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A Comprehensive Review of Medium Access Control Protocols for WBAN

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Abstract: Wireless Body Area Network (WBAN) promises a new healthcare system through allowing inexpensive, unobtrusive and non-invasive monitoring of human's health-status. WBAN comprises of tiny, lightweight, low-cost, intelligent wireless sensor devices which are placed on key points of the human body and connected by means of a wireless network. The vital physiological body parameters are sensed and sent to remote servers for health care monitoring. WBAN can be connected to the remote server by a range of telecommunication network such as WLAN, Wi-Fi or a dedicated hospital network. Efficient MAC protocols are required to meet the major requirements of low power consumptions and energy efficiency of the sensors. The MAC protocol typically needs to address two issues: channel assignment to decide which channels are to be used by which hosts and medium access to resolve the contention problem. This study analyzes the existing MAC protocols for WBAN on different perspectives such as throughput, delay and power. IEEE 802.15.6 the new standard for WBAN has also been discussed.

Key words: Wireless, sensor, network, protocol, MAC, WBAN

INTRODUCTION

The rising cost of rendering health care has driven the technological advancement of Wireless Body Area Network (WBAN) and its use in patient data collection and health monitoring. Current techniques and traditional methods of monitoring health condition of patients use fixed equipments along with wired systems. These systems are also location specific such as hospitals where sick patients are required to stay for observation and treatment. Patients with critical illness may be required to stay for even longer period of time.

WBAN can be used for a number of applications like health care, fitness and entertainment. Due to market need, WBAN research is mainly focused on health care and sports related application. WBAN is used to provide vital physiological data like ECG, blood pressure, blood glucose level and blood oxidation for constant monitoring by medical and other health care professionals.

WIRELESS BODY AREA NETWORK

WBAN can be used for monitoring in different ways: individual patient from home; inmates of an ALF; patients in a hospital-Intensive Care Units (ICU) or patients in wards. Wireless sensors can be placed either on the body (non-invasive) or inside the body (invasive). Sensor nodes can be placed on various parts of the body or can be fabricated inside clothes.

WBAN technology emerges as the natural by product of existing sensor network technology and biomedical engineering. WBAN consists of tiny, lightweight, low-cost, intelligent wireless sensor nodes or devices that are placed on key points of the human body and connected by means of a wireless network. The vital physiological body parameters are sensed and sent to remote servers for health care monitoring. WBAN can be connected to the remote server by a range of telecommunication network such as WLAN, Wi-Fi or a dedicated hospital network.

Each node has a sensor which is used to collect data from the environment, a microcontroller for processing of data collected by the sensors, a memory to store temporary data during its processing, a radio transceiver (with the antenna) for transmission and reception and powered battery that provides charges for all these devices for the whole duration of the network lifetime (Verdone *et al*., 2010). The sensor node architecture is shown in Fig. 1.

Basically in a sensor network, multiple numbers of sensor nodes cooperate to accomplish a specific task for a given application. A WBAN operates close to 1-2 m range or within the human body and is concerned with the connectivity of nodes operating within this space. A Wireless Personal Area Network (WPAN) is based on the standard IEEE 802.15, a network for interconnecting devices operating up to 10 m around the human body. It is normally associated with non-medical applications in

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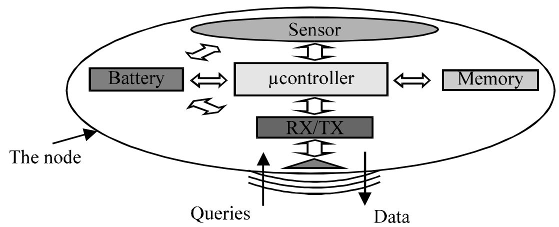

Fig. 1: Architecture of a sensor node

which the connections are wireless. A Wireless Local Area Network (WLAN) allows interconnection and the sharing of resources between independent devices within a moderately sized geographic area and typically has a range of up to 30 m depending on protocol type and has fixed power requirements (Verdone *et al*., 2010).

Communication among wireless sensor nodes is usually achieved by means of a unique channel. It is the characteristic of this channel that only a single node can transmit or receive a message at any given time. Therefore, shared access of the channel requires the establishment of a Medium Access Control (MAC) protocol among the sensor nodes. The objective of the MAC protocol is to regulate access to the shared wireless medium such that the performance requirements of the underlying application are satisfied. From the perspective of the Open Systems Interconnection (OSI) reference model, the MAC protocol functionalities are provided by the lower sublayer of the data link layer. The subdivision of the data link layer into two sub layers is necessary to accommodate the logic required to access a shared access communications medium (IEEE, 2011).

Maximizing the network lifetime is a common objective of sensor network research, since sensor nodes are generally not reusable and discarded when they have no battery power. Under these circumstances, the MAC protocol must necessarily be energy efficient by reducing the potential energy wastes. The major sources of energy waste in wireless network can be classified into five types namely collision, overhearing, packet overhead, Idle listening and over emitting. The performance of a MAC protocol is generally evaluated on basis of energy consumption per bit metrics, average packet latency and network throughput (IEEE, 2006). Radio activity is controlled by MAC and therefore it is necessary to design an ultra low power and energy efficient MAC layer suitable for WBAN. Likewise, the application requirements could also have an impact on the data transmission rates. The challenging issues of WBAN (Ullah *et al*., 2010) can therefore be summarized to include multiple aspects that range from low-level to high-level design issues like cost, coverage, efficiency, bandwidth, Quality of Service (QoS) and network lifetime.

OVERVIEW OF IEEE 802.15.4 STANDARD

The standardization of IEEE 802.15.4 for Wireless Personal Area Networks (WPANs) (IEEE, 2006, 2011) was to define very low-cost and low-power communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements.

