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Channel Modelling and Optimization of Wireless Body Area Network (WBAN)

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***Abstract*— IEEE 802.15.4 is a standard used for low data rate Wireless Personal Area Networks (WPANs). It offers device level connectivity in applications with limited power and relaxed throughput requirements. Devices with IEEE 802.15.4 technology can be used in many potential applications such as home networking, industry/environments monitoring, healthcare equipments etc. due to its extremely low power features. Medium Access Control layer (MAC) of IEEE 802.15.4 plays an important role in the performance of Wireless Body Area Network (WBAN). The unique feature of this MAC layer is the superframe structure, which allows devices to access channels in a Contention Access Period (CAP) or Collision Free Period (CFP) and use beacon based synchronization mechanism. Performance evaluation study reveals on Throughput and Packet Delivery ratio which are the tradeoffs inherent in this MAC protocol. The proposed work on IEEE 802.15.4 MAC includes the following features:**

1) Beacon based mode and non-beacon enabled mode

2) Association tree formation and Network Configuration

3) Orphaning and co-ordinator relocation

4) Carrier sense multiple access with collision avoidance (CSMA-CA), both un-slotted and slotted

5) Direct, indirect and guaranteed time slot (GTS) data transmissions

Considering the above factors, strategy is to maximize the Throughput and Packet Delivery ratio for WBAN. This analysis enables the user to choose the suitable 802.15.4 MAC device depending on the health condition of his/her body. Thus depending on the performance different types of devices are designed.

Keywords: IEEE 802.15.4, Wireless Body Area Networks (WBANs), RFD, FFD, Medium Access Control (MAC) layer, Superframe structure, Performance Metrics.

I. INTRODUCTION

The combination of Wireless Body Sensor Network (WBSN) and Wireless Personal Area Network (WPAN) forms a Wireless Body Area Network (WBAN). It allows the integration of intelligent, miniaturized, low-power, invasive/non-invasive sensor nodes in and around a human body that are used to monitor body functions and surrounding environment. Each intelligent node has enough capability to process and forward information to a base station for diagnosis and prescription. Illustration of WBAN is shown in Fig. 1. It is used to develop a smart and affordable health care system which can be a part of diagnostic procedure, maintenance of the chronic condition, supervised recovery from a surgical procedure and can handle emergency events. Common objective in WBAN is to achieve maximum throughput, minimum delay and maximize the network lifetime by controlling the main sources of energy waste i.e., collision, idle listening, overhearing, and control packet overhead [1].

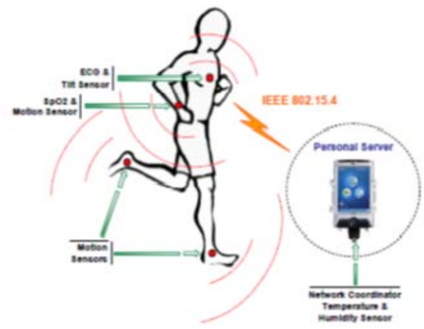


Fig. 1. Illustration of WBAN [1]

A. Why 802.15.4 MAC?

The development of low-power MAC protocol for WBAN has been a hot research topic for the last few years. Some of the MAC Protocols available are: S-MAC, T-MAC, D MAC, med MAC, B-MAC, G-MAC and IEEE 802.15.4 etc. Among all, the IEEE 802.15.4 MAC is the most promising for wireless sensor networks [2] because of several reasons: It is well layered and provides a combination of link management mechanisms that can be enabled selectively depending on the user configuration. Also has a comprehensive specification which addresses the basic deployment requirements such as network configuration, management and security services to guarantee data confidentiality and integrity. It is the first standard which allows simple sensors and actuators to share standard wireless platform. Highly configurable and supports acknowledgements which can be turned on and off based on the requirement. It also achieves efficient reliability with fewest numbers of retransmissions.

B. Device Classes

There are two kinds of devices used in WBAN which can be classified as Reduced Functionality Device (RFD) and Full Functionality Device (FFD). Star topology is an example for RFD. Device can communicate only with the Network Coordinator and devices cannot become a Coordinator as shown in Fig. 2. Any topology i.e., Peer- to - peer or Cluster- Tree can be used as an example for FFD. All devices have the Network Coordinator capability and device can communicate with any other device as in Fig. 3.

