Modification of 802.15.4 MAC for Body Area Networks Applications

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Abstract – Body area network (BAN) is an emerging field in the healthcare industry. These networks have stringent technical requirements and to suite these requirements suitable communication standard is desired. Out of the available communication standards, IEEE 802.15.4 seems to be the nearest suitable candidate for BAN. However research efforts carried out till now have shown unsuitability of IEEE 802.15.4 for applications involving high data rates or large number of persons. Particularly scalability is the main issue required to be handled. Accordingly current scenario necessitates to have research efforts in modifying IEEE 802.15.4 standard so as to suite BAN applications. This paper presents modification in the superframe structure of existing 802.15.4 and verifies the modified structure for single BAN in terms of throughput, power consumption and delay . Simulation results show superior performance of modified 802.15.4 MAC compared to that of the existing IEEE 802.15.4 MAC. For higher data rate, the existing 802.15.4 showed poor performance for throughput ,delay and power consumption parameters. However for the modified protocol, the throughput showed no deterioration for high data rate applications. The end to end delay also showed remarkable improvement and reached only 50 ms for high data rates. This was around one-sixth the delay obtained for the existing 802.15.4 standard. The end to end delay started rising exponentially for existing 802.15.4 after 9 leads only. Also the power consumption showed reduction by almost 17 percent even with increased number of leads. Hence by modifying superframe structure scalability issue have been addressed.

Keywords– IEEE802.15.4, Superframe, WBAN , WPAN

I. Introduction

According to the Department of Health and Human Services, the elderly segment of the population (65+) will continue to grow significantly in the future and there is a need to have some healthcare units to look after these people. To address this issue a Wearable body area network (WBAN) concept has arisen. It is the emerging technology that is particularly useful for wearable monitoring application. In near future WBAN will be able to provide efficient healthcare services to common man and help in ongoing clinical research. Also a task group 802.15.6 is established which will be dedicated only to BAN applications. Existing research in this area has highlighted some issues involved in practical implementation of BAN. Some of the issues are scalability, power optimization, and reliability [1]. There is no existing communication standard which fully meets requirements of BAN. But through research and experiments carried out so far it is observed that some modifications to IEEE 802.15.4 can be made so as to suit the stringent requirements of BAN. This very conclusion has lead IEEE to establish a separate task group IEEE 802.15.6 for BAN.

A. Related work

IEEE 802.15.4 is a low-rate low-power WPAN suitable for sensor n/w applications. As 802.15.4 seems to be a suitable candidate for medical BAN, researchers have presented their contribution for evaluating performance of 802.15.4. Extensive evaluation of 802.15.4 for BAN brought about its shortcomings. Reference [2] cited the scalability issue in MAC. It stated that existing IEEE WPAN technologies have major constraints to efficiently support large number of medical sensors. The maximum of 16 slots is not enough for ECG and EEG applications. Secondly, coexistence of 802.11 and 802.15.4 poses interference problems. Also in [3] it was stated that IEEE 802.15.4 protocol offers limited answer in its non -beacon form.

Research work done till now have suggested about modification of 802.15.4 standard. But no paper have given actual modifications till now. This paper presents modification in the superframe structure of 802.15.4 and shows results for throughput, delay and power consumption by using modified superframe structure. Results are produced by using Qualnet as a simulation tool for this analysis.

The rest of this paper is organized as follows. Section II gives an overview of BAN. Section III presents the overview of existing IEEE 802.15.4 MAC. Section IV presents calculations for modification of superframe structure. The simulation model and results are presented in section V. Section VI offers a final discussion and concludes the paper by a brief outlook on future work.

II. Overview of BAN

BAN, as far as the class of communication is concerned, have been derived from the concept of wireless local area network (WLAN). The term BAN was first coined at Massachusetts Institute of Technology & Science, USA during the year 2002 by the researchers [3]. The BAN connected sensors continuously measure and transmit vital constants, audio, images or positioning information to health service providers and brokers. This way the BAN

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facilitates remote monitoring of vital signs of patients anytime and everywhere and hence enables proactive disease prevention and management. BANs can be classified as external BAN and implant BAN. Table I shows certain distinct features for BAN [3] .