The objectives of WPAN also known as Low Rate WPAN (LR-WPAN) are ease of installation, reliable data transfer, extremely low cost and a reasonable battery life while maintaining a simple and flexible protocol. The standard is defined for fixed, portable and moving devices with limited battery consumption requirements typically operating in the Personal Operating Space (POS) relatively for short distances of 10 m or less. Battery-powered devices requires duty-cycling to reduce power consumption. These devices spend most of their operational life in a sleep state and each device periodically listens to the RF channel to determine whether a message is pending. This mechanism allows deciding on the balance between battery consumption and message latency. Higher powered devices have the option of listening to the RF channel continuously.

Devices in the network have limited power, available storage and power drain. These constraints limit the choice of cryptographic algorithms and protocols that influence the design of the security architecture (Latre *et al*., 2011). Some of the capabilities provided by this standard are star or peer-to-peer operation, unique 64 bit extended address or allocated 16 bit short address, optional allocation of Guaranteed Time Slots (GTSs), Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) or ALOHA channel access, fully acknowledged protocol for transfer reliability, low power consumption, Energy Detection (ED) and Link Quality Indication (LQI).

Specifications for WPAN: The basic component of the standard is the device. There are two different types of devices in a network, namely, a Full-Function Device (FFD) and a Reduced-Function Device (RFD). Two or more devices communicating on the same physical channel constitute a WPAN. The WPAN includes at least one FFD where an FFD is a device that is capable of serving or operating as a Personal Area Network (PAN) coordinator or a coordinator. An RFD is a device that is not capable of operating as a coordinator but can be deployed to send and receive data. RFD can be a relatively simple device such as a light switch or a passive infrared sensor and it does not have the need to send large amounts of data and only associates with a single FFD at a time. The RFD can be implemented using minimal resources and memory capacity (IEEE, 2011). LR-WPAN operates in star topology or the peer-to-peer topology. In star topology, communication is established between devices and a single central controller, called the PAN coordinator. The PAN coordinator is the primary controller used to initiate, terminate or route communication around the network. All devices operating on a network of have unique addresses called extended addresses. The PAN coordinator will be mains powered and the devices will mostly be battery powered. In a star network, when an FFD is activated, it establishes its own network and become the PAN coordinator. All star networks operate independently from all other star networks currently in operation. PAN coordinator allows other devices both FFDs and RFDs to join its network. In peer to peer network, each device is capable of communicating with any other device within its radio communications range.

Architecture of IEEE 802.15.4: The IEEE 802.15.4 architecture is defined in terms of layers: physical, MAC and upper layer. Each layer is responsible for services to the higher layers and interfaces between the layers serve as logical links.

Physical layer: The Physical layer (PHY) contains the Radio Frequency (RF) transceiver along with its low-level control mechanism. PHY is responsible for transmitting and receiving packets across the physical medium and in addition other functions such as activation and deactivation of the radio transceiver, ED, LQI, channel selection and Clear Channel Assessment (CCA). Multiple Physical layers (PHYs) are defined to support a variety of frequency bands for devices operating in the license-free 868-868.6, 902-928 and 2400-2483.5 MHz bands with precision ranging, extended range and enhanced robustness and mobility. Frequency bands 314-316, 430-434 and 779-787 MHz are used in China and 950-956 MHz in Japan.

MAC layer: MAC sublayer provides access to the physical channel for transfer of data and control information. MAC sublayer provides two services, the MAC data service and MAC management service. The MAC data service enables the transmission and reception of MAC Protocol Data Units (MPDUs) across the PHY data service. The features of the MAC sublayer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association and disassociation. It also provides hooks for implementing application-appropriate security mechanisms.

The standard defines four MAC frame structures that are beacon frame used by a coordinator to transmit beacons, data frame for all transfers of data acknowledgment frame for confirming successful frame reception and MAC command frame for handling all MAC peer entity control transfers. The MAC frames are passed to the PHY as the PHY Service Data Unit (PSDU) which becomes the PHY payload.

Upper layers: The upper layers consist of a network layer which provides network configuration, manipulation and message routing and an application layer which provides the intended function of the device.

MEDIUM ACCESS CONTROL PROTOCOLS FOR WBAN

Some of the key protocols commonly used for WBAN are explained and discussed in this study.

IEEE 802.15.4 MAC protocol: IEEE 802.15.4 MAC protocol supports two operational modes of CSMA/CA, namely beacon-enabled mode and non beacon-enabled mode. In beacon-enabled mode the beacons are periodically generated by the coordinator to synchronize with attached devices and to identify the nodes in the network. A beacon frame embeds all data frames exchanged between the nodes and the PAN coordinator (IEEE, 2011). Data transmissions between nodes are allowed during the super frame duration. The frame structures are designed to keep the complexity to a minimum while at the same time making them sufficiently robust for transmission on a noisy channel. The superframe structure is shown in Fig. 2.

The superframe consists of active and inactive periods. The active period has three components: a beacon, a Contention Access Period (CAP) and a Contention Free Period (CFP). The superframe is bounded by network beacons sent by the coordinator and is divided into 16 slots of equal duration. The beacon frame transmission starts at the beginning of the first slot of each superframe. Beacon transmission can be switched off during inactive periods and the coordinator enters low-power mode. Devices can try to access the channel only during the Contention Access Period (CAP). For low latency applications or applications requiring specific data bandwidth, the PAN coordinator dedicates portions of the active superframe to that application. These portions are called Guaranteed Time Slots (GTS) which forms the Contention Free Period (CFP). CAPs are always at the end of the active superframe and the PAN coordinator can allocate up to seven of these GTSs. A GTS is allowed to occupy more than one slot period. However, a sufficient

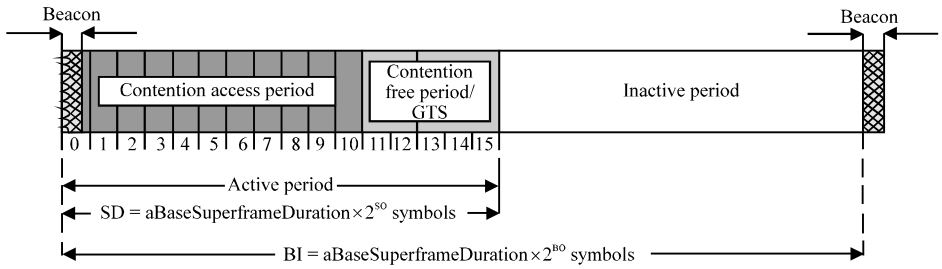

Fig. 2: Superframe structure of IEEE 802.15.4

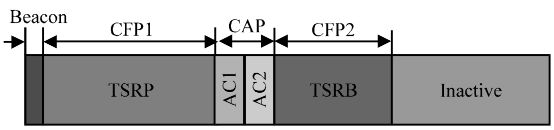

Fig. 3: Superframe structure of the priority-guaranteed MAC

portion of the CAP remains for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions are completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP. MAC protocol (IEEE, 2006, 2011) offers three operational frequency bands of 2.4 GHz, 868 MHz and 915 MHz (IEEE, 2006).

