Performance Evaluation of IEEE 802.15.4 for Wireless Body Area Network (WBAN)

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Abstract—**IEEE 802.15.4 is a current major technology for low-rate low-power wireless networks. To study the applicability of IEEE 802.15.4 over a wireless body area network (WBAN), in this paper we evaluate its three different access schemes' performance through several metrics. Considering the coexistence of contention access period (CAP) and contention-free period (CFP), we also study the mutual influences of these two traffics. The results show the unslotted mode has better performance than the slotted one in terms of throughput and latency but with the cost of much power consumption. In addition, the guaranteed time slot (GTS) in CFP can not guarantee the successful transmission of the CFP frames without sufficient GTS allocation. Finally, we give the suggestions for the novel medium access control (MAC) design for a WBAN.**

Keywords-WBAN; WPAN; IEEE 802.15.4; MAC

I. INTRODUCTION

There are standardization activities in IEEE 802.15.6 WBAN task group (TG) which is contributing to the new standard for short range, wireless communication in the vicinity of, or inside human body [1]. Relative to the technology of WPAN, WBAN provides closer interconnection (2-5 meters) with more strict technical requirements such as the high reliability, extreme power efficiency and security, especially the safety for human body.

IEEE 802.15.4 provides a solution for low-rate low-power WPAN in the personal operating space (POS) of 10 meters, typically sensor network [2]. One area of increasing interest is the adaptation of this technology to operate in and around the human body, connected via a WBAN. There are many potential applications that will be based on WBAN technology, including health care service, assistance to people with disabilities, and body interaction and entertainment [3].

Since the first version was released in 2003, IEEE 802.15.4 has attracted plenty of interests both from academia and business. There are three access schemes in IEEE 802.15.4 MAC, unslotted carrier sensing multiple access with collision avoidance (CSMA-CA), slotted CSMA-CA and CFP scheme. Many researchers paid attention to the latter two schemes. In [4], the IEEE 802.15.4 MAC prototype was implemented and the performance evaluations were provided, focusing on the beacon-enabled mode without considering the beaconless mode. Reference [5] developed an NS-2 simulator for IEEE 802.15.4 to study its performance on various features with emphasis on the packet delivery ratio. [6] presented a mathematical analysis of the IEEE 802.15.4 performance in relation to medical sensor body area networks only considering the power consumption issue, i.e., the lifetime of the network. [7,8] analyzed the slotted CSMA-CA scheme of IEEE 802.15.4 with the unique metric of throughput. In [9], other than the throughput, the energy consumption was also analyzed. [10] evaluated the IEEE 802.15.4 performance via several sets of practical experiments without considering the latency.

Most of the previous work focused on the slotted version of the IEEE 802.15.4 MAC only, and didn't investigate the mutual influences of CAP and CFP. Also, there is no comparison between the different MAC schemes in IEEE 802.15.4. In addition, the Poisson traffic was commonly assumed. However among the applications based on a WBAN especially in the medical scenarios, the periodic type traffic is thought as the primary type of traffic which consumes the most part of the bandwidth [11]. In this paper, we consider the IEEE 802.15.4 standard that is a likely candidate for low bit rate WBAN applications and give the detailed performance evaluation results in the aspects of the throughput, delay, dropping rate and energy consumption and compared the three schemes of IEEE 802.15.4 MAC. Our objectives are to answer a number of questions concerning the performance of IEEE 802.15.4 over a WBAN, for example: What's the quantitative performance considering all the metrics? What's the capacity of the network using the given MAC? How is the slotted MAC comparing with the unslotted one? What's the influence between the CAP and the CFP? And the most important one, what can we obtain from this evaluation for the design of the novel MAC for the future WBAN?

The rest of this paper is organized as follows. Section II briefly describes the IEEE 802.15.4 MAC protocol. The simulation model and results are presented in Section III. Section IV offers a final discussion and concludes the paper by a brief outlook on future work.

II. OVERVIEW OF IEEE 802.15.4 MAC

The IEEE 802.15.4 standard defines the physical layer (PHY) and MAC sublayer specifications for supporting simple devices that consume minimal power in a WPAN.

