very costly, in addition to the possibility of losing some of the manufactured product in the process. In this context, the benefits of using a wireless sensor network can be numerous in terms of safety, cost, efficiency and productivity. Wireless sensor networks are gaining in popularity for industrial monitoring applications due to their relatively low cost and simplicity for retrofitting into existing infrastructure. They are particularly suited to this type of applications as they do not require cabling, which will lead to shorter outages during installation and a lower capital outlay than their wired equivalent. However, some of the desired

J. Zheng, D. Simplot-Ryl, V.C.M. Leung (Eds.): ADHOCNETS 2010, LNICST 49, pp. 359–370, 2010.

measurements for industrial monitoring applications, such as vibration and acceleration, may generate tens of kilobits of data with bandwidth, reliability and soft latency requirements (of a couple of seconds) for long sampling periods. In order to satisfy these demands and to fully exploit the benefits of a WSN, a QoS aware multihop solution must be developed.

The most used WSN communication protocol to date is the IEEE 802.15.4 [2] protocol stack as it has been designed specifically for low power, low cost wireless communications. Its specification defines the physical (PHY) and medium access control (MAC) layers. The IEEE 802.15.4 MAC protocol supports two operational modes: the beaconless mode, in which nodes stay active all the time, and the beacon mode, in which beacon frames are periodically sent by coordinators to synchronize sensor nodes. The advantage of this synchronization scheme is that all nodes can wake up and sleep at the same time allowing very low duty cycles and hence save energy. In addition, when the beacon mode is used, nodes can use Guaranteed Time Slots specifically designed to fulfill application's QoS requirements.

In order to use the beacon mode for multihop networks, beacon scheduling mechanisms have to be utilized to avoid direct and indirect collisions of the beacon frames. Most designs for beacon scheduling, if not all, are based on two main techniques initially proposed by the Task Group (TG) 15.4b [3]: Superframe Duration Scheduling (SDS) and Beacon Only Period (BOP). These designs, like in star based networks, allow the use of CSMA/CA transmissions and GTS transmissions. CSMA/CA based media access is not a reliable communications mechanism due to the likelihood of packet collisions and the inability to reliably estimate and guarantee communication delays. This leaves the GTS feature as the best option for reliable communications where each guaranteed time slot is allocated by the coordinator for the sole use of a single node.

Although GTS communications are possible with the beacon scheduling designs alluded to above, both schemes present problems in terms of bandwidth usability, delay and scalability when the GTSs are used (see section 3.1.). Also, if the standard way of allocating GTSs is used (peer-to-peer) a complete GTS allocation from source to destination of the information cannot be guaranteed.

To overcome these problems, in this paper we propose two solutions: First, to solve the scalability problems of the current beacon scheduling techniques when using GTS communications, we propose a IEEE802.15.4 MAC modification based on the BOP beacon scheduling technique. Second, we propose a multihop GTS allocation technique to ensure reliable and latency-aware mesh communications. Our technique will reactively search for a reliable end-to-end GTS route that fulfils the specific application requirements using MAC and Routing layer information. Results show that our techniques improve greatly the reliability of multihop GTS communications.

The rest of this paper is organised as follows. In Section 2, the IEEE 802.15.4 MAC is described. In section 3, the challenges presented when trying to use GTS communications in multihop networks and the solutions adopted to overcome those problems are presented. Section 4 describes the simulation scenarios and results that accentuate the distinct advantages of the proposed approaches when compared with other schemes. Finally, conclusions are drawn and future work is described in Section 5.

2 IEEE 802.15.4 MAC

The IEEE 802.15.4 standard describes the physical layer and the MAC sub-layer for Low-Rate Wireless Personal Area Networks (LR-WPANs). The MAC sub-layer has two operational modes: beacon-enabled and non beacon-enabled. Medium access can be contention based (slotted or unslotted CSMA/CA) or contention free based (only when the beacon-enabled mode is active).