Table I - BAN Draft Specifications

Distance	2 m standard 5 m special use
Network Density	2 - 4 nets / m2
Network Size	Max: 100 devices / network
Power Consumption	~1 mW / Mbps
Latency (end to end)	10 ms
Network setup time	< 1 sec (Per device setup time excludes network initialization)
Frequency band	Regulatory and/or medical authorities approved communication bands for in and around human body

The task group 802.15.6 for BAN have proposed following MAC functionalities for communication standard to be used for BAN. [5]

1. Support of scalable data rates.
2. Support of no. of devices.
3. Medical application traffic latency(<125 ms)
4. Low power consumption.
5. Coexistance of atleast 10 BANs in the proposed on body communication band.
6. Support of security.

A. Suitability of 802.15.4b for BAN

For short-range BANs, the frequency bands below 1GHz are preferable in terms of body attenuation and low-cost transceiver implementation. However, the available bands are either crowded, as is the case in the 433MHz spectrum range (such as MICS and WMTS), or not usable on a global basis. Currently, the worldwide 2.4GHz ISM band appears to be the most promising spectrum, although it already accommodates a number of concurrent connectivity standards, such as IEEE 802.15.1 Bluetooth, IEEE 802.11b/g Wireless LANs and IEEE 802.15.4 Wireless PANs. Also IEEE 802.11b WLAN technology is power hungry to such an extent that users would need to replace the batteries after only a few hours of operation. In this respect the wireless personal area standards, IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 are much better suited for battery-powered body area networks.
However, IEEE 802.15.4 scores over IEEE 802.15.1 due to its faster, more flexible and scalable networking features along with less consumption of energy, processing and memory resources. It also supports standard-based security. In addition, IEEE 802.15.4 lays the foundation for ZigBee adding multi-hop networking and an application support layer. ZigBee's multi-hop routing capability enables wireless connectivity of ambient sensors scattered all over the user's home. Therefore, as of today, IEEE 802.15.4b appears to be the standard wireless technology of choice for BANs.
BAN for medical applications have variable data rates based on the applications. Following table gives data rates for various medical applications.

Table II : Data rates for medical applications[3]

Application	Data rate
ECG	192 kbps(6kbps/lead, 32 leads)
EEG	86.4 kbps (3.6 kbps/lead, 24 leads)
Drug Delivery	<16 kbps
Deep brain simulations	<320 kbps
Heart Rate	0.05 kbps
Blood Pressure	0.05 kbps
Body Temperature	0.05 kbps

III. Overview of IEEE 802.15.4 MAC

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 (contention Access period). An example of the superframe with CAP, CFP and inactive period is shown in figure 1 [4].

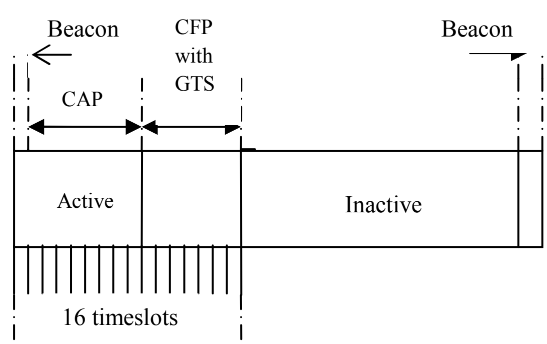

Fig. 1 – Superframe structure of existing IEEE 802.15.4 MAC

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. Thus 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

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with GTS. The first scheme is working in the beaconless mode and the remaining two schemes are both working in the beacon enabled mode.

A. Why modification in 802.15.4 MAC?

From the simulation results obtained for IEEE 802.15.4 MAC protocol, it was found that it provides a limited answer to the low data rate applications of BAN. As shown in figure 5a (results section) the throughput obtained for the various modes of 802.15.4 appears to be deteriorating with increase in number of leads. Moreover, for high data rate applications like ECG, EEG, large delays were obtained for the CAP which makes it highly unsuitable for such applications. Also, with the restriction of the maximum number of GTS slots being 7, these applications cannot be supported as the requirement is more than 7 leads (ECG-32 leads, EEG- 24 leads). Hence, suitable modifications are required in the superframe structure of 802.15.4 MAC so as to make it suitable for BAN applications.

