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Investigating the efficiency of IEEE 802.15.4 for Medical Monitoring Applications

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Abstract—**Recent advancements in wireless communications technologies bring us one step closer to provide reliable Telecare services as an alternative to patients staying in a hospital mainly for monitoring purposes. In this research we investigate the efficiency of IEEE 802.15.4 in a simple scenario where a patient is being monitored using an ECG and a blood analysis module. This approach binds well with assisted living solutions, by sharing the network infrastructure for both monitoring and control while taking advantage of the low power features of the protocol. Such applications are becoming more and more realistic to implement as IEEE 802.15.4 compatible hardware becomes increasingly available. Our aim is to examine the impact of Beacon and Superframe Order in the medium access delay, dropped packets, end to end delay, average retransmission attempts and consumed power focusing on this bandwidth demanding situation where the network load does not allow low duty cycles, in order to draw some conclusions on the effect that this will have to telemonitoring applications.**

I. INTRODUCTION

ACCORDING to the United Nations population ageing report [1] the number of elder people in developed countries has exceeded the number of children since 1998, and by 2045 this will hold true for the rest of the world. The consequences of the unprecedented ageing rate have become more than noticeable on health care expenses. This has forced health care providers to consider alternative methods of care delivery, especially in cases where monitoring is involved. It has been suggested [2] that chronic conditions contribute to nearly 70% of expenses in the health care sector. This is an excellent scenario where wireless sensor networks may provide the desired infrastructure for cost effective solutions [3] without decreasing the quality of service.

IEEE's response to the increased demand for Wireless Personal Area Network (WPAN) low power connectivity comes in the form of the 802.15.4 protocol where PHY and MAC layers are specified while network and application layers are left open for implementation. In telemonitoring scenarios Zigbee is arguably the most widely known implementation of the upper layers and has attracted a lot of attention for wireless sensor network (WSN) applications.

This approach offers new possibilities for monitoring and control, combining home automation with remote care in assisted living solutions [4]. As an example, a Zigbee wireless network can be deployed in a house where medical data will be collected at the patient's convenience, a mobile phone can be used as a friendly user interface for accessing this information and data can be stored in a plugged computer before being forwarded to a central database. The same infrastructure may be employed for home automation by using USB dongle 802.15.4 transceivers within the context of assisted living solutions. In this kind of deployment a major challenge is to interface Zigbee with a mobile phone due to the lack of compatible commercially available hardware. This has changed recently with the introduction of the first Zigbee microSD transceiver being released [5] expanding the connectivity possibilities. This type of application has several advantages for all the interested parties: health care providers optimize their resource management in order to reduce expenses, patients receive high quality care remotely and home automation options add value to the network infrastructure as optional services for those who need it. Nevertheless, careful consideration must be taken into configuring and optimizing the network setup to tackle particular challenges arising from the application requirements. In this simulation we are focusing on a patient using an ECG and a blood analysis module, and investigate protocol parameters for the optimization of network behavior and energy consumption.

The IEEE 802.15.4 protocol defines the PHY and MAC layers. MAC configurations supports star, tree, cluster tree and mesh topologies featuring two types of devices, either Full Function Devices (FFDs) that can organize, route and participate in a network or Reduced Function Devices (RFD's) that may join the network but not route or provide management services. The network has two modes of operation configured by the Personal Area Network (PAN) coordinator:

1. *Beacon enabled mode, with slotted CSMA/CA*
2. *Non Beacon enabled mode, with un-slotted CSMA/CA.*

In the first case, the PAN coordinator emits regular beacons that indicate the start of the Contention Access Period (CAP) where nodes are allowed to access the medium and transmit information ruled by the slotted CSMA/CA mechanism. In addition to the CAP slots, 802.15.4 defines an optional Contention Free Period utilizing the Guaranteed Time Slot

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technique (GTS) where devices may request the coordinator to reserve time slots when reliability and speed is crucial. The protocol is also designed towards energy efficiency and the duty cycle of the devices can be throttled down where the offered load allows it. This is achieved through the configurable Beacon Interval (BI) along with the adjustable Superframe Duration (SD). BI specifies the interval between two subsequent beacons and SD determines the duration of the active portion of the Superframe where transmissions are allowed. The user is free to modify this according to the application needs, adjusting the duty cycle to very low values thus extending the battery time. However, where the offered load is higher the system is forced to use higher duty cycles in order to avoid buffer overflows.