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The IEEE 802.15.4 MAC can operate in two modes: beacon-enabled and beaconless.

In the beacon-enabled mode, the PAN coordinator broadcasts a periodic beacon containing information about the PAN. The period between two consecutive beacons defines a superframe structure. A superframe is always initiated by the beacon, while the remainder may be used for data communication by means of random access, and form the so called CAP. The beacon contains information related to the PAN identification, synchronization, and superframe structure.

In this case, two types of data transactions exist:

1) Transfer from a device to the coordinator - a device willing to transfer data to the coordinator uses slotted CSMA-CA. The coordinator may confirm the successful data reception with an optional acknowledgment following the data frame.

2) Transfer from the coordinator to a device - when the coordinator has data pending for a device, it announces so in the beacon. The interested device adopts slotted CSMA-CA to send a request to the coordinator, indicating that it is ready to receive the data. When the coordinator receives the data request message, it selects a free slot and sends data using slotted CSMA-CA as well.

In order to support time critical data applications, the PAN coordinator can reserve one or more slots that are assigned to devices running such applications without need for contention with other devices. Such slots are referred to as GTSs, and they form the CFP of the superframe. Note that CFP can not operate independently and is always integrated with CAP. An example of the superframe with CAP, CFP and inactive period is shown in Fig. 1 [2].

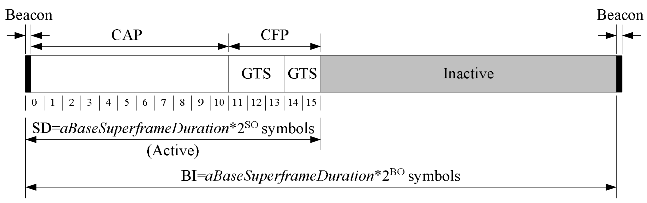

Figure 1. An example of the superframe

In the nonbeacon-enabled mode there is no explicit synchronization provided by the PAN coordinator. Since there is no superframe defined in the nonbeacon-enabled mode and no slot synchronization is available, no GTS can be reserved, and only random access is adopted for medium sharing.

The CSMA-CA algorithm shall be used before the transmission of data or MAC command frames transmitted within the CAP. The IEEE 802.15.4 uses two types of CSMA-CA algorithms as follows.

In the case of a nonbeacon-enabled network, when a device needs to send data it picks a random backoff delay, defined as a multiple of a backoff time unit. When the backoff delay expires, the device performs a clear channel assessment (CCA) operation, consisting in listening to the channel in order to determine if it is idle. If the channel is idle the device immediately transmits the data packet; oppositely, if the channel is busy the device repeats the procedure by picking a new backoff delay before trying to access the channel again.

In a beacon enabled network the devices use a slotted version of the previous protocol to access the medium in the CAP portion of the superframe. The main difference compared to the unslotted version is that at the end of the random backoff delay the device performs a CCA operation at the beginning of the next backoff unit; if the channel is idle, however, the device does not transmit the data packet immediately, but repeats the CCA for a number of backoff units defined by the value of a parameter called contention window (CW). If the channel is idle for all the backoff units within the CW the device transmits the data. If during one of the units in the CW the channel is detected to be busy, the device repeats the procedure by picking a new backoff delay.

In both cases, the algorithm is implemented using units of time called backoff periods, where one backoff period shall be equal to a constant, i.e. *aUnitBackoffPeriod*. The maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure is specified as *macMaxCSMABackoffs*. Note that the CSMA-CA algorithm shall not be used for the transmission of beacon frames, acknowledgements, or data frames transmitted in the CFP.

According to the descriptions in this section, totally there are three types of channel access mechanism for IEEE 802.15.4 MAC, i.e., unslotted CSMA-CA, slotted CSMA-CA, and slotted CSMA-CA integrated with GTS. The first scheme is working in the beaconless mode and the remaining two schemes are both working in the beacon enabled mode.

III. PERFORMANCE EVALUATION

In this paper, simulations based on standard C are made by modeling the IEEE 802.15.4 network closely and carefully, including beacon, superframe, CAP and CFP etc. We simulate the three mechanisms in IEEE 802.15.4 MAC.