When the beacon-enabled mode is active, the Personal Area Network Coordinator (PANC) sends beacon frames at the start of every Beacon Interval (BI). The beacon frames are used to identify the PAN, to allow the synchronisation of associated devices and to inform the nodes of the superframe structure -consisting of an active period and, optionally, an inactive period. The active period of the Superframe Duration (SD) is divided into 16 equally sized time slots, during which data transmission is allowed. Each active period of the SD can be further divided into a Contention Access Period (CAP) and an optional Contention Free Period (CFP) – composed of GTSs. Slotted CSMA/CA is used during the CAP.

The superframe structure is characterized by two parameters, the Superframe Order (SO) and the Beacon Order (BO), which establish the active period (Superframe Duration -SD) and the length of the superframe (Beacon Interval -BI) respectively. When establishing the values of both parameters, the following relationship must be satisfied: $0 \leq SO \leq BO \leq 14$. BI and SD are defined as follows:

$$BI = aBaseSuperframeDuration \times 2\hat{}BO \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2\hat{}SO \quad (2)$$

The aBaseSuperframeDuration constant represents the minimum length of the superframe when *BO* is equal to 0.

The PANC allocates the GTSs. When receiving a GTS allocation request, the PANC verifies whether there are sufficient resources and, if possible, allocates the requested GTS on a first come first served basis. The PANC can allocate up to 7 GTSs in each superframe and each allocation can be composed of one or more time slots. When allocating GTSs, the PANC must reserve a minimum length for the CAP. Any device with an allocated GTS can also transmit during the CAP.

3 GTS Use in Beacon-Enabled IEEE802.15.4 Multihop Networks

This section describes the challenges associated to using GTS communications in mesh networks and the solutions proposed to overcome the described problems.

3.1 Problem Specification

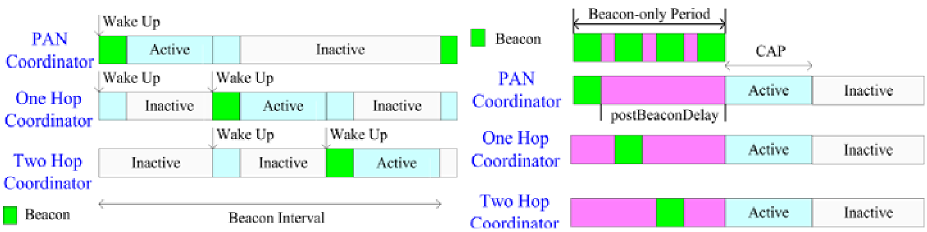
As stated before, the Task Group (TG) 15.4b, a group formed to enhance the 2003 version of the IEEE 802.15.4 standard, proposed two beacon scheduling techniques to avoid beacon collisions in the beacon mode and hence facilitate multihop beacon-enabled communications in IEEE 802.15.4 WSN. In the first approach, namely superframe duration scheduling (SDS) each coordinator transmits its superframe during the inactive period of its neighbours and its neighbours' neighbours to avoid direct and indirect beacon collisions (Fig. 1 a)). In the second approach, a beacon-only-period (BOP) is created at the start of the superframe where every coordinator selects a free time-slot to transmit its own beacon and thus avoid collisions (Fig. 1 b)). However, the two beacon scheduling approaches considered by the TG4b were not included in the revision of the standard in 2006 [4]. While research has continued in this field, it is unclear if these mechanisms will be included in future releases of the standard, i.e 802.14.4e, as some beacon scheduling proposals have appeared within the group [5].

Inline with this, several researchers have employed SDS as the beacon scheduling mechanism to enable multihop topologies over the beacon-enabled mode [6][7][8]. Each and every one of these techniques allows the full use of the GTS slots without any modification and due to the way the scheduling is performed, reliability is assured since direct and indirect collisions among transmitting nodes in the CFP are eliminated. However, the scheduling design has a drawback: the delay introduced in each hop makes it unsuitable and not scalable for delay bounded communications since, on average, a node would have to wait BI/2 sec. to transmit to a neighbor of the mesh network (Fig. 2 a)).