II. METHODOLOGY

In this paper we investigate the impact of different BI settings on energy consumption, medium access delay, dropped packets, end to end delay and retransmission attempts in a simple simulation scenario where a patient is using an ECG and a Blood monitor providing a considerable effective load of 56 Kbits / sec from two different nodes towards the PAN coordinator.

The simulation has been conducted using OPNET modeler v.16.0. This version comes with its own relatively new Zigbee model (802.15.4 PHY and MAC) that currently has several limitations, including lack of slotted CSMA/CA, Contention Free Period (CFP) access and source locked node models.

The IPP-HURRAY! Research group have also developed their own model for 802.15.4 [6] with a published slotted CSMA/CA study [7]. Slotted CSMA/CA is more interesting in terms of functionality and since the default OPNET model does not support it, this study relied on the open-ZB implementation from IPP-HURRAY!

Related Work

Similar work in this topic includes, Golmie [8] where the National Institute of Standards and Technology team developed an ns2 802.15.4 simulation model investigating interference between two different WPANs and between a WPAN and a WLAN. Zheng [9] developed another ns2 simulation model for 802.15.4 and investigated the association efficiency, orphaning procedure, collisions occurrence and direct / indirect data transmissions within a large WSN network. Some raise concerns on the accuracy of the results from ns2 as it was designed for IP based protocols [10]. Koubaa [7] simulated 802.15.4 to investigate the performance of slotted CSMA/CA in regards to throughput, average delay and probability of successful transmission on a 100 node WSN network, while Jurcik [11] proposed a Time Division Scheduling Tool for beacon enabled cluster tree WSNs.

IEEE 802.15.4 Features

The most important characteristic of beacon enabled mode is the ability to set the duty cycle via the Beacon Order (BO) and the Superframe Order (SO). The coordinator will transmit a Beacon on a regular interval BI which is calculated using the BO in the following formula:

$$BI = aBaseSuperFrameDuration * 2^{BO}$$

$$0<BO<14$$

aBaseSuperFrameDuration is defined as 960 symbols in the 802 specification which translates to 960 * 4 / 250.000 = 15.36 ms for 250 Kbit data rate and 4 bits per Symbol as specified in the modulation scheme. The Superframe Duration is calculated as:

$$SD = aBaseSuperFrameDuration *2^{SO}$$

$$SO \leq BO$$

When SO = BO, the duty cycle is set to 100%, otherwise the active portion of the superframe is equal to SD within the beacon boundaries of BI. Nodes are allowed to transmit during SD and may go into sleep mode for the inactive duration until the next beacon is emitted.

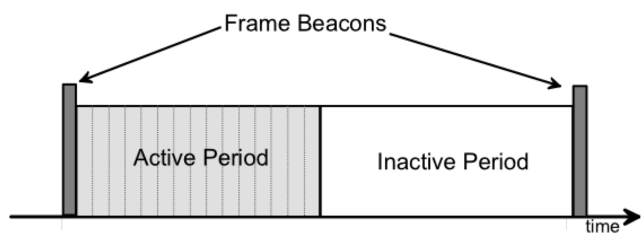

Fig. 1. 802.15.4 Active and Inactive Periods

The active period is arranged into 16 slots and may be further divided into the CAP and the CFP. During the CAP nodes compete for access based on CSMA/CA, while during CFP nodes are assigned slots from the coordinator per request in order to guarantee the transmission of time sensitive data.

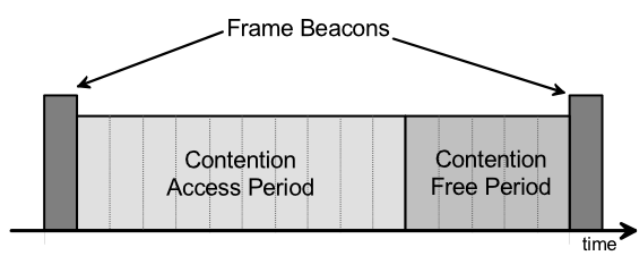

Fig. 2. 802.15.4 CAP and CFP

In this research we do not use the GTS mode for the CFP period, but rather examine acknowledged contested transmissions during the CAP. CFP is an excellent facility of the protocol but its increased complexity and slightly higher overhead make it an option one would consider only when necessary. Normally CFP is meant to be reserved for time critical information and not for general use.