A. Simulation Model

We consider a single BAN consists of one BAN coordinator (BC) and several sensor nodes (SNs). For simplification, a sensor node has either contention or contention-free traffic which will be transmitted in the CAP or the CFP of a superframe. The number of these two types of nodes is denoted as N_C and N_{CF}. The network topology is a one-hop star type which is showed in Fig. 2. In addition, considering the medical sensing such as electrocardiogram (ECG) where all the data transmissions are initiated by the sensor nodes, the downlink traffic from the BC is not considered in this paper.

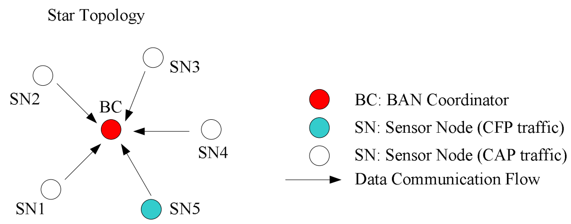

Figure 2. Network topology

Parameters used in the simulation of IEEE 802.15.4 MAC are tabulated in Table I. Besides, the effect of bit errors in the channel is neglected. Each node generates a periodic data flow. The application traffic is a constant distribution with the fixed data rate of 2 kbps. All nodes generate their first data frame randomly in one cycle. The data frame has the fixed payload length in any simulation scenario. For simplification, the payload size of a beacon frame is also assumed constant. In addition, the radio characteristics are shown in Table II (from [12]). All simulations were run independently and their results averaged under 1000 different seeds. A simulation in any scenario held on for 100 seconds.

TABLE I. SIMULATION PARAMETERS

Parameter	Default Value
Frequency Band	2400-2483.5 MHz
Channel Rate	250 kbps
aBaseSuperframeDuration	960 symbols (15.36 ms)
macBeaconOrder (BO)	4
macSuperframeOrder (SO)	4,3,2 (DC=1,0.5,0.25)
BeaconInterval (BI)	245.76 ms
aNumSuperframeSlots	16
aUnitBackoffPeriod	20 symbols (320 µs)
macMinBE	3
macMaxBE	5
macMaxCSMABackoffs	4
macMaxFrameRetries	3
aMaxSIFSFrameSize	18 octets
aTurnaroundTime	12 symbols (192 µs)
CCA Detection Time	8 symbols (128 µs)
t_{ack}	12 symbols (192 µs)
SIFS	12 symbols (192 µs)
LIFS	40 symbols (640 µs)
macAckWaitDuration	54 symbols (864 µs)
MACBeaconSize	20 Octets
MACPayloadSize	20 Octets
MACAckSize	5 Octets
MACGTSReqCommSize	11 Octets
MACCFPFrmPayloadSize	20 Octets
MAC Header	9 Octets
PHY Header	6 Octets
BufferSpace	1000 Octets

TABLE II. RADIO PARAMETERS

Operation mode	Power consumption
Transmit	36.5 mW
Receive	41.4 mW
Idle	41.4 mW
Inactive (Sleep)	42 µW

B. Simulation Results

The performance requirements quite depend on the application. For example, the latency requirement of a real time application such as ECG is much lower than a normal sensing data. And regarding the power consumption, cardiac defibrillators and pace makers have a lifetime of more than 5 years whereas swallowable camera pills typically have lifetime of 12 hours. Generally, in this paper the performance metrics we evaluated are: average delay, normalized throughput (PHY on-air bit rate), frame dropping rate and average power consumption (mW/node). To conveniently analyze the transmission efficiency of different MAC schemes, we define the transmission ratio, T_{ratio} as the ratio of all the transmission times for the data frames to the successful transmission times.