On the other hand, research has been conducted studying the BOP approach to enable mesh networking [9][10][11]. The problem with BOP based approaches and the use of the GTS lies in the fact that since nodes share the same superframe duration, once a node occupies a GTS, its neighbors and neighbors' neighbors can not reuse it to avoid collisions. Additionally, in order to make neighbours aware of blocked GTS, all GTS command transactions have to be broadcasted which makes the command frames vulnerable to the hidden terminal problem. Although this approach is more efficient in terms of delay than the SDS approach, the blocking and collision problems make it impractical and not scalable (Fig. 2 b)).

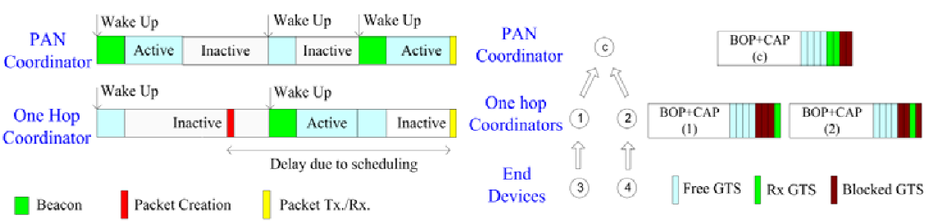
Therefore, given the fact that the available beacon scheduling techniques are unsuitable for performing mesh GTS communications with reliability and latency demands, a different approach must be taken for this part of the superframe. In this work, we propose a modification of the CFP of the BOP approach so reliable and scalable GTS communications can be performed in mesh beacon-enabled IEEE 802.15.4 WSN.

However, even if the GTS usage problem is solved, there still exists one unanswered issue: how to allocate the necessary GTS resources along a route from source to destination in the mesh network while fulfilling all the application requirements. Current trends in allocating GTSs in multihop networks are based on peer-to-peer allocation mechanisms such as proposed by TG4e [12], as proposed in the IEEE802.15.5 standard [13] or as per the proposal in [14]. However, due to the fact that the number of slots is limited, a multihop peer-to-peer allocation can be unsuccessful if a node in the multihop path has all GTSs slots in use, which may likely happen near sinks or clusterhead nodes. In addition, end-to-end delay from source to destination cannot be estimated until all peer-to-peer connections have been established and hence it is not possible to guarantee that the application's end-to-end demand will be met. One could argue that a reactive routing protocol could be used to find a suitable GTS route between two nodes of the mesh network. This way, once a route is found and communicated to the source node, the source node could start requesting peer-to-peer GTSs along that route. We think however that once the best route or a suitable route that fulfills the application requirements is known, the nodes along the path to the source can directly reserve the GTS resources when receiving confirmation of the route formation (in a destination-origin order) and hence reduce the route establishment time and overhead. Therefore, we think that a cross-layer reactive GTS allocation technique is needed to guarantee that reliability, bandwidth (GTS slot is guaranteed from origin to destination) and delay constraints are met. Additionally, we propose a GTS path recovery mechanism not considered by peer-to-peer allocation methods. It is worth highlighting that the ZigBee specification [15] for mesh IEEE802.15.4 WSNs only considers the non beacon-enabled mode (which does not support GTS) and hence does not contemplate this situation.



a) Superframe Duration Scheduling (SDS) b) Beacon-only-period Scheduling (BOP)

Fig. 1. Task Group 15.4b beacon scheduling approaches



a) Delay problem with SDS b) GTS blockage problem with BOP

Fig. 2. GTS usage problems with different Beacon Scheduling techniques

3.2 Solution to the Problem

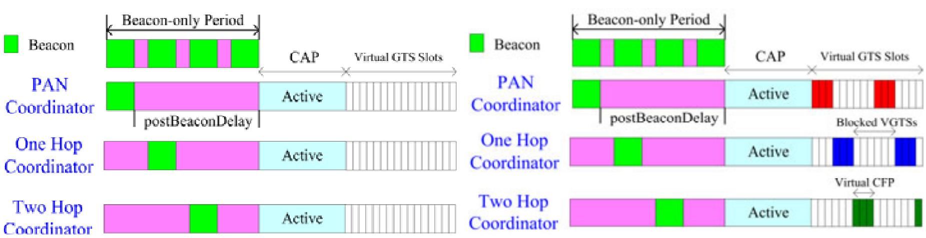
Here we describe the two solutions we propose to improve GTS communications in multihop beacon-enabled IEEE802.15.4 WSNs.