Briefly, in slotted CSMA/CA mode, the node performs Clear Channel Assessment (CCA) twice (or otherwise equal to Contention Window (CW)) on the medium to determine if anyone is using it before accessing it. If the first CCA fails the Number of Backoffs (NB) and the Backoff Exponent (BE) are increased. BE may increase up to aMaxBE (default is 5) and will be used to calculate $2^{BE} - 1$ Backoff Periods (BP) for the node to wait before trying another CCA. If NB reaches the value of aMaxCSMABackoffs = 5 then transmission fails. CCAs have to begin from a boundary of a BP while the BP boundaries have to be aligned according to the superframe slot. If the remaining BPs are not enough for the transmission the frame is deferred to the next superframe. Hidden nodes could become a problem since no RTS/CTS scheme is employed and acknowledgment frames may also contribute to some increase in medium access delay due to unforeseen frame collisions.

We have simulated a simple scenario of a patient using an ECG sensor and a Blood Analysis module as RFD devices transmitting data to the PAN Coordinator 1 meter away. The modulation used is 250 Kbit QPSK with free space propagation model. The coordinator is transmitting with 100 mW of power while the end devices use 1 mW. The power consumption model is based on the Telos-B mote specification.

The offered load for the ECG and the Blood analysis module are based on Golmie's work [8] and are set to 1.5 Kb / 0.25 Sec and 1 Kb / Sec respectively. Thus the combined load is 48.000 + 8192 = 56192 bps. Due to the traffic requirements in this case we cannot employ very low duty cycles, hence we decided to model only the 100% duty cycle scenario for this investigation. We considered short simulation times limited to 4 minutes as the results trend was similar for longer simulation times.

When WSNs are used for control or low data rate sensor nodes ACK frames maybe considered unnecessary. However, in this scenario, with constant sensitive data flow it is more realistic to employ the ACK scheme with the default maximum retransmission attempts (3) and at the same time observe the impact on medium access delay.

The maximum BE is set to 4 and minimum BE is set to 3, but since the BatteryLife Extension is also set to true, BE effectively starts from 2. Given the high duty cycle we expect a very small number of failed attempts and try to optimize the medium access delay.

III. Results

We run the simulation for all valid BO=SO values from 0 to 14 and collect data for consumed power as shown in Fig.3, dropped packets in Fig.4, average medium access delay in Fig.5, average end to end delay and average retransmission attempts in Fig.6.

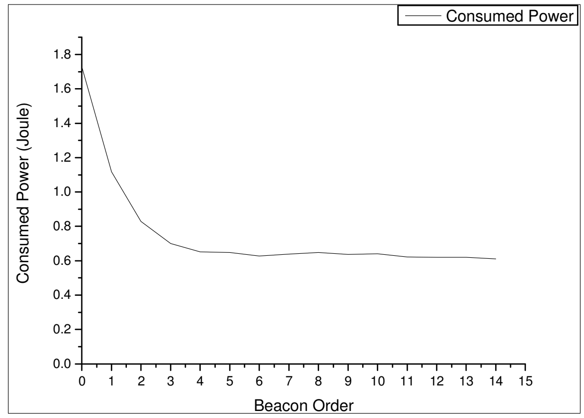

Fig. 3. Consumed Power as a function of BO

Beacon orders lower than 3 which equal to a BI of 122.9 ms appear to be using more power on average compared to the higher order BOs. This is expected as with a short SD and some considerable network load, some of the frames would get deferred to the next beacon as a result of getting two successful CCAs very close to the boundary of the last slot in the CAP. These frames have a good chance of colliding immediately in the beginning of the first time slot of the next beacon; since the BatteryLifeExtension is enabled the starting BE has a value of 2 hence $BP = 2^{BE} - 1$ would result to 1, 2 or 3. Now if both nodes draw the same random number the frames will collide again. The effect fades for higher BOs as the number of deferred frames per second decreases.

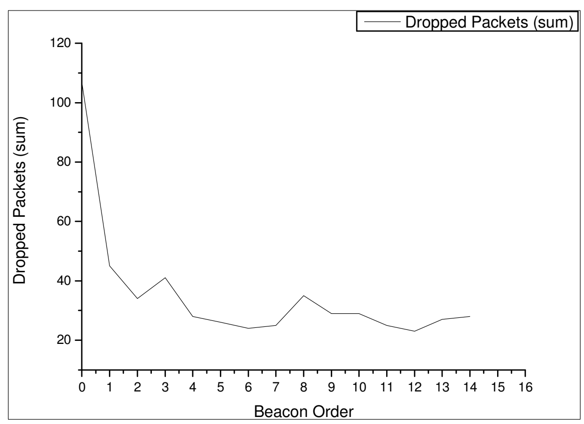

Fig. 4. Average Dropped Packets as a function of BO

Fig. 4 displays the packets that are dropped by the physical layer due to CSMA being unable to resolve access to the medium before aMaxCSMABackOffs. Again lower BOs suffer from more failures as explained earlier; the only difference in this graph, is that the average dropped packets appear to spike randomly due to the randomness in selecting a different number in every collision using $BP = 2^{BE} - 1$.