For performance comparison, we also give the results of ALOHA protocol. In addition, considering the CFP traffic, we assume there are three CFP nodes in the network, i.e., $N_{CF} = 3$. Due to the dedicated GTS allocation, further we assume it as 1 or 2 GTS/sensor, therefore the duration of CFP in a superframe may be 3 slots or 6 slots, which are noted as $SLOT_{CFP} = 3$ and 6, respectively. Then we consider seven scenarios in the simulations as follows, ALOHA, IEEE 802.15.4 unslotted CSMA-CA, slotted CSMA-CA (duty cycle (DC) = 1, 0.5, 0.25, without CFP; DC = 0.5, $SLOT_{CFP}$ = 3, 6). Fig. 3 plots the average delay versus the number of sensor nodes with contention traffic, N_C. Relatively, unslotted CSMA-CA has the lowest delay. In the slotted version, there is a little deterioration for the delay performance, and later we will explain it referring to the throughput in Fig. 5. With the duty cycle decreases, the capacity of a CAP decreases and the contention makes the delay performance deteriorate drastically. When the duty cycle equals to 0.25, the delay performance of the slotted CSMA-CA is worse than ALOHA in all N_C cases. The CFP traffic also deduces the transmission capacity of the CAP. With the number of the allocated GTSs increases, the average delay of CAP traffic increases. For CFP traffic, due to the dedicated slot allocation, its delay only depends on the superframe structure and the related GTS allocation. Once there are more GTSs allocated to a node, more CFP frames kept in the buffer can be transmitted in one superframe, which increases the average delay of all the CFP frames. In the CFP scenarios, when $SLOT_{CFP}$ = 3 and 6, the average delay of CFP traffic is stable as 124ms and 127ms, respectively.

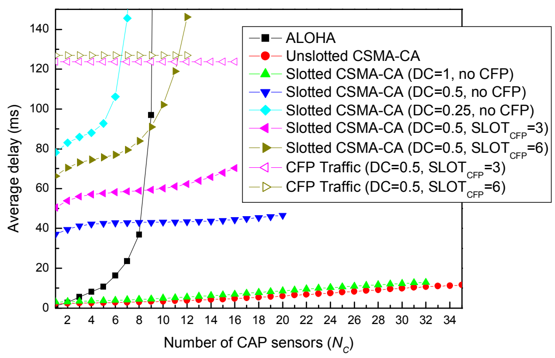

Figure 3. Average delay versus N_C

For 15.4 CSMA-CA protocol, the only reason to drop a frame is that the MAC process abnormity, which includes two cases. One is the channel access failure due to the number of backoff processes is greater than *macMaxCSMABackoffs*. And the other is an acknowledgment of a data frame is still not received after *macMaxFrameRetries* retransmissions. Fig. 4 shows the frame dropping rate as a function of N_C. As contention scheme, the dropping rate increases fast when the traffic load is close to the network capacity. Any reasons which may decrease the capacity of the CAP, such as the decreased duty cycle or the increased CFP duration, also make the dropping rate of CAP frames higher. In addition, it's worth noting that even for CFP traffic, if the dedicated GTSs are not sufficient for the generated traffic frames, CFP can not guarantee the successful transmission of all CFP frames. Those buffered frames which cannot be transmitted in the current superframe will be dropped in the next superframe. For example, when $SLOT_{CFP} = 3$, the dropping rate of CFP frame is 2.5%.