3.2.1 Contention Free Period Modification for BOP

The BOP approach for scheduling beacons and superframes has the inconvenience that the use of the GTS suffers from blockages that reduce the bandwidth utilization and limit the scalability. However, a BOP design has an advantage in that it introduces less delay than a SDS design. Here we propose a modification of the GTS part of the superframe to be used with BOP scheduling to improve the bandwidth usage and increase scalability.

It is conceivable that dividing the inactive period into virtual time slots, the same approach adopted by the IEEE802.15.5 standard [13], would solve the BOP scalability problem (Fig. 3 a)). This is true in the sense that by doing so the number of usable slots is increased. However, this solution still presents one difficulty, in order to use a slot for GTS frame reception, neighbors must be notified so they do not use the same slot to receive GTS frames or transmit to other neighbors. In order to notify other nodes, notification packets are broadcasted whenever a slot is allocated. Considering the collision prone nature of CSMA/CA communications and the fact that broadcast packets can not be acknowledged or combined with RTS/CTS techniques, this approach is not reliable –a failure in receiving a blocked slot warning translates into jeopardized GTS communications in neighboring nodes. Therefore, a different approach must be taken.

Here, we propose dividing the sleep time into Virtual Contention Free Periods (VCFP) composed of Virtual GTS slots (VGTS), and then assign these in a distributed and periodic fashion to different nodes (Fig. 3 b)). With this design, each node has a different set of VCFP within its two hop neighborhood so data frame collisions are avoided. This also eliminates the need for broadcasting control packets so acknowledgements between the interested nodes can be used. The distributed allocation of the VCFPs is performed using a similar algorithm used by MeshMAC approach for distributed beacon scheduling [8] and it is done at the time of the association. The term virtual is used because the coordinator does not need to stay active in the VGTS if the slot is not allocated to any node which in turn saves energy. All VCFPs are composed of 5 VGTS (each VGTS lasts approx 1ms) – 5 is the minimum size to transmit the maximum IEEE802.15.4 frame length (127 bytes plus headers). The periodicity of the VCFPs depends on the expected number of two hop neighbors per node, i.e., if a node is expected to have a maximum five neighbors in the two hop vicinity, the periodicity of its own VCFPs will be every five VCFP.



a) BOP modification based on IEEE802.15.5 b) Proposed BOP modification of the CFP

Fig. 3. Contention Free Period modifications for BOP Beacon Scheduling

3.2.2 Multihop Cross-Layer Reactive GTS Allocation Mechanism

In this work we propose a reactive cross-layer protocol that seeks a route with enough GTSs resources that fulfils the bandwidth and delay demands of the application and after that reserves the GTS slots along that route on a destination-source order. Unlike peer-to-peer allocation methods that ask for resources on a hop-by-hop basis, our mechanism ensures that all nodes in a selected route are able to provide the requested GTS resources.

The proposed mechanism works as follows: Nodes start the mesh GTS route search by broadcasting the Mesh GTS Allocation Request (MGA-Req) in the CAP (Fig. 4). Nodes that have free GTS slots that match the GTS Characteristics requirements rebroadcast the packet until the destination is reached and reserve the selected slots until the Mesh GTS Allocation Confirm (MGA-Con) is received or a timeout expires. On receiving more than one MGA-Req for the same route, the MGA-Req packet with the lowest accumulated delay will be re-broadcasted to reduce flooding of requests, given that the maximum tolerated delay requirement of the application is fulfilled. The accumulated delay per hop is calculated as the time that covers a GTS frame reception in the node's own reserved slot to the transmission of the frame in the previous hop node. To calculate this delay, the reserved slots information is passed from one node to the next locally. A node might occupy more than one VCFP if necessary. Also, in order to decrease request flooding, packets will expire when a predefined hop count is reached. The best path information is stored in the Mesh Cross-Layer GTS Allocation Table while the node waits for confirmation. Request packets have a unique ID that together with the delay information avoid loop formation.