Priority-guaranteed medium-access control protocol: This protocol (Zhang and Dolmans, 2009) uses slotted ALOHA mechanism. The protocol is proposed mainly to support heterogeneous applications in the WBAN. The data and control channels are split to support collision-free high data rate communication. The frame structure of the priority-guaranteed MAC protocol is shown in Fig. 3.

The active part of a super frame is divided into five parts. The two control channels, AC1 and AC2 use randomized slotted ALOHA access mechanism. The node can select one time slot randomly to send a link request from given time slots. Nodes with medical data send resource requests through AC1 channel. These requests are triggered only at the beginning of a new monitoring period and occur at very low frequency. AC2 channel is used for other consumer electronics applications for request of resources. Depending on traffic demand and application, the node will send the request to reserve the resource for a period of time. On requests received by the control channels, the master node will decide the resource allocation in a centralized way depending on the priority for the data to be transferred for different applications.

There are two data channels namely Time slot Reserved for Periodic traffic (TSRP) and Time slot Reserved for Bursty Traffic (TSRB). These channels are allocated on demand with TDMA scheduling. Periodic traffic uses TSRP channel and bursty traffic uses TSRB channel. The resource allocation on the data channels can be discontinuous for some applications with high latency requirement.

The performance evaluation was done using Monte Carlo simulations on Matlab assuming a star topology where the master node acts as the central controller. Researchers have concluded that application-specific dedicated control channels restrict random access contention. This would enable priority for medical applications to be guaranteed, make the data channels collision free and support high data rate communications. An increase in the number of users could cause data congestion and complex super frame structure may result in inadaptability to emergency traffic.

Power efficient medium-access control protocol: Kwak *et al*. (2009) proposes a slotted ALOHA mechanism where protocol functions on two basic wakeup mechanisms, namely, the wakeup by traffic-based patterns for normal traffic and the wakeup by radio for emergency and on-demand traffic. The basic assumption is that significant amount of energy can be saved using suitable wakeup mechanisms as the device wakeups only when necessary. The lifetime of the network can be increased. The WBAN traffic is categorized into normal, on demand and emergency traffic. For normal traffic, wakeup table is maintained by the coordinator. Emergency events are initiated by the nodes while on demand state is initiated by the coordinator. A new superframe structure was as shown in Fig. 4.

Configurable Contention Access Period (CCAP) was used to accommodate short burst of data and a Contention Free Period (CFP) where Guaranteed Time Slots (GTS) are assigned to end nodes for collision free communication. In CCAP, slotted ALOHA protocol was used. The wakeup schemes for both on demand and emergency schemes were modeled assuming uniform random arrival. The system was designed to keep count and track of number of events and duration of an event to measure the packets, throughput and wakeup time and energy consumption. The average power in the 3 states the sleep, wakeup and communication state for each and every node were considered for a fixed packet inter-arrival time. Simulation results based upon Monte Carlo Method for poisson and deterministic traffic showed it performed better for various scenarios. The result showed that the protocol consumed less power than Wise MAC and S-MAC WSN protocols.

Use of Low Power Listening (LPL) during the sleep state may not be an optimal choice for implanted and on-body sensor nodes communication due to the power required to sustain this activity.

Body medium-access control protocol: Fang and Dutkiewicz (2009) proposes energy efficient TDMA MAC protocol for WBAN in which packet collision, idle listening and control packet overhead are reduced by allocating three bandwidth management schemes such as burst bandwidth, periodic bandwidth and adjust bandwidth which would improve energy efficiency of the system. An efficient sleep node is introduced to turn off a node's radio, especially for the nodes supporting low duty cycle applications. As shown in Fig. 5, MAC frame is divided into three parts; a beacon, a downlink and uplink.

Synchronization among the frame is achieved by the beacon. Downlink is used for data communication from coordinator node to sensor nodes in order to accommodate the on demand traffic. While the uplink frame is divided into Contention Access Period (CAP) and Contention Free Period (CFP). Contention Access Period (CAP) is based on CSMA/CA concept. Here, the nodes

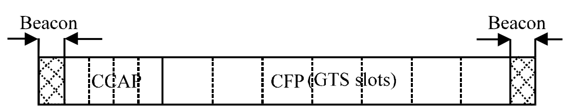

Fig. 4: Superframe structure power efficient medium-access control protocol

compete to send control packets to coordinator for the Guaranteed Time Slots (GTS). However, the nodes communicate for small data packets during this period. During Contention Free Period (CFP), the coordinator assigns Guaranteed Time Slots (GTS) to sensor nodes to avoid collision. Communication using Contention Free Period (CFP) improves the energy efficiency. However, there is high energy consumption due to Clear Channel Assessment (CCA) and collision issues for uplink frame in CAP, CSMA/CA. The main advantage is that the nodes can enter into sleep mode and wake up only when they have data to send to the gateway as the nodes and gateway are synchronized in time. The simulation results reveal that the body MAC protocol shows better performance than IEEE 802.15.4 in terms of end to end delay and energy saving.