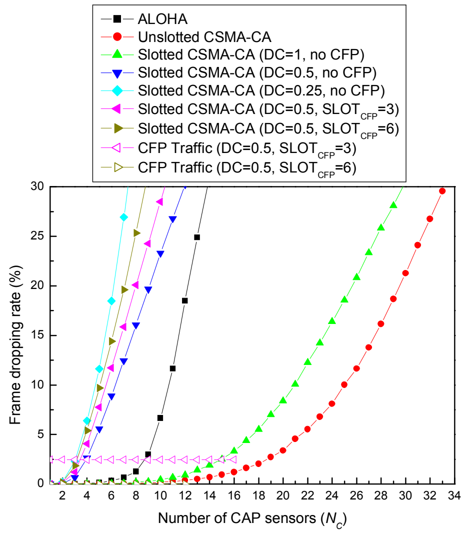

Figure 4. Frame dropping rate versus N_C

As we know, the requirements of quality of service (QoS) always depend on the application. The frame dropping rate is thought as one of the measures of the network dependability. In this paper, if we consider the maximum allowable frame dropping rate as 5%, under the predefined traffic model, the maximum number of CAP nodes, N_{max} can be supported in a WBAN is obtained as follows. For ALOHA, N_{max} = 9. For unslotted CSMA-CA, N_{max} = 21. For slotted CSMA-CA, N_{max} = 17, 4 and 3 in case of the duty cycle is configured to be 1, 0.5 and 0.25, respectively. When the duty cycle is set to be 0.5 and there is CFP traffic while the number of the GTSs is not beyond 6, N_{max} decreases from 4 to 3. Referring to the average delay (in Fig. 3), another aspect of the QoS, in all N_{max} cases the worst one happens in ALOHA where the average delay is 96.98ms and the best one is in unslotted CSMA-CA where it equals to 6.48ms. All of these delay cases which are not beyond one hundred milliseconds are considered as acceptable for the general WBAN applications.

Fig. 5 depicts the normalized throughput as a function of N_C. As the traffic load of the network increases, the throughput of each MAC protocol increases till the maximum value and then falls down due to the saturated contention. When the number of the contention nodes equals to 30, unslotted CSMA-CA achieved the maximum throughput 0.435. For slotted CSMA-CA, the maximum throughput value is 0.384, 0.167 and 0.094 when the number of the nodes is 29, 16 and 7 in the condition of the duty cycle equals to 1, 0.5 and 0.25, respectively. If the CFP traffic exists in the active period of a superframe, the capacity of the CSMA-CA will be deduced. When the number of GTSs is 3 and 6, the maximum throughput of CSMA-CA decreased from 0.167 to 0.14 and 0.114 in cases of 13 and 10 CAP nodes, respectively.

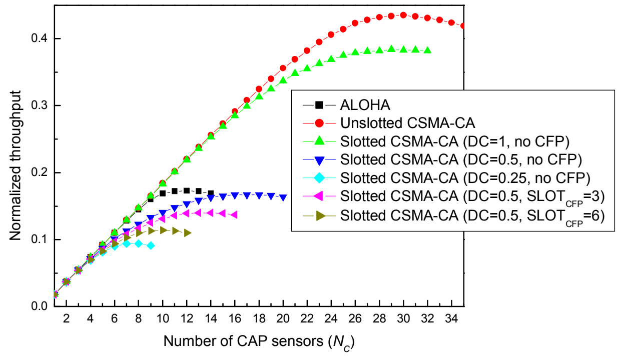

Figure 5. Normalized throughput versus N_C

In general, the slotted method has better performance than the unslotted one [13]. But we have to pay attention to that there is a limitary condition that the propagation delay of the packet cannot be negligible. While in the BAN, if we consider the distance is 3 meters and the payload size of one packet is 20 bytes, the ratio of the propagation delay to the packet transmission time will be lower than 0.00001 under 250 kbps channel rate. It's small enough and that's why the propagation delay is neglected in the simulation. Therefore, according to the results in [13], when the propagation delay goes to zero, for the nonpersistent CSMA, which is the most similar to the IEEE 802.15.4 MAC, the throughput in the unslotted scheme will achieve the same value with it in the slotted one. However, for IEEE 802.15.4 MAC, the performance of the slotted version is worse due to the following two reasons: (1) the influence of the beacon frame. The slotted MAC is beacon enabled. Not only the beacon frames consume the channel resource, but also the frame before the beacon can not be transmitted if it can not be done before the end of the current superframe. (2) the influence of the CW. In the slotted CSMA-CA, there are two CWs for each try of transmission. The ratio of the CW to the transmission time of one data frame is 2/3.5 = 0.57, which results in the lower throughput. As references, the conclusions in [6] and [10] are consistent with our results.