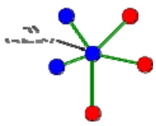


Fig. 2. Star Topology [2]

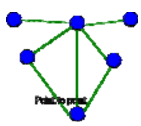


Fig. 3. Peer-to-Peer Topology [2]

II. 802.15.4 ARCHITECTURE IN NS2

The Architecture for 802.15.4 standard is entirely based on OSI model in the network. Each layer is responsible for one part of the standard and offers services to higher layers. 802.15.4 Standard defines both Physical and MAC layers of Zigbee Standard as shown in Fig. 4. Main features of PHY layer are activation and deactivation of the radio transceiver, Energy Detection (ED), Link Quality Indication (LQI) for received packets and Clear Channel Assessment (CCA). MAC sub-layer provides an interface between the Service Specific Convergence Sub-layer (SSCS) and PHY. MAC Sub-layer handles all access to the physical radio channel and is responsible for providing services to the Application layer through two groups: MAC Data Service and MAC Layer Management Entity. MAC Layer Management Entity (MLME) is the Management Entity included in MAC Sub-layer. This is accessed through MLME-SAP. MLME also responsible for maintaining a database of managed objects referred to as the MAC sub-layer PIB. MAC data service is accessed through the MAC Common Part Sub-layer (MCPS) data SAP.

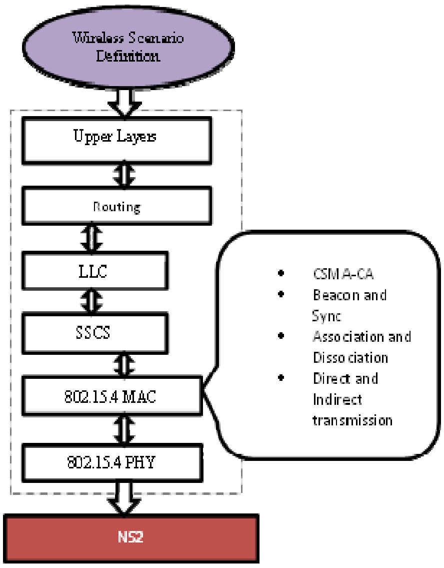


Fig. 4. Architecture of 802.15.4 MAC [2]

A. PHY Layer

The PHY layer specification dictates how IEEE 802.15.4 may communicate with each other over the wireless channel. Use of frequency bands are allowed with varying data rates. The bit rates are 20 Kbps in the European for 868 MHz band (868-868.6 MHz) with a single channel between this band, 40 Kbps in the North American for 915 MHz band (902-928 MHz) with 10 channels and 250 Kbps in the worldwide for 2.45 GHz band (2.4-2.4835 GHz) with 16 channels between this band. All these frequency bands are based on Direct Sequence Spread Spectrum (DSSS) spreading technique.

The 865 MHz and the 915 MHz radio map each data symbols onto a 15-chip PN sequence, followed by binary phase-shift keying (BPSK) for chip modulation. On the other hand, 2.45 GHz Industrial Scientific Medical (ISM) radio band maps each 4 bits of information onto a 32 chip PN sequence followed by offset orthogonal phase shift keying (O-QPSK). Fig. 5 shows an Operating frequencies and the channel utilization of those particular bands.

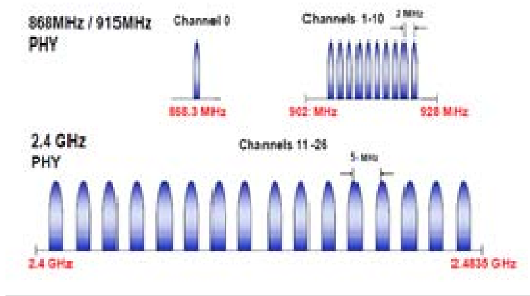


Fig. 5. Operating Frequencies and Bands [2]

B. 802.15.4 MAC Operational modes

MAC layer is responsible for Beacon Management, Channel Access, Frame Validation, Acknowledged Frame delivery, Association and Dissociation. The MAC supports two operational modes as described in Fig. 6.