Since, nodes and gateway are synchronized in time, nodes can enter into sleep mode and wake up only when they have data to send to the gateway. The slot allocation in CFP is collision free which improves packet transmission and hence saves energy. The protocol uses CSMA/CA in the uplink frame of CAP period which is not reliable scheme due to its unreliable CCA and collision issues.

Battery aware TDMA medium-access control protocol: Su and Zhang (2009) proposes battery's recovery capacity effect that shows the battery can yield a longer lifespan if it has more rest time between two consecutive discharge states. The battery-aware TDMA scheduling based MAC protocols is proposed. The aim of this protocol is to maximize the idle periods for the batteries of sensor nodes. Figure 6 shows the frame structure of battery aware TDMA protocol.

The proposed schemes consider the joint effect of the battery dynamics, the wireless-channel qualities at the physical layer and queuing characteristics at the data link layer. The main idea is to make the sensor nodes to efficiently utilize the time slots. In this method, the sensor nodes may hold the packets until there are sufficient packets available and the channel is in good state. By doing so the number of idle time slots may increase which in turn help the battery to recover capacity which further

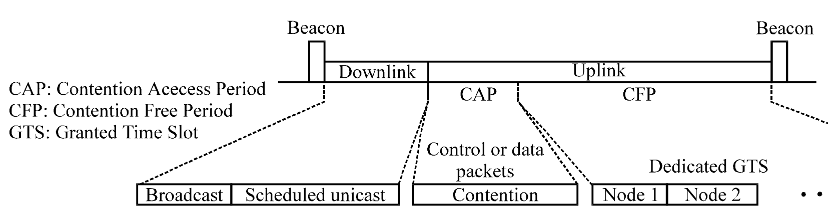

Fig. 5: MAC frame of body MAC protocol

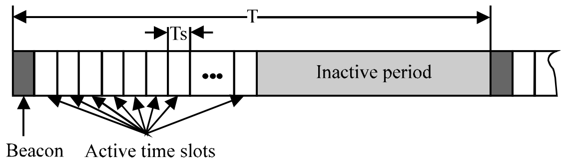

Fig. 6: Frame structure of battery aware TDMA protocol

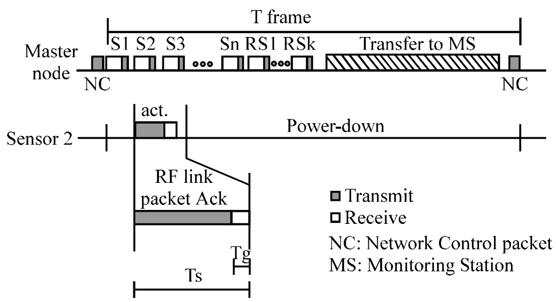

Fig. 7: Frame structure of energy efficient low duty cycle MAC protocol

increases the lifespan of the sensor node. The system architecture consists of finite-length First In First Out (FIFO) queue/buffer at the sensor nodes. The new arriving packets will be dropped if the buffer is full. The adaptive modulation is done to maximize the data rate by adjusting transmission parameters while maintaining a predetermined bit error rate.

Larger packet delay and packet drop rate of the sensor nodes occur due to the holding of more packets in the buffer. Long delay would prove to be major problem when it comes to WBAN applications which transmit time-critical health care information.

Energy efficient low duty cycle medium-access control protocol: Marinkovi *et al.* (2009) propose a low duty cycle TDMA based MAC protocol, developed for a single-hop communication to support streaming of physiological signal data. The protocol exploited the fixed network structure of WBAN to implement an effective TDMA strategy. Figure 7 shows the TDMA timing diagram of the protocol.

Time slots are allocated to n different nodes which are separated by a guard time (g T). Insertion of g T prevents transmission overlaps and reduces bandwidth waste. The communication between MN and MS can be established in two aspects: MN with one transceiver and MN with two transceivers. Researchers contention is that transmission based on duty cycle instead of fixed superstructure leads to low energy consumption. The protocol performance was compared for two cases; the

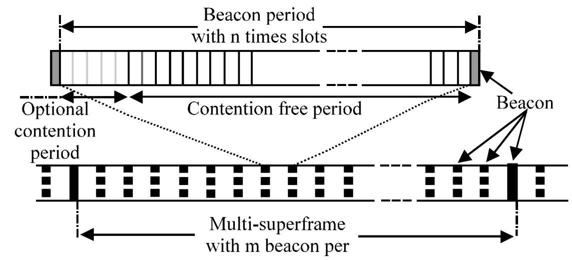

Fig. 8: Multi-superframe structures for the Med MAC protocol

low duty cycle and low power protocols for the sampling data rate of 2500 bit sec^{-1}. The duty cycle values were represented in terms of two data rates of 19.2 and 250 kbit sec^{-1} and power consumption versus data generation interval was compared. The protocol was seen to greatly reduce power consumption for streaming data. The protocol is energy-efficient for sending short bursts of data. The protocol overcomes the collisions by using effective TDMA strategy. The protocol can be used in a real time Electroencephalogram (EEG) monitoring scenario and the scheme results in reliable data transfer which is crucial especially in medical applications. Due to the static network topology adapted in the TDMA strategy, the protocol may not respond well when the topology is dynamic and also there is no mechanism for on-demand traffic.

Med medium-access control protocol: The Medical Medium Access Control (Med MAC) protocol (Timmons and Scanlon, 2009) is an adaptive TDMA based MAC protocol for WBAN that provides a reduction in energy dissipation and improvisation of the channel access in body area networks. A star network configuration of IEEE 802.15.4 standard at 2.4 GHz is considered and incorporates a novel synchronization mechanism where a node can sleep through a number of beacon periods. The beacon period consists of a Contention Free Period (CFP) and optional Contention Access Period (CAP) which are made up of 2-256 time slots as shown in Fig. 8.

The duration of the multi-super frame is defined by synchronization mechanism. Synchronization between the coordinator and the other nodes can be maintained by the combination of time stamp scavenging and an Adaptive Guard Band Algorithm (AGBA). AGBA allows the node to sleep through many beacon broadcasts by introducing a Guard Band (GB) for each time slots to track the actual drift. The Drift Adjustment Factor (DAF) minimizes the bandwidth waste. At the start of multi-superframe, all the nodes are brought into synchronization by use of a timestamp. Here, the algorithm AGBA is used to calculate the GB for each node.