B. Modified MAC structure of 802.15.4

IEEE 802.15.4 protocol provides flexibility to adjust the total superframe length by adjusting the beacon order (0≤BO≤14) and also the active portion in the superframe by adjusting the superframe order (0≤SO≤14). However it possesses restriction on the total slots in the superframe being 16 and the maximum number of GTS slots being 7. These two parameters are modified so that they can support BAN applications.
The proposed MAC protocol is very similar to the beacon enabled mode of IEEE 802.15.4 MAC protocol. The proposed superframe structure is shown in figure 2.

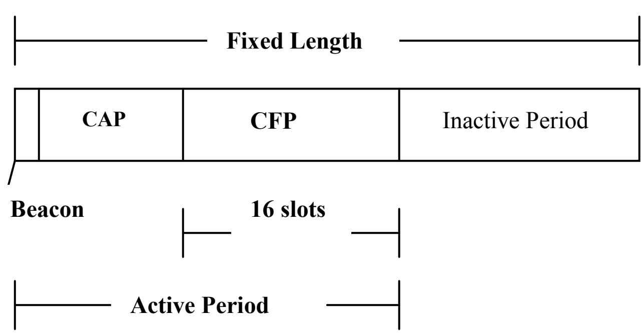

Fig. 2 - Proposed Superframe Structure.

The superframe is of fixed length bounded by network beacons and is divided into equally sized slots.

a) BEACON:

The beacon frame is sent in the first slot of each superframe. The beacons are used to synchronize the attached devices, to identify the coordinator and to describe the structure of superframe. The superframe can have an active and an inactive portion. The active portion consists of contention access period (CAP) and contention free period (CFP).

b) CAP:

The CAP is used only for network management activities and GTS maintenance. The length of the CAP is always fixed.

c) CFP:

The CFP shall start on a slot boundary immediately following the CAP and extends to the end of the active portion of the superframe. It contains various GTSs (Guaranteed Time Slots). The length of the CFP is determined by the total length of all of the combined GTSs. No transmissions within the CFP shall use a CSMA-CA mechanism. A device transmitting in the CFP shall ensure that its transmissions are complete one IFS (Inter Frame Space) period before the end of its GTS. The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP. IFS time is the amount of time necessary to process the received packet by the PHY. Transmitted frames shall be followed by an IFS period. A GTS allows a device to operate on the channel within a portion of the superframe that is dedicated exclusively to that device. A GTS shall be allocated only by the coordinator. A single GTS can extend over only one superframe slot. The management of the GTSs shall be undertaken by the coordinator only. The device will request for the GTS in the CAP.

d) Inactive Period:

The inactive period exists only when all the GTS slots are not used. During the inactive mode, the sensor may not interact with its coordinator and may enter into a low-power mode.

e) Energy Saving:

As the data is sent only in the GTS slots, it has the inherent advantage of power saving over existing 802.15.4. Once the sensor is allocated a slot, it has to remain active only to receive the beacon and during its reserved slot to send the data.
The following section calculates the number of GTS slots, the slot duration and the total superframe length.

IV. Calculations

Having seen the basic functionality of the proposed protocol, calculation of superframe length, duration of the CAP and the number of GTS slots is done.
The basic idea is to first find the appropriate superframe orders (SO) which satisfy the requirements. Once they are found, the various superframe lengths and the slot durations which could support the BAN applications are obtained.
Reference [7] calculates the maximum number of CFP slots available in 802.15.4 as a function of SO. A similar approach is followed, with the difference being the total number of slots kept variable and not fixed at 16.
The various medical applications along with the parameters they require for monitoring are shown in table III.

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Table III - leads required for various medical cases

Medical cases	Parameters to be monitored	Number of leads
Ischemic heart disease	ECG + blood pressure	33
Patient on ventilator	ECG + SPo2 + blood pressure + pulse+ body temperature	36
Epilepsy (convulsions)	EEG +ECG+ pulse rate+ blood pressure +SPo2 + temp.	60
Liver failure	EEG+ Ammonia +SPo2	34

From the table, it is evident that the maximum number of leads required for monitoring are 60. Hence, the frame length which could support up to 64 leads (flexibility of 4 slots is provided) are studied. Also, the frame is designed such that it can support high data rate applications (up to 1 Mbps).
MAC header is also modified for the BAN application so that overheads can be reduced.
The MAC frame format is shown in figure 3.