The destination, upon receiving the reservation requests, will estimate which paths fulfil the application delay requirements by checking the "Accumulated Delay" and "Tolerated delay" fields of the MGA-Req packet. Once the path is selected, it will start the allocation and confirm process by unicasting a MGA-Con packet to its selected neighbour (Fig. 5) containing the allocated GTS information. A node receiving a MGA-Con will acknowledge the packet and it will unicast it to the following neighbour. In addition, the node will store the GTS allocation information in the allocation table. The process stops when the origin node is reached and, at this time, the node can start sending packets through the newly established multihop GTS connection.

Bits:	1 … 16	17 … 32	33 … 40	41 … 56	57 … 72	73 … 80	81 … 88	89 … 89+8*nCFP
	Destination Address	Source Address	GTS Characteristics	Tolerated Delay	Accumulated Delay	Hop Count	Req. ID	Reserved Slots

Fig. 4. MGA-Req packet format

Bits:	1 … 16	17 … 32	33 … 48	49 … 49+16*nCFP
	Destination Address	Source Address	GTS Characteristics	Allocated GTS

Fig. 5. MGA-Con packet format

3.2.2.1 Multihop GTS Allocation Maintenance

Another drawback of the peer-to-peer GTS allocation mechanisms available in the literature is that they do not provide recovery mechanisms for multihop GTS allocation. In a WSN, a route may suddenly become unavailable because of changes in the wireless channel, node failure or due to node mobility. The link failure might happen once the route is established or even in the route establishment process. Therefore, route maintenance mechanisms must be available.

If a failure occurs in the GTS allocation process, for example if an MGA-Con is not acknowledged, the failure must be communicated to the nodes that have already reserved resources so they can free them. Also, if a failure occurs after the route is established, detected when nodes cannot hear beacon frames of their data packet destinations or because nodes do not receive data packets in the allocated GTSs, the link failure must also be communicated. In all these cases, a deallocation packet (Mesh GTS Deallocation Request MGD-Req) will be sent indicating the direction of the deallocation (towards the destination or towards the source) and if the deallocation is performed due to a link failure - to differentiate it from a normal deallocation (Fig. 6). A node receiving a failure deallocation packet towards the origin will start a new allocation process towards the destination to find an alternative route.

Fig. 6. MGD-Req packet format

4 Simulation Scenario and Results

In designing the experimental environment we rely on the multihop IEEE802.15.4 OPNET simulation model [16] developed with OPNET Modeler [17] as a basis for implementing and testing our BOP modification and multihop GTS allocation mechanism. In addition, we use a distributed version of BOP named DBOP presented in [16] to perform our simulations.

Typical industrial scenarios may have multiple sinks with the number of sinks being far smaller than the total number of nodes. Also, they may be composed by between 10 to 200 field devices and usually, they have a maximum number of hops of 20 [18]. We use a random network topology composed of 30 MicaZ nodes [19]. The maximum distance between two nodes is 12 hops and there are between 1 to 5 neighbours per node. The network has 4 sinks and nodes select a destination sink randomly.

All nodes send data frames of 127 bytes (the maximum possible size). The buffer size for all nodes is limited to 1250 bytes. Nodes detect tool monitoring events such as vibrations or acceleration randomly and report the generated data to the corresponding sink. The time a node is detecting an event is referred to as a session and their duration is modeled with an exponential distribution of mean 300 seconds. The interarrival times between sessions follow a Poisson distribution with means ranging from 300s to 1800s (in steps of 300s). Varying the session interarrival times has the same effect as fixing them and varying the number of nodes. In our simulation rounds, we fix SO to 2 and BO to 6. Finally, data generation rates per session are also varied (1kbps and 3.5kbps) to examine how requesting more or less resources affects the overall performance.