Each node had a dedicated time slot in which there are no collision occurrences. Default GB for subsequent beacon of multi-superframe and Slot Start Times (SST) for each slot was computed. Power efficiency of Med MAC was compared with IEEE 802.15.4 of medical applications such as respiration, temperature and pulse monitor using OPNET simulations. Simulation showed that the IEEE 802.15.4 Model consistently suffered node failures. Med MAC outperformed IEEE 802.15.4 in terms of power efficiency in low and medium data rate applications. The energy waste caused by collisions is reduced by making use of a GTS. Besides, each device has exclusive use of the channel for a fixed time slot which mitigates the synchronization overhead. The protocol focuses only on low data rate medical applications whereas the data rates of on body and in body nodes of WBAN can sometimes be high.

Heartbeat-driven medium-access control protocol: Heartbeat-Driven Medium-Access Control Protocol (H-MAC) (Li and Tan, 2010) is a MAC protocol designed for WBANs that exploits heartbeat rhythm to perform time synchronization for TDMA. Though heartbeat is a key parameter that can be monitored as part of a WBAN by an ECG sensor, nodes can use the heart rate waveform peaks as a mechanism for node synchronization within a WBAN. Nodes can achieve synchronization by using the heartbeat rhythm without having to turn on their radio. The energy cost for time synchronization can be avoided by increasing the lifetime of the network dramatically.

The coordinator could be a wrist worn pulse monitoring watch, a PDA or a smart cell phone. Since, these external devices can be recharged easily they possess more computing resources and serve as a gateway to other networks. As a TDMA protocol, H-MAC time slots are assigned to each biosensor to guarantee collision-free transmission. It also takes the advantage of heartbeat rhythm that is inherent in every human body and achieves the TDMA time synchronization without distributing periodic timing information which reduces the energy cost. The algorithms were verified using a subset of 100 patient records of the real-world data from the MIT-BIH multi parameter database which contains continuous data recorded from patient monitors in the medical, surgical and cardiac intensive care units.

H-MAC has the limitation of a single point of failure, i.e., the reliance on the human heart for synchronization. This could affect patients with weak heart or those suffering from a cardiovascular condition where some sensor nodes may not be able to detect the synchronization data. Sensor nodes may request varying channel resources under different scenarios. Steady state monitoring for example EEG or blood glucose transmissions could yield channel priority to heart rate and ECG sensor data which depending on the criticality of the patient could be classified as high priority.

MB star medium-access control protocol: MB star a TDMA based protocol (Zhu *et al*., 2011) uses the star topology for communication and is designed to support a message rate as high as 400 Hz. The physical layer of MB star consists of 802.15.4 (DSSS) compatible radio above which a higher-frequency, reliable, TDMA MAC layer is built. There is a simple application layer designed for security purpose on the top of MAC. It is assumed that a gateway is connected with access point(s) and a number of sensors are connected to the access point wirelessly. The physical layer utilizes 802.15.4 compatible radio for low power consumption. The TDMA is used for real-time packet delivery. A time stringent time slot with only 2.5 msec is available. The features of MB star protocol are higher frequency, real-time, reliable, secure and supports. Experimental results showed an error ratio of around 10-5% for normal office environment. For noisy environment, the functionality of channel blacklist and reliability mitigates the packet loss ratio greatly. Comparison revealed much better results than Bluetooth and Wi-Fi and ZigBee and was found to be quite suitable for real time application.

Traffic-aware dynamic MAC protocol: This study proposes (Alam *et al*., 2012) Novel Traffic-Aware Dynamic MAC (TAD-MAC) protocol. This protocol was designed for both invasive and noninvasive body area networks by considering a hybrid network topology which includes star network for in body and mesh network for on body.

Each node adapts its wake up interval dynamically with the amount of traffic it receives and optimizes the energy consumption. A Traffic Status Register (TSR) was continuously updated with the traffic information. For invasive network, the coordinator contains the TSR for all the nodes in the body network. For the noninvasive network, each node maintains a TSR of their neighbor nodes. However, as the majority of the communication only takes place with the coordinating node, the coordinator estimates the best wake up time interval for each transmit node.

The protocol was tested using network simulator WSNet and the performance was compared with other protocols such as BMAC, XMAC, RICER and WiseMAC. The results showed that TAD-MAC performed well when compared to WiseMAC for fixed traffic rates. Lifetime of the network was estimated and found to be 3-6 times