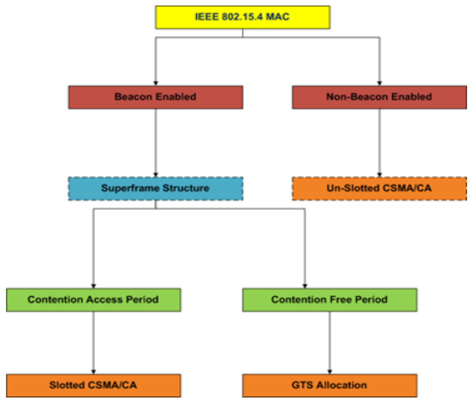


Fig. 6. IEEE 802.15.4 MAC Operational modes [2]

Non-Beacon Enabled mode: A network node can send data to the coordinator at its will by using unslotted CSMA-CA. And to receive data from the coordinator, the node must power up and poll the coordinator. Advantage is that the node's receiver does not have to regularly power-up to receive the beacon. Disadvantage is the coordinator cannot communicate at will with the node but must wait to be invited by the node to communicate.

Beacon Enabled mode: The network is fully synchronized as the coordinator sends out periodic packets or beacons.This mode uses the Superframe structure of 802.15.4 MAC.

C. Superframe Structure

Key feature of 802.15.4 MAC layer are the superframe structure, which allows devices to access channels in a Contention Access Period (CAP) or a Collision Free Period (CFP) and the beacon based synchronization mechanism [3]. The format of the superframe structure is determined by the coordinator. Structure of superframe is described by the values of macBeaconOrder (BO) and macSuperframeOrder (SO) as in Fig. 7. MacBeaconOrder defines the interval at which the coordinator shall transmit its beacon frames. MacSuperframeOrder defines the length of active portion of the superframe along with the beacon.

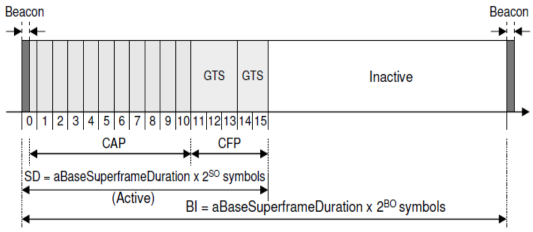


Fig. 7. Superframe format of 802.15.4 Beacon Enabled mode

For 0 <= BO <= 14, Beacon Interval (BI) = aBaseSuperframeDuration * 2^{BO}… (1.1)

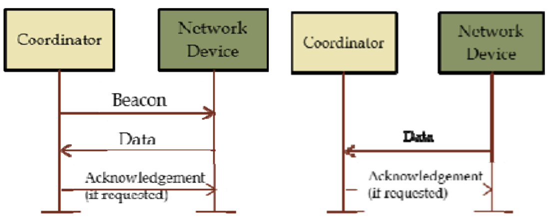
For 0 <= SO <= 14, Superframe Duration (SD) = aBaseSuperframeDuration * 2^{SO} … (1.2)

III. Data Transfer Models

There are three kinds of Data Transfer transactions exist in 802.15.4 w. r. t Beacon Enabled and Non-Beacon Enabled modes. First is the data transfer to a Coordinator from a device. Second is the data transfer to a device from a Coordinator. Third transaction is between two peer devices.

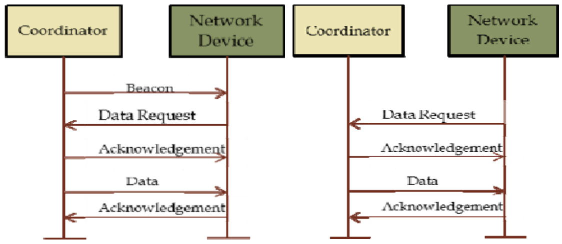
In case of Beacon Enabled mode, when a device wishes to transmit data to a coordinator, it listens for network beacon. If beacon found, device start synchronizing to the Superframe Structure. At a particular time, device transmits data using Slotted CSMA-CA to the coordinator [4]. Acknowledgement frame is optional. But in case of Non-Beacon Enabled Mode, device transmits data frame using un-slotted CSMA-CA to the coordinator [5]. Acknowledgement is again an option. Sequences are summarized in Fig. 8(A) and Fig. 8 (B) respectively.

In case of Beacon Enabled mode, when a coordinator wishes to transmit data, it indicates in the network beacon that the data is pending. Device listens for network beacon and transmits MAC command requesting data using slotted CSMA-CA. Acknowledgement frame is sent from the coordinator for data request and pending data frame is sent to the device immediately after the acknowledgement. But in Non-Beacon Enabled mode, Coordinator stores the data for the appropriate device to make contact and request the data. This contact is done by transmitting the MAC command requesting the data, using un-slotted CSMA-CA, to the coordinator at an application-defined rate. This data request command is acknowledged by transmitting an acknowledgement frame. If a data frame is pending, coordinator transmits the data frame to the device using un-slotted CSMA-CA. If no data frame is pending, this is indicated by the coordinator in the acknowledgement frame or data frame with a zero-length payload. Sequences are summarized in Fig. 9(A) and Fig. 9(B).