2	1	0/2	0/2/8	0/2	0/2/8	variable	2
FC	SQ	Dst. PAN address	Dst. address	Src PAN address	Src address	Payload MSDU	FCS

Fig. 3- Modified MAC frame format

FC- Frame control, SQ- Sequence number,
Dst–Destination , Src - Source
All numeric fields shown above are in bytes.

The source address field (Src address) specifies the sensor (that is placed on the body) sending the data and the source PAN field (Src PAN address) helps in identifying the person (every person has 1 PAN to which all sensors are sending the data). The 15.6 task group limits the number of sensors on the human body as 256 maximum and hence 8 bits (1 byte) are sufficient to represent the source address. The source PAN address is kept at 2 bytes (maximum allowed). Also, the destination for any packet is already known (the main hospital server) so the destination address fields are eliminated. So, the MAC header reduces to

$$\textit{MAC header} = 2+1+2+1+2 = 8 \textit{ bytes.} \qquad (1)$$

Hence the total number of CFP slots required for 64 leads $= (64 * 1.7415)/ 2^{SO}$. (2)

Also the applications like ECG have a data rate of 192 kbps with 32 leads sending at 6 kbps each. Thus each lead sends a 36 byte payload every 48 ms. Similarly EEG has a data rate of 86.4 kbps with 24 leads sending at 3.6 kbps each. Thus each lead sends a 36 byte payload every 80 ms.
Thus the total superframe length has to be less than 40 ms or else the ECG lead would have to suffer unnecessary queuing delay.

*Total Superframe duration= Total no. of slots * 1 slot duration*
$= T * 240*2^{SO}\ \mu s.$ (3)

In addition, the total CFP slots available must be greater than the number of CFP slots available in the frame.
Thus, from Equations (1), (2), (3)

$CFPmax = T - (11.766/2^{SO}) \geq (64 * 1.7415)/ 2^{SO}$
And $T * 240*2^{SO}\ \mu s. \leq 48\ ms$

The following table depicts the slot calculations for various superframe orders (SO).

Table IV – Slot calculations for various superframe orders (SO)

SO	0	1	2	3
CFP slots required/lead	2	1	1	1
Total CFP slots required	128	64	64	64
Minimum CAP and beacon slots	12	6	3	2
CFP max available	T-12	T-6	T-3	T-2
Superframe duration (µs)	240*T	480*T	960*T	1920*T
Minimum T required	140	70	67	64
Minimum superframe duration (ms)	33.6	33.6	64.32	122.88
Is So satisfying the conditions	yes	yes	no	no

Further SOs are not shown in the table as the superframe duration doubles with every SO and already for SO=3, superframe duration is much greater than 48 ms. As shown in the table, only 2 SOs i.e. 0 and 1 satisfy our requirements. But for SO=0, two slots would be required for every lead. Reference [8] recommends usage of fewer GTS slots. Hence SO=1 is taken. For SO=1, minimum CAP and beacon slots required are 6. But, 8 slots are provided, so that the network management activities can be easily completed.
Thus, we have a total of 64+8=72 slots in the superframe each of duration 480 µs with 8 CAP (and beacon) slots and 64 CFP slots. Thus, the proposed frame structure is as shown in figure 4.

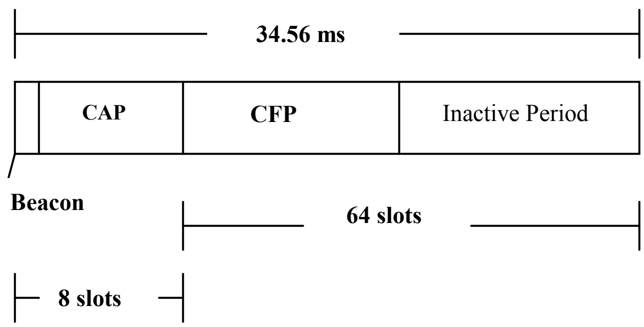

Fig. 4 – Modified superframe structure

As shown in figure 4 , when all 64 CFPs are not used for data transfer, the remaining slots are used for inactive period.