Table 1: Comparative analysis of WBAN protocols

Protocol	Access mechanisms	Type	Benefits	Limitations
IEEE 802.15.4 MAC protocol	CSMA/CA	Contention-based	Non-beacon enabled uses un-slotted CSMA/CA which performs well in terms of bandwidth utilization and latency	In beacon mode, scalability is at the expense of degradation of QoS parameters and slightly increased power consumption Non-beacon enabled mode, Clear Channel Assessment (CCA) leads to high energy consumption
Priority-guaranteed MAC protocol	Slotted ALOHA	Scheduled-based	Supports high data rate communications due to dedicated control channels and data channels are collision free Resource efficiency on the control channel is improved using randomized slotted ALOHA	The packets are prone to collision with the increase in number of users Inadaptability to emergency traffic is present due to complex super frame structure
Power efficient MAC protocol	Slotted-ALOHA	Scheduled-based	Traffic based wakeup mechanism improves efficiency	Implementation is highly complex and no proper mechanism is given to handle on-demand traffic
Body MAC protocol	TDMA	Scheduled-based	Since nodes and gateway are synchronized in time, nodes can enter into sleep mode and wake up only when they have data to send to the gateway thereby saving power The slot allocation in CFP allows the system to be collision free and improves packet transmission which results in energy saving	CSMA/CA protocol in uplink frame of CAP period is not reliable for a WBAN due to unreliable CCA and collision issues
Battery aware TDMA MAC protocol	TDMA	Scheduled-based	Lifespan of wireless sensor nodes are increased Reliable and timely delivery of packets is achieved using GTS	Holding of packets in buffer for long time, leads to high average delay and packet drop rate There is no mechanism defined for emergency data traffic
Energy efficient low duty cycle MAC protocol	TDMA	Scheduled-based	Energy-efficient while transmitting short bursts of data and overcomes collision using the effective TDMA Can be used in a real time EEG monitoring scenario for reliable data transfer	Due to the static network topology adapted in the TDMA, the protocol do not respond well when the topology is dynamic
Med MAC protocol	TDMA	Scheduled-based	The energy waste caused by collisions is reduced by using GTS Exclusive use of fixed time slot reduces synchronization overhead	The protocol focuses only on low data rate medical applicationss Data rates of on-body and in-body nodes of WBAN can be high and is not dealt with
Heartbeat-driven MAC protocol	TDMA	Scheduled-based	Exploits heartbeat rhythm to perform time synchronization for TDMA Energy cost for time synchronization is avoided, thereby increasing the lifetime of the network	Network is inefficient due to single point of failure as human heart beat is used for time synchronization This could affect patients with weak heart or those suffering from a cardiovascular condition. In such cases, synchronization would also not work properly Heart rate and ECG would have to be assignedhigh priority which may not be true for all medicalconditions
MB star MAC protocol	TDMA	Scheduled-based	MAC layer adopts channel hopping and channel blacklist to minimize the effect of noise on any particular channel Transmission acknowledgement and retransmission facility provided to attain high reliability Supports a higher bandwidth than current low-power wireless protocols Application layer providing data security is available	High retransmission rates would increase packet loss and power consumption
Traffic-aware dynamic MAC protocol	TDMA	Unscheduled based	Traffic based wakeup mechanism improves efficiency Lifespan of network is increased	Maintenance of traffic status registers is likely to increase power consumption Mechanisms for handling priority or emergency traffic not defined

better than other protocols. The results showed that TAD-MAC performed better than all the other protocols under both fixed and variable traffic rates.

Comparative analysis of WBAN protocols: WBAN devices have battery restriction hence use of energy resources becomes one of the important issues. Existing protocols have primarily focused on trying to avoid energy dissipation due to collision, overhearing and idle listening with reduced control packet overhead and implementation complexities. Efficient bandwidth utilization, reliable communication, minimum delay and reduced synchronization cost are some of the other issues dealt with (Ullah *et al*., 2013).

Table 1 shows a comparative analysis of the MAC protocols discussed giving the access mechanism, key benefits and limitations. The benefits and limitations of these protocols are in context of energy minimization, resource utilization, how these protocols tackle energy inefficiency, idle listening, overhearing and control packet overhead.

The classification also shows whether the protocol is scheduled-based or contention based random access protocols. Schedule-based protocols (IEEE, 2006) are contention-free protocols in which wireless users access the medium in an orderly manner. They are based on access schemes in which nodes can access the medium based on pre-allocated channels or slots. Contention-based random access protocols (IEEE, 2006) operate in either infrastructure-based wireless networks or infrastructure less (ad hoc) networks in which a random back-off procedure is applied to reduce any collisions.

The protocols compared have various limitations in their design and implementation. These include low data rate, transmission delay and failure to support scalability. Hence, the selection of the appropriate MAC protocols becomes application and/or hardware dependent. Changes to the existing protocol are often required to meet the desired application needs and overcome its drawbacks.

A BRIEF OVERVIEW OF IEEE 802.15.6 STANDARD FOR WBAN

Current Personal Area Networks (PANs) do not fully meet the medical and relevant communication demands and regulations for some of the application environments. IEEE 802.15.4 based protocols have drawbacks in their suitability for WBAN applications as they have limited scalability issue, relatively more power consumption and significant degradation of QoS (Ullah *et al*., 2010). The gap in meeting the requirements of WBAN has lead to the realization of a new standard for WBAN. The standard IEEE 802.15.6 is intended to support the bio-friendly needs of WBAN and also include support for safety, security and QoS such as low power, data rate and reliability (Kwak *et al*., 2010).

In November 2007, IEEE 802 established a task group for the standardization of WBAN called IEEE 802.15.6 (IEEE Standards Association, 2012). The objective of standard is to provide an international communications standard for a short-range (i.e., about human body range), low power and highly reliable wireless communication for use in close proximity to or inside, a human body. Data rates, typically up to 10 Mbps can be offered to satisfy an evolutionary set of entertainment and healthcare services. The final version of the standard was published in February 2012. The available frequency bands for WBANs are shown in Fig. 9.

The Medical Implant Communications Service (MICS) band in the frequency range of 402-405 MHz is defined to be a licensed band for implant communications. Wireless Medical Telemetry Services (WMTSs) is a licensed band to be used for medical telemetry systems. The disadvantage of MICS and WMTS bands are their inability to support high data-rate applications. The Industrial, Scientific and Medical (ISM) and Ultra-Wideband (UWB) bands support high-data rate applications, however, there exist a high probability of interference because, many wireless devices including those using the IEEE 802.11 and IEEE 802.15.4 standards, operate in the same 2.4 GHz band. Human Body Communication (HBC) operates in the frequency band of 5-50 MHz.

Topology of WBAN: The basic framework of the standard is nodes and hubs (also known as coordinators). These nodes and hubs are organized into logical sets called Body Area Networks (BANs). The organization of nodes are illustrated in Fig. 10.