(A) Beacon Enabled (B) Non-beacon Enabled

Fig. 8. Communication to a coordinator in 802.15.4 MAC [6]



(A) Beacon Enabled (B) Non-beacon Enabled

Fig. 9. Communication from a coordinator in 802.15.4 MAC [6]

In case of Peer-to-Peer transaction, every device may communicate with every other device in its radio sphere of influence. Devices wishing to communicate must be constantly synchronized with each other.

IV. Starting And Maintaining Bans

The working of Body Area networks (BAN) is shown in Fig. 10 which describes all the modules involved.

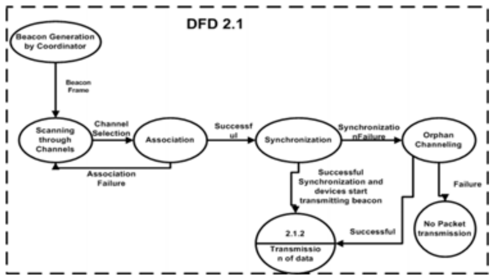


Fig. 10. Data Flow Diagram for BAN

A. *Channel Scanning*

All devices are capable of performing Passive and Orphan scans across a specified list of channels. But FFDs are able to perform Energy Detection (ED) and active scans as well [7], [8]. ED scan allows a device to obtain a measure of peak energy in each requested channel. During this scan, MAC Sub-layer discards all frames received over PHY data service. This scan is terminated when the number of channel ED measurements stored equals the implementation specified maximum energy. An active channel scan allows a device to locate any coordinator transmitting beacon frames within its Personal Operating Space of 10m. During this scan, MAC sub-layer discards all the frames received over PHY data service that are not beacon frames. Passive scan is similar to the Active scan. But beacon request command not transmitted in Passive Scan. Both Active and Passive Scans are performed by a device prior to association to choose a suitable Personal Area Network (PAN). An Orphan Scan allows a device to attempt to relocate its coordinator following a loss of synchronization. During this scan, MAC sub-layer discards all the frames which are not coordinator realignment command frames.

B. *Beacon Frame Format*

Beacon is a type of frame which is sent by an access point to indicate that it is on. Device is permitted to transmit Beacons when the logical address is not a broadcast address.

Devices shall begin to transmit Beacons when macBeaconOrder is less than 15 [9]. Beacon frame structure is implemented as in the Fig. 11.

Octs:2	1	4/10	2	1	0/1	var	var	var	2
Frame Control	Seq no	Addr Fields	Superframe Spec	GTS Spec	GTS Directions	GTS List	Pending Address Fields	Beacon Payload	FCS

Fig. 11. Beacon Frame Format [9]

C. Association and Dissociation

Devices shall begin transmitting beacon frames only when it has successfully associated with a PAN. Association starts only after performing a MAC sub-layer reset. The MAC sub-layer of an un-associated device initiates the association procedure by sending an association request command to the coordinator of an existing BAN. Coordinator sends an acknowledgement to this request. But this acknowledgement does not mean that the device has associated. The coordinator takes some time to determine whether the current resources available are sufficient to allow other devices to associate. This decision has to be taken by the coordinator within aresponseWaitTime symbols.

When a coordinator wants one of its associated devices to leave the BAN, dissociation notification command is sent to the device from the coordinator using indirect transmission. If the device in the BAN wants to leave the network, then the device sends a dissociation notification command to its coordinator either using Direct or Indirect transmission.

D. Synchronization

For all devices operating on a Beacon Enabled mode, synchronization is performed by receiving and decoding the beacon frames. Devices shall be able to acquire beacon synchronization in order to detect any pending message or to track the beacon. All devices operating on a Non-Beacon Enabled mode, shall poll the coordinator for data at the discretions of the next higher layer [10].

E. Orphaned Device Realignment

If the next higher layer receives repeated communication failures following its request to transmit data, it is said to be orphaned [11]. Then it may instruct the MLME to either perform Orphaned device Realignment procedure or reset the MAC sub-layer and perform the association procedure. If this procedure is successful, the device shall update its MAC PIB with the BAN information contained in coordinator realignment command.

V. Results Of Simulation

The simulation scenario for Beacon- Enabled mode for RFDs is setup in NS2 Simulator [11] by using the parameters mentioned in Table I.