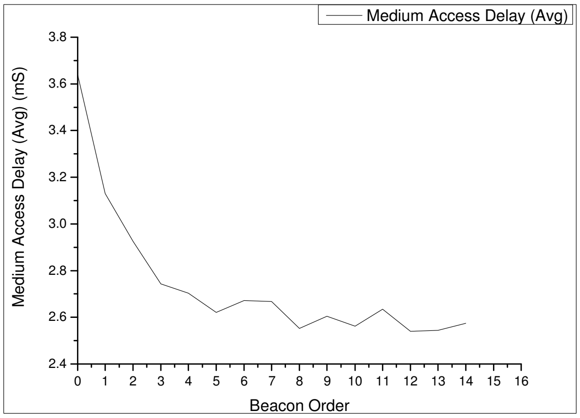

Fig. 5. Avg Medium Access Delay as a function of BO

The medium access delay follows a similar trend to the average dropped packets differing in that delay is affected by all packets that remain in the buffer waiting for random BPs to conduct new CCAs and not just from the dropped packets that fail aMaxCSMABackOffs. However, in this scenario since the duty cycle is 100% the MAC does not suffer from queues that would create long delays. We consider the delays observed in the graph as practically negligible. An important contributor to retransmissions in this setup is the ACK frames, regardless of their small size, may trigger longer BPs in any frame.

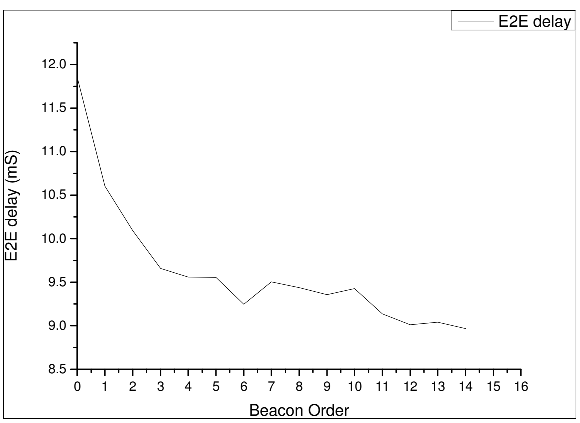

Fig. 6. End to End Delay as a function of BO

End to end delay represents the time between the instantiation of the packet in the application layer of the transmitter and the arrival of the same packet in the application layer of the receiver. The collected values do not necessarily reflect real life situations with noise, interference and realistic path loss but serve as a tool to confirm the validity of the rest of the results. It is evident that overall in this particular scenario, BOs of higher than 3 give better performance results.

The average retransmission attempts follow the same pattern as the dropped packets in Fig. 4. The same randomness factor differentiates them as the retransmission attempts also count for packets that did not drop eventually, this demonstrated behavior improves for BOs higher than 4.

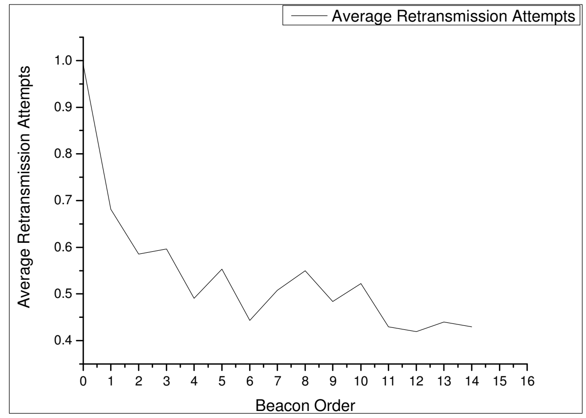

Fig. 7. Average Retransmission Attempts as a function of BO

IV. CONCLUSION

In this paper we investigated the impact of BO in a hypothetical medical monitoring scenario with a load of 56 Kbps and a duty cycle of 100 %. We found out that BOs higher than 3-4 perform better than lower BOs in terms of consumed power, delays, dropped packets and retransmissions. We also concluded that the Battery Life extension attribute will not produce the expected results in lower BOs due to the effect of CSMA deference. As demonstrated, appropriate configuration settings may double the battery life on 802.15.4 transceiver. Further research will reveal if the same behavior is repeated in different scenarios.

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