V. Results

Qualnet is used as a simulation tool for analysis. The various scenarios that were simulated for the existing and modified protocol are listed below. For every scenario, the comparison of existing protocol and modified protocol is shown. Single BAN with low and high data rate application have been considered for simulation.

A. Scenario 1: Low data rate application for single BAN. A single BAN consisting of one BAN coordinator (BC) and several sensor nodes (SNs) is choosen for simulation.
Here single BAN refers to one patient. And the effect of increase in number of leads on performance metrices have been shown.

Simulation setup:
Simulation time : 10 min.
Phy. Layer : IEEE 802.15.4
MAC layer: IEEE802.15.4
Beacon order : 4
Data rate : 100 bps/ lead
Superframe Order : 3(Duty cycle= 50%),
4(Duty cycle = 100%)
In all the simulation plots, unslotted refers to non beacon mode of IEEE 802.15.4 whereas DC= 0.5 and DC=1 refers to beacon enabled mode of IEEE 802.15.4

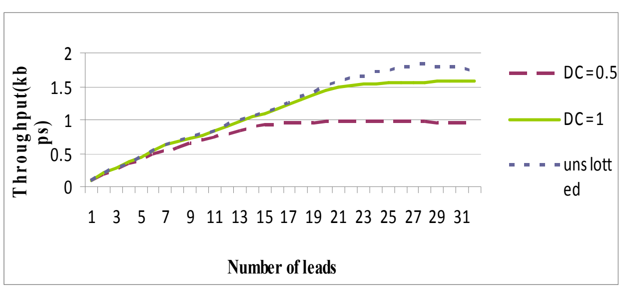

Fig. 5a – Throughput (kbps) vs. no. of leads

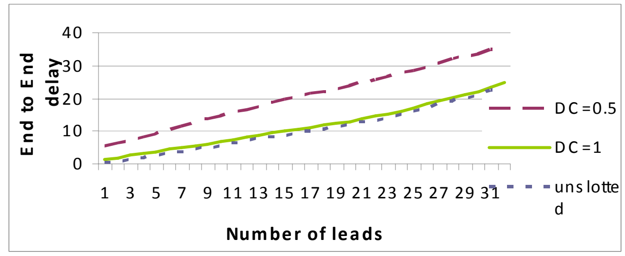

Fig. 5b – Delay (ms) vs. no. of leads

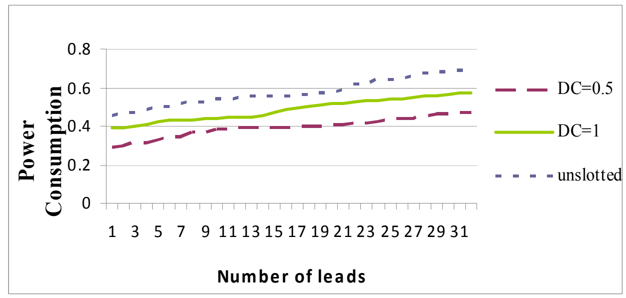

Fig. 5c – Power consumption (mW) vs. no. of leads

As shown in figure 5a the throughput obtained for the various modes of 802.15.4 appears to be deteriorating with increase in number of leads. This feature is due to the fact that in 802.15.4 CAP, every lead has to compete with other leads when it has to send data using slotted CSMA-CA mechanism for beacon mode and unslotted CSMA-CA for non beacon mode. Thus with increase in number of leads throughput decreases and delay increases. Unslotted mode gives better results for these parameters but power consumption is highest. This is due to the fact that node has to be awake for longer time period. From the graphs it can be seen that beacon mode with 100% duty cycle provides the best compromise between all three mechanisms of CSMA-CA.