From Fig. 6 which plots the average power consumption (mW/node) versus N_C, we can see that the power consumption mainly depends on the duty cycle. The least power consumption exists when the duty cycle equals to 0.25, not only for each sensor node but also for the BC. However, because there is no inactive period in the MAC process, ALOHA, unslotted CSMA-CA and slotted CSMA-CA (DC = 1) always consume the most energy. That shows the best way to conserve power is to turn off the radio subsystem whenever possible. Note that in the energy model considered in our simulation, during the active period a node in transmitting mode consumes less energy than in other modes. Therefore, as N_C increases, there are more retransmissions due to the contention and the power of each sensor node decreases then. In other words, in the same duty cycle, the power consumption of sensor nodes changes slightly according to the possibility of transmission, i.e., large T_{ratio} results in less consumed energy, which can be proved in Fig. 7 where the relationship of T_{ratio} versus N_C is plotted and T_{ratio} increases as N_C increases. In addition, the CFP traffic makes the CAP traffic congested and T_{ratio} increases, and then the energy consumption decreases. For example, in the condition of half active period (DC = 0.5), a CAP sensor node in case of 6-GTS CFP consumes less energy than it in 3- and 0-GTS CFP. To sum up, to save the energy consumption, the lower duty cycle is the best choice but with the cost of the reduction of the network capacity.

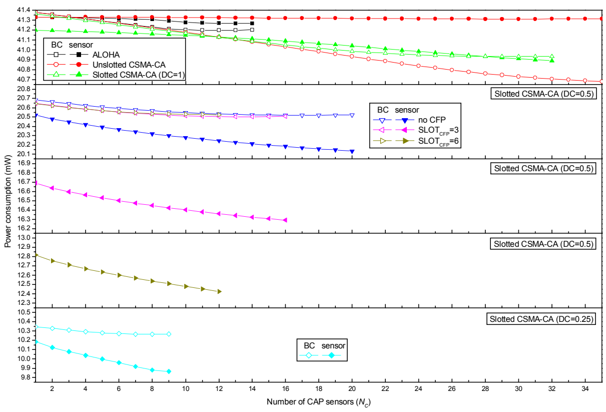

Figure 6. Power consumption versus N_C

The parameter of T_{ratio} can also be used to evaluate the transmission efficiency of a protocol. In ideal condition, T_{ratio} equals to 1, which means for any frame, only one time of transmission can make it successful and there is no any retransmission at all. As we can see in Fig. 7, as the number of the nodes increases T_{ratio} increases fast, which also proves the network becomes saturated. And also, the CFP traffic will deduce the transmission efficiency of the CAP and then T_{ratio} increases further if there is CFP traffic in the network.

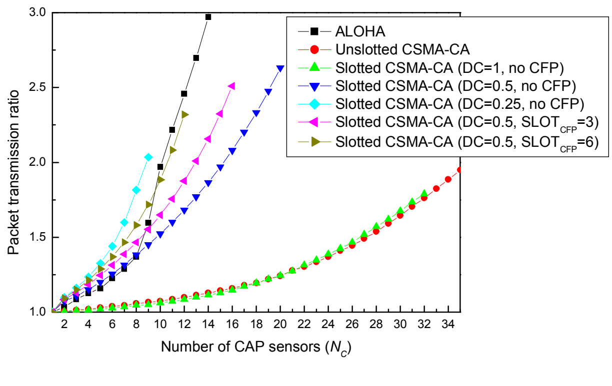

Figure 7. Transmission ratio versus N_C

IV. Conclusions

Considering the traffic characteristics of WBAN, this paper studied the application of IEEE 802.15.4 on it. It's worth noting that our effort aims to study the capacity of IEEE 802.15.4 MAC, therefore the traffic load of the network is relatively heavy to the real WBAN such as the medical application. According to the simulation in this paper, it's showed that the unslotted version of IEEE 802.15.4 MAC has higher throughput and smaller latency than the slotted one. But considering the energy consumption in a WBAN, the unslotted MAC is not a good option because the network is always in active mode. To save the energy consumption, the low duty cycle is a good choice but with the cost of the reduction of the network capacity. Besides, for time critical traffic, the GTS can not guarantee the successful transmission of a frame if there is not enough dedicated GTS allocation.

In the future, to design the novel MAC for a WBAN, the superframe structure with low and adaptive duty cycle is suggested. Also, to get the convincing results, the network simulation has to consider the channel model of the WBAN. Other than that, considering the possible application where the sensor nodes response for the coordinator's command such as the tiny medical robot in the body, the downlink traffic from the WBAN coordinator is needed to be studied.

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