Finally, To test the benefits of our MAC layer modification and multihop GTS allocation algorithm, we compare first with the BOP modification based on IEEE802.15.5 MAC (Fig. 3 a)), referred to as 15.5BOP with our own MAC modification (Fig. 3 b)), referred to as Distributed CFP BOP (DCBOP) using a peer-to-peer GTS allocation method. Afterwards, using our MAC modification, we compare the peer-to-peer GTS allocation method with our reactive allocation method. Every time the peer-to-peer GTS allocation is used, AODV [20] is used first to find a route if the route is not already known. We select a typical value of Active Route Time-Out (ART) of 300 seconds [21].

4.1 Simulation Results

Fig. 7 depicts the number of successfully established multihop GTS connections for 15.5BOP and DCBOP MAC modifications with a peer-to-peer allocation method and DCBOP with the reactive allocation method for data generation rates per session of 3.5kbps. When both MACs are compared with the same allocation method (red-circle and black-triangle lines) we can see the clear benefit produced when our MAC modification is used. Since allocation requests do not have to be broadcasted to make other neighbors aware of GTS slots usage when our MAC modification is used (because the CFP is not shared among neighboring nodes), the problems caused by the hidden terminal problem are eliminated and therefore the number of successfully established multihop GTS connections is increased. If our reactive allocation method is added to our modified MAC (blue line), the gains are even greater. It has to be noted that for the selected data generation rate (3.5kbps) and BO/SO parameters the network is congested and therefore it is not possible to satisfy all GTS connections (successful connections are below 60% at all cases).

Fig. 8 depicts the successfully established multihop GTS connections for our DCBOP MAC modification combined with a peer-to-peer allocation method and our reactive allocation method for data generation rates per session of 1kbps and 3.5kbps. As can be seen, our reactive allocation method always outperforms the peer-to-peer method because routes are established through nodes that have available resources at the request time. Peer-to-peer allocation methods cannot check if the nodes in the route (obtained using AODV) have available resources at the request time and therefore it is not possible to ensure that the connection will be successful beforehand even though the path to a given destination is known. If the data generation rate per session is decreased from 3.5kbps to 1kbps the occupancy of resources is decreased and the performance of the allocation methods is obviously improved.

Fig. 9 shows the overhead caused by the peer-to-peer and reactive allocation methods for session interarrival times of 600s and 1800s and for 1 and 3.5 kbps data generation rates. As can be observed, the control bits / data bits ratio is quite low in both cases. This is due to the fact that sessions are quite long (condition monitoring events such as vibrations in industrial machinery can last for minutes generating tens of kilobits of data) and hence the number of control packets is low compared to the number of data packets. The difference between the peer-to-peer allocation method and our reactive method is also minimal since the peer-to-peer allocation method uses AODV reactive routing first to find the routes if a new route is needed or the previous one has expired. Therefore, the use of our reactive approach is justified.

Finally, Fig. 10 depicts the Cumulative Distribution Function of the end-to-end delay for all received packets at all network sinks. As can be seen, both allocation mechanisms are able to maintain the end-to-end delay below 1.5 seconds for 90% of received packets which is sufficient for industrial monitoring applications that can tolerate up to a couple of seconds of delay. Our reactive scheme introduces slightly more delay than the peer-to-peer allocation method because it does not always choose the optimal path in terms of delay since that path may have all of its GTS resources occupied.