B. Scenario 2 : High Data Rate Application for single BAN**.**
In this scenario, 1 patient was considered and the effect of increase in data rate as well as number of leads on the performance metrics was studied by using both existing and modified superframe structure.
The data rate considered was **6 kbps/lead**.
The graphs for throughput, end-to-end delay and power consumption using existing and modified superframe structure are shown in figures. *Duty cycle(DC) = 1 indicates existing superframe structure and BAN indicates modified superframe structure.*

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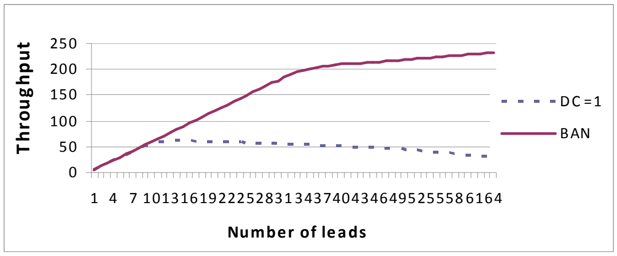

Fig. 6a – Throughput (kbps) vs. no. of leads

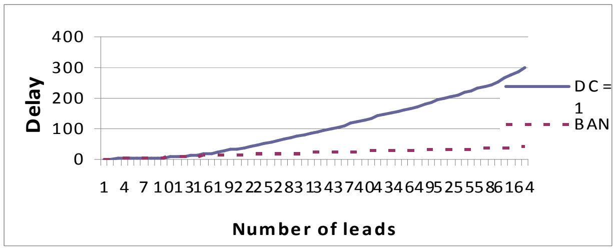

Fig. 6b – Delay (ms) vs. no. of leads

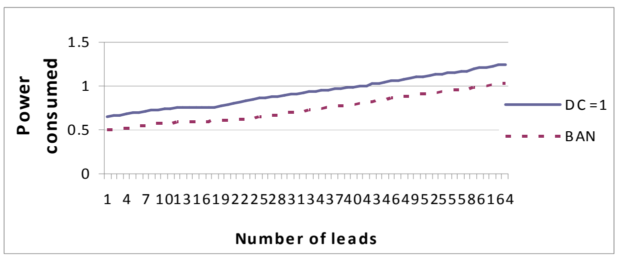

Fig. 6c – Power consumed (mW) vs. no. of leads

As shown in figure 6(a, b, c) when the data rate of every lead was increased from 100 bps to 6 kbps, the performance of existing 802.15.4 (DC=1) get worsened.
The throughput started deteriorating just after 9 leads (figure 6a compared to figure 5a). However for the modified protocol (BAN), the throughput showed no such deterioration even when the number of leads become 64. The end to end delay also showed remarkable improvement and reached only 50 ms even for 64 leads. This was around one-sixth the delay obtained for the 802.15.4 beacon mode with duty cycle as 100 percent. The end to end delay started rising exponentially for 802.15.4 after 9 leads only (figure 5b). Also the power consumption showed reduction by almost 17 percent even when the number of leads were increased to 64 (figure 6c).
Thus, the modified protocol easily supports the high data rate applications even upto 64 leads for 1 person.

VI. Conclusions and future work

This paper have presented the modified superframe structure of 802.15.4 and the results shows tremendous improvement in the performance metrics.
It was found that for low data rate applications, 802.15.4 provided a limited answer to the scalability issue in its beacon mode (with DC=1) at the expense of slight degradation of the QoS parameters and slightly increased power consumption. For high data rate applications, even for a few number of leads, this mode was highly unsuitable because of the significant degradation of QoS parameters after 9 leads. Hence it was concluded that CAP of IEEE 802.15.4 cannot support all types of BAN applications.
For accommodating all types of data rate applications of BAN, following modifications in the 802.15.4 MAC superframe are suggested in this paper.

a) Frequency band used: 2.36-2.4 GHz.
b) The superframe consisted of 72 slots.
c) CAP is of 8 slots including beacon frame and is fixed.
d) Maximum number of GTS slots in one superframe = 64.
e) 1 Slot duration= 480 microseconds.
f) The inactive period exists in the unused CFP slots.

With above modifications in the existing 802.15.4 protocol, all QoS parameters get improved.
However research work in BAN area is still in the primitive stage and hence issues such as security, sensor design need to be resolved. Other than that, considering the possible application where the sensor nodes respond 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. This issue is still in dark.

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