TABLE I
PARAMETERS OF NS_CONFIG

Field Area	Description
Channel Type	Wireless Channel
Radio Propagation Model	Two Ray Ground
Antenna	Omni Antenna
MAC type	IEEE 802.15.4
Traffic type	FTP
Number of nodes	7
Packet Size	50-70 bytes
Initial Energy	13000 J

Code for Beacon-Enabled Star network in WBAN is executed to obtain a trace file. AWK script is used to extract the data from the trace file. Parameters such as macBeaconOrder and macSuperframeOrder are modified for every simulation to obtain graphs dynamically for some of the Network Metrics such as Throughput and Packet Delivery Ratio as shown in Fig. 12 and Fig. 13 respectively.

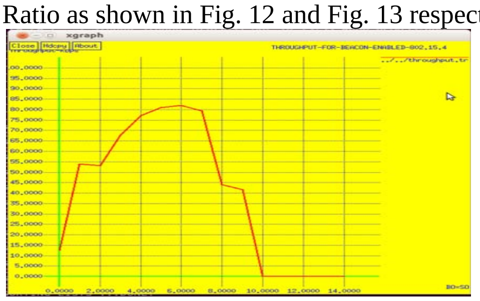


Fig. 12. Throughput vs BO=SO in Star Topology in Beacon- Enabled Mode

Fig. 13. Throughput vs BO=SO in Star Topology in Beacon- Enabled

Since the number of nodes cannot be changed dynamically in NS2, using Excel or Lab-view tool, both the metrics are analyzed w.r.t the Number of nodes as shown in Fig. 14 and Fig. 15.

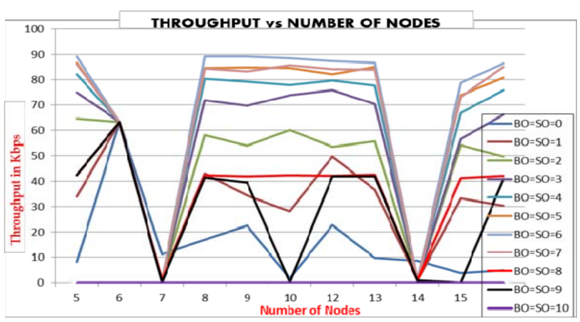


Fig. 14. Throughput vs Number of Nodes in FFD in Beacon- Enabled

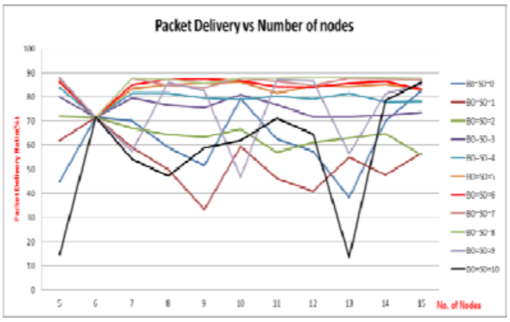


Fig. 15. Throughput vs Number of Nodes in FFD in Beacon- Enabled

VI. Conclusion And Future Work

Using NS2 Simulator, behavior of IEEE 802.15.4 MAC standard in WBAN is analyzed for different Beacon Order and Superframe Order in Beacon- Enabled Operational mode. Maximum throughput can be obtained for BO=SO=6 in case of RFD as in Fig. 10 and for FFD throughput varies randomly for different BO and SO as in Fig. 11. Depending on the association of devices and scanning methods used by the devices, Packet delivery ratio is maximum for 6<=BO<= 9 as in Fig. 12. From the Fig. 13, it is concluded that when the number of nodes are multiple of 7, it is better to use RFD to achieve maximum throughput. Also from the Fig. 13, Packet Delivery ratio is 80% to 90% for 4<=BO=SO<=8 when the number of nodes varies between 6 to 15. Hence depending on the application and urgency, the MAC device used for data transfer between the human body sensor and the coordinator should be bought by the user. But whenever the device has to be used by heart patients or any other critical conditioned patient, the specification of MAC ensures that the cost slightly increases w.r.t its throughput and packet delivery ratio. Thus versions of 802.15.4 MAC devices are designed depending on the Performance metrics required for the application.

The Guaranteed Time Slot (GTS) management is one such issue which has not yet been implemented. Development of software modules for GTS implementation in NS2 can be a part of a very good future work. Concepts like efficient bandwidth utilization with GTS and CAP, reliable data transfer can be investigated.

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