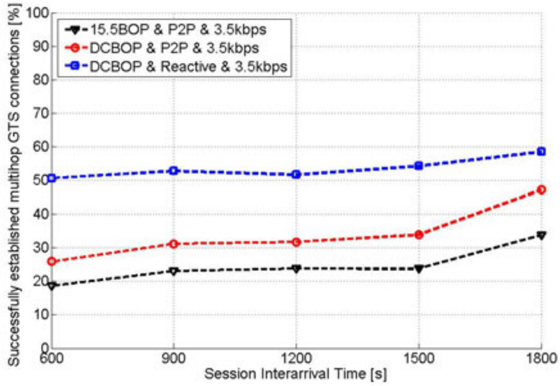


Fig. 7. Successfully established multihop GTS connections for different BOP CFP modifications

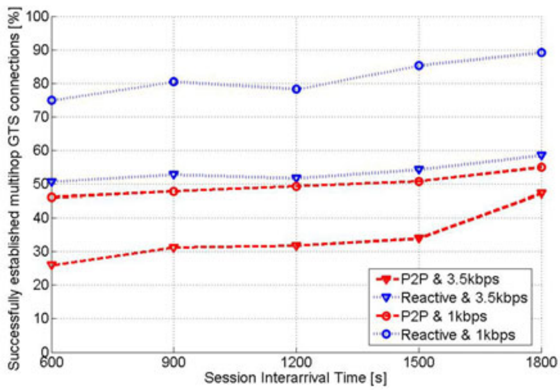


Fig. 8. Successfully established multihop GTS connections for different allocation methods

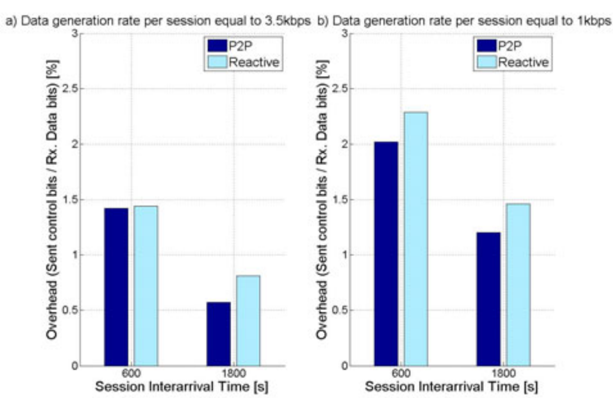


Fig. 9. Overhead introduced by the different multihop GTS allocation methods

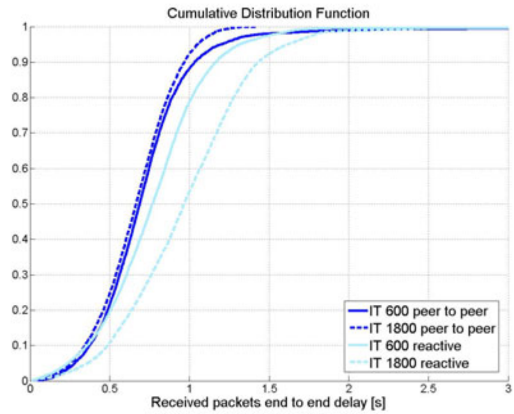


Fig. 10. Received packets end-to-end delay

5 Conclusion and Future Work

In this work, we have proposed a distributed IEEE802.15.4 MAC modification to improve GTS usability and scalability in mesh networks. Also, we have proposed a reactive multihop GTS allocation technique based on our MAC modification to guarantee reliable and latency aware communications from source to destination in mesh beacon-enabled IEEE802.15.4 WSNs. As shown by our simulation results, both techniques increase the reliability of the network communications since more GTS connections are established successfully which permits more hidden-terminal-free communications in mesh networks. We also show that the cost of using our reactive allocation method is minimal in terms of overhead for our targeted industrial monitoring applications.

Future work will be based on combining service differentiation techniques with our allocation method to distribute the available resources when the network is congested.