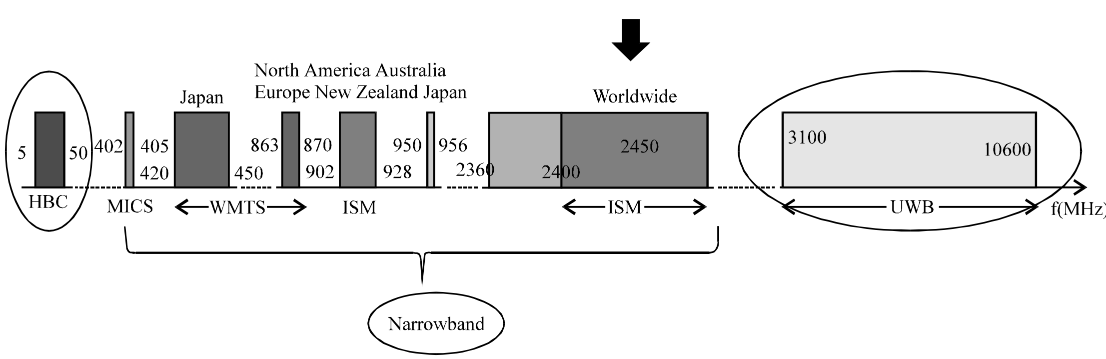

Fig. 9: Available frequency bands for WBANs

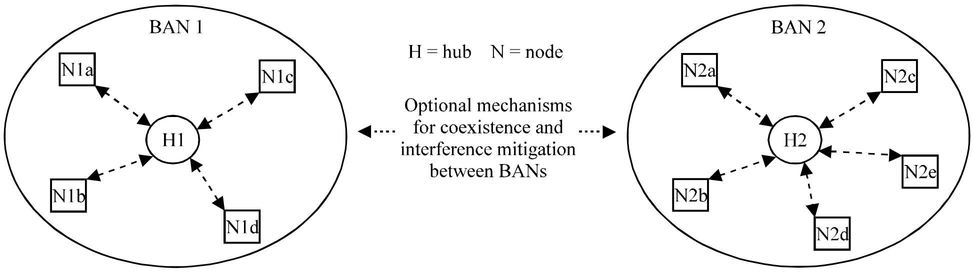

Fig. 10: Network topology of BAN

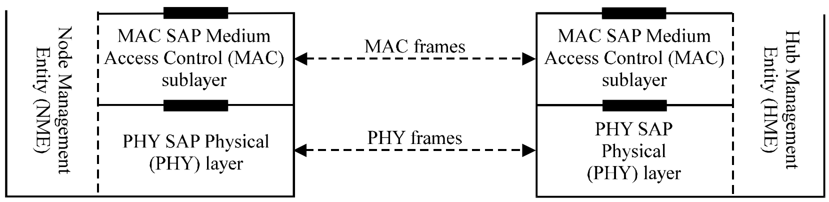

Fig. 11: Reference Model of IEEE 802.15.6

Each BAN in a network will have one hub and the number of nodes can vary from zero to mMaxBANSize. For one-hop star BAN, frame exchanges occur directly between nodes and the hub of the BAN and in a two-hop extended star BAN, the hub and node exchange frames optionally through a relay-capable node. The nodes and hubs in BAN are internally partitioned into a Physical (PHY) layer and a Medium Access Control (MAC) sublayer.

Reference model: The nodes and hubs are partitioned internally into a Physical (PHY) layer and a Medium Access Control (MAC) sublayer as shown in Fig. 11. A node and a hub communicate at the PHY layer and MAC sublayer using one operating channel at any given time. MAC sublayer provides message security services and security key generations that take place inside and/or outside the MAC sublayer. MAC also provides services to the MAC client through the MAC Service Access Point (SAP). At the transmitting end, the MAC client passes MAC Service Data Units (MSDUs) to the MAC sublayer via the MAC SAP. PHY provides service to the MAC through the PHY SAP and MAC layer passes MAC frames to the PHY layer through the PHY SAP during transmission.

At the receiving end, PHY layer passes MAC frames to the MAC sublayer via the PHY SAP and the MAC sublayer passes MSDUs to the MAC client via the MAC SAP. Logical Node Management Entity (NME) and Hub Management Entity (HME) exchanges network management information with the PHY and MAC and other layers.

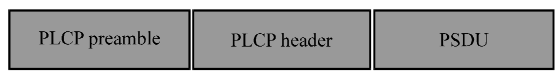

Fig. 12: NB PHY frame format

Physical layer: The standard defines, support for three Physical (PHY) layers such as Narrowband (NB), Ultra-Wideband (UWB) and Human Body Communications (HBC) layers. PHY supports different frequencies bands and the selection of each PHY depends on the application requirements (IEEE Standards Association, 2012). The functions of the Narrowband PHY layer are activation and deactivation of the radio transceiver to enable Clear Channel Assessment (CCA) and transmission and reception of data. The NB PHY frame format illustrated in Fig. 12.

Physical-layer Service Data Unit (PSDU) is transformed into a Physical-layer Protocol Data Unit (PPDU) by appending PDDU with a physical-layer preamble and a physical-layer header. The preamble and header help in modulation, coding and delivery of the PSDU during transmission and for demodulation, decoding and delivery of the PSDU during reception. A compliant device supports transmission and reception in at least one of the following frequency bands: 402-405, 420-450, 863-870, 902-928, 950-958, 2360-2400 and 2400-2483.5 MHz.

The Ultra Wide Band Physical (UWB PHY) layer provides three levels of functionality. They are activation and deactivation of the radio transceivers, construction of PPDU by concatenating the Synchronization Header (SHR), Physical layer Header (PHR) and Physical layer

Fig. 13: UWB PHY frame format

Service Data Unit (PSDU) by Physical Layer Convergence Protocol (PLCP) in addition PPDU bits are converted into RF signals for transmission in the wireless medium and provide Clear Channel Assessment (CCA) indication to the MAC to verify activity in the wireless medium during transmission and reception. The UWB PHY frame format illustrated in Fig. 13.

PPDU is formed by concatenating SHR, PHR and PSDU. The UWB operates in frequency range of 3100-10600 MHZ into two bands namely low band and high band. Each band is divided into channels, all of them characterized by a bandwidth of 499.2 MHz. Low band consists of 3 channels (1-3) only and channel 2 has a central frequency of 3993.6 MHz and is considered a mandatory channel. The high band consists of eight channels (4-11) where channel 7 with a central frequency 7987.2 MHz is considered a mandatory channel while all other channels are optional. A compliant device supports transmissions and reception in the 21 MHz band. Transceivers support MICS band providing safe power levels for the human body and low interference to other devices.