References

1. Baker, P.C., Catterson, V.M., McArthur, S.D.J.: Integrating an Agent-based Wireless Sensor Network within an Existing Multi-agent Condition Monitoring System. In: International Conference on Intelligent System Applications to Power Systems (ISAP 2009), November 8-12 (2009)
2. IEEE 802.15.4 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks, LR-WPANs (2003)
3. Lee, M., Zheng, J., Zhang, J., Liu, Y., Dai, H., Shao, H.R.: Combined Beacon Scheduling Proposal to 802.15.4, TG4b (September 16, 2004)
4. IEEE 802.15.4 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks, LR-WPANs (2006)
5. Shin, C., Jeong, W., Hwang, S., Lee, A., Joo, S.: Beacon collision avoidance mechanism for TG4e MAC, TG4e (September 2008)

6. Koubâa, A., Cunha, A., Alves, M., Tovar, E.: TDBS: a time division beacon scheduling mechanism for ZigBee cluster-tree wireless sensor networks. Real-Time Systems 40(3), 321–354H.-I (2008)
7. Burda, R., Wietfeld, C.: A Distributed and Autonomous Beacon Scheduling Algorithm for IEEE802.15.4/ZigBee Networks. In: Proc. of IEEE MASS 2007, Pisa, Italy (October 2007)
8. Muthukumaran, P.S., de Paz, R., Špinar, R., Pesch, D.: MeshMAC: Enabling Mesh Networking over IEEE802.15.4 through distributed beacon scheduling. In: Zheng, J., et al. (eds.) ADHOCNETS 2009. LNICST, vol. 28, pp. 561–575 (2009)
9. Jeon, H., Kim, Y.: BOP (Beacon-Only Period) and Beacon Scheduling for MEU (Mesh-Enabled USN) Devices. In: The 9th International Conference on Advanced Communication Technology, vol. 2, pp. 1139–1142 (February 2007)
10. Kim, E., Choi, H.: EBBS: Energy-efficient BOP based Beacon Transmission Scheduling for WSNs. In: Proceedings of PIMRC 2008 (2008)
11. Ferrari, M., Pizziniaco, L.: An Adaptive Scheme for Active Periods Schedule in IEEE 802.15.4 Wireless Networks. In: 3rd International Symposium on Wireless Communication Systems (2006)
12. Shen, J., Yao, D., Xing, T., Zhao, Z.F., Liu, H.: Supporting Peer to Peer Network and Improving throughput by enhanced GTS, TG4e (September 2008)
13. IEEE 802.15.5 Mesh Topology Capability in Wireless Personal Area Networks (WPANs) (2009)
14. Khayyat, A., Safwat, A.: The Synchronized Peer-to-Peer Framework and Distributed Contention-Free Medium Access for Multihop Wireless Sensor Networks. Journal of Sensors 2008, Article ID 728415, 28 pages (2008)
15. ZigBee Alliance Document 053474r17, ZigBee Specification, v. 1.0 r17 (2007)
16. Carballido Villaverde, B., De Paz Alberola, R., Rea, S., Pesch, D.: Experimental Evaluation of Beacon Scheduling Mechanisms for Multihop IEEE 802.15.4 Wireless Sensor Networks. In: The Fourth International Conference on Sensor Technologies and Applications, Sensorcomm 2010 (2010)
17. Opnet Tech. Inc., Opnet Modeler - version 14.5, http://www.opnet.com/ (Last accessed 23/06/10)
18. Industrial Routing Requirements in Low Power and Lossy Networks. Work In Progress Internet Draft. Networking Working Group, Internet Engineering Task Force, http://tools.ietf.org/html/draft-ietf-roll-indus-routing-reqs-05 (Last accessed 23/06/10)
19. MicaZ motes datasheet from Crossbow Technology, http://www.xbow.com/Products/productdetails.aspx?sid=164 (Last accessed 23/06/10)
20. Perkins, C.E., Royer, E.M.: Ad hoc On-Demand Distance Vector Routing. In: Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications, New Orleans, LA, pp. 90–100 (1999)
21. Richard, C., Perkins, C.E., Westphal, C.: Defining an Optimal Active Route Timeout for the AODV Routing Protocol. In: Second Annual IEEE Communications Society Conference on Sensor and Ad-Hoc Communications and Networks, IEEE SECON 2005, California, USA, September 26-29 (2005)