Human Body Communications Physical (HBC PHY) layer is an Electrostatic Field Communication (EFC) specification of PHY that covers the entire protocol for WBAN such as packet structure, modulation, preamble/ (Start Frame Delimiter) SFD, etc., Fig. 14 describes the PPDU structure of EFC.

The PPDU structure is composed of a preamble, SFD, PHY header and PSDU. The preamble and SFD are fixed data patterns. They are pre-generated and sent ahead of the PLCP header and PSDU payload. The preamble sequence is transmitted four times in order to ensure packet synchronization while the SFD is transmitted only once. When the packet is received by the receiver, it finds the start of the packet by detecting the preamble sequence and then it finds the start of the frame by detecting the SFD. HBC PHY operates in the frequency band of 5-50 MHz centered at 21 MHz.

MAC layer: The MAC sublayer of IEEE 802.15.6 basically provides channel access control mechanisms to several communicating devices. The functionalities are preparing MAC frames, maintaining MAC clock synchronization and guard time, support channel access, power management and interference mitigation between BANs. The standard defines MAC superframe structures. Each

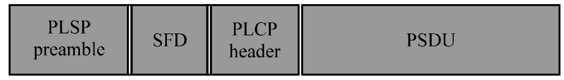

Fig. 14: PPDU structure of EFC

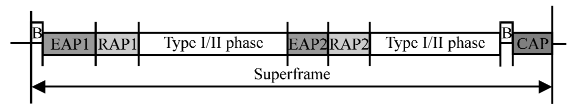

Fig. 15: IEEE 802.15.6 superframe structure

superframe is bounded by a beacon period of equal length. The hub selects the boundaries of the beacon period and thereby selects the allocation slots and can shift the offsets of the beacon period. Generally, the beacons are transmitted in each beacon period except in inactive superframes. Figure 15 shows the superframe structure of IEEE 802.15.6. The standard defines three communication modes for operation of the network: beacon mode, non-beacon mode with and without superframe boundaries. In beacon mode, the beacons are transmitted by the hub in each beacon period except in inactive superframes.

The superframe structure is divided into Exclusive Access Phase 1 (EAP1), Random Access Phase 1 (RAP1), type I/II phase, Exclusive Access Phase 2 (EAP 2), Random Access Phase 2 (RAP 2), type I/II phase and a Contention Access Phase (CAP). In EAP, RAP and CAP periods, nodes contend for the resource allocation using either CSMA/CA or a slotted Aloha access procedure. The EAP1 and EAP2 are used for highest priority traffic such as reporting emergency events. The RAP1, RAP2 and CAP are used for regular traffic only. Type I/II phases are used for uplink, downlink or for bilink allocation intervals. Polling is used for allocation. An uplink communications is for transfer of management and data traffic from a node to a hub. A downlink communications is established for the transfer of management and data traffic from a hub to a node. The hub initiates one or more frame transactions to transmit management and data traffic to a node and the node returns acknowledgment if required. A bilink communications link is transfer of management and data traffic from a hub to a node or/and vice versa. Bilink allocation can happen when the node waits to receive a poll from the hub before initiating the frame transaction (s). Depending on the application requirements, the coordinator can disable any of these periods by setting the duration length to zero.

In Non-beacon mode with superframe boundaries, the entire superframe duration is covered either by a type I or a type II access phase but not by both phases.

In non-beacon mode without superframe boundaries, the coordinator provides unscheduled type II polled allocation only. The access mechanisms used in each period of the superframe are divided into three categories namely random access mechanism, improvised and unscheduled access and scheduled access have been comprehensively discussed in the standard.

IEEE 802.15.6 security specifications: Support is provided for three security levels with different security properties, protection levels and frame formats (IEEE, 2011; Latre *et al*., 2011; Ullah *et al*., 2013). Level 0 is unsecured communication where messages are transmitted in unsecured frames. There are no measures for message authentication, integrity, confidentiality, privacy protection or replay defense. Level 1 provides authentication but not encryption. Measures are available for message authenticity and integrity validation and replay defense but not confidentiality and privacy protection. Level 2 provides authentication and encryption. Messages can be transmitted in secured authenticated and encrypted frames. Additional measures from Level 1 include support for confidentiality and privacy protection and replay defense. Support has been defined for Diffie-Hellman key exchange based on elliptic curve public key cryptography. Message authentication and encryption based on the Advanced Encryption Standard (AES) forward cipher function for 128 bit keys operating on counter mode and Cipher Block Chaining (CBC) mode has been explained. Security level is first established between nodes and hubs. All subsequent unicast and multicast communication follows the established security level for frame exchanges has been discussed.

CONCLUSION

This study presents a study of some of the existing MAC protocols based on IEEE 802.15.4. A comparative analysis of these protocols giving their benefits and limitation has also been given. IEEE 802.15.4 was essentially proposed for personal area networks and has its own limitations when applied for WBAN. This study also gives a brief overview of the new standard IEEE 802.15.6 which has been specifically designed for WBAN. IEEE 802.15.6 is intended to address the unique requirements of WBAN and its applications and has been developed to support its bio-friendly needs and QoS which includes security and reliability. This study also briefly mentions the various protocols which have been proposed for the new standard which are still in the research stage and are yet to be implemented. It is believed that this study will inspire researchers to develop novel and energy-efficient MAC protocols for WBANs.

RECOMMENDATIONS

A number of MAC protocols based on the new IEEE 802.15.6 standard have been proposed (Bradai *et al*., 2011). These protocols are yet to be implemented and hence their performance is yet to be evaluated. Each of these protocols has their own benefits and limitations. A number of research issues have yet to be fully addressed. These include efficient handling of resources, maintaining a high performance, smooth flow in the network, power saving and low delay.

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