ENERGY-SAVING MAC PROTOCOL DESIGN FOR BODY SENSOR NETWORKS

By

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ABSTRACT

ENERGY-SAVING MAC PROTOCOL DESIGN FOR BODY SENSOR NETWORKS

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Remote and online patient monitoring can significantly reduce the cost for the health care system. Body Sensor Network (BSN) plays a key role in real-time remote health monitoring. Although the BSN can reduce the health monitoring cost, some technical challenges arise. One of the major challenges in BSN is the power consumption. The power recharge is very difficult and inconvenient in BSNs. Therefore, energy saving is one of the most appropriate approaches to prolong the network lifetime. In the thesis, we propose a context-aware Medium Access Control (MAC) design to extend the network lifetime of the BSN. The proposed MAC reduces data transmission by determining the more valuable fraction of data. The high-value portion of the data is transmitted, while the low-value fraction of the data is omitted, at the sensor node. The simulation results demonstrate that the proposed method can reduce the transmission energy by up to 30% compared to the existing method called burst communications.

Abstract Approval: Committee Chair

Department Chair

Graduate Dean

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Chapter 1

INTRODUCTION

1.1 Body Sensor Networks

For many years medical and ambulatory caregivers have been measuring vital parameters manually and have been reporting the results to hospitals or to specialist physicians by phone or other devices. Researchers are looking for a quicker and more reliable alternative for manual data measurement and transfer. Computer networks and electronic developments offer a brand new solution using the Body Sensor Network (BSN). The BSN presents a real time, reliable and continuous measurement and transmission solution to monitor and report health parameters. The BSN can monitor parameters from an ambulatory subject and transmit it to a mobile caregiver in a short time [15]. BSN is formed by a number of sensor nodes and a Central Control Unit (CCU). Sensor nodes measure vital parameters from body's organs. The vital parameters in the human's body can be electrocardiography (ECG), electroencephalography (EEG), glucose level, blood pressure, oxygen level in blood(SpO_2), temperature and body movement. Each sensor node is specially designed for each vital parameter. Figure 1.1 shows a sensor node's components including a sensor, analog to digital (A/D) convertor, light processor, small memory, transmitter and receiver.

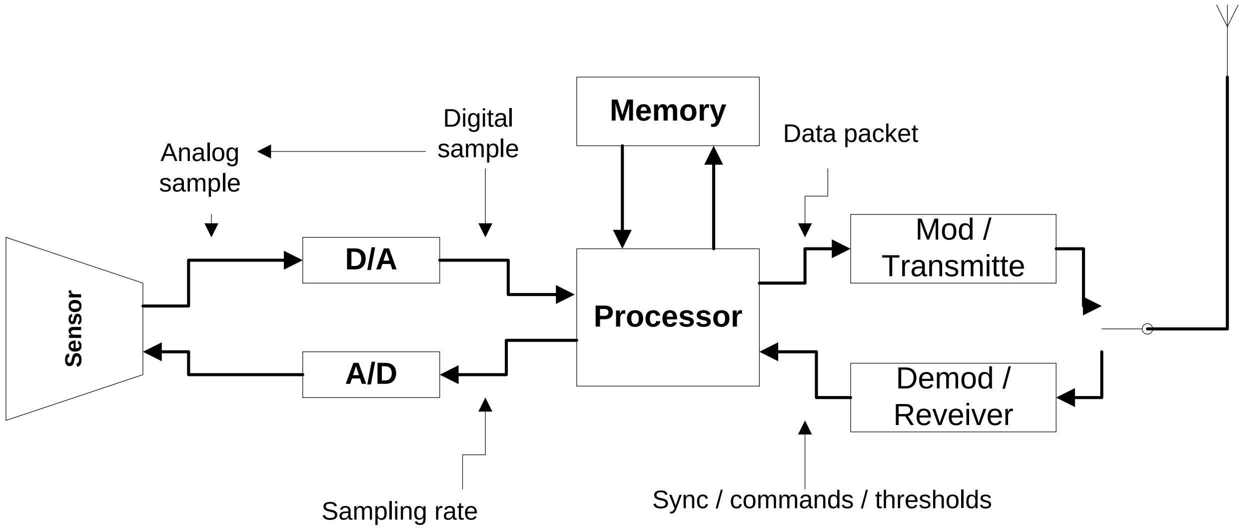

Figure 1.1 Sensor node schematic

Each sensor node receives a synchronization signal and a working status command from the CCU through an antenna and receiver. It captures the samples according to the CCU's command, digitizes them and compares them to the alarm thresholds [39]. Alarm thresholds specified by physician are downloaded by the CCU to the sensor node. The processor classifies the data as alarm data when they exceed the alarm thresholds and as normal data when they do not. Normal data will be stored and sent in data time-slot. Alarm data will be sent in the first possible transmission.

The CCU collects the data from sensor nodes and transmits the data to a server as shown in figure 1.2. Data might be both normal and abnormal data in the case of life threatening situations. Regardless of the distance between server and subject, both are connected by one or more wireless connections such as Wireless Fidelity (WiFi) or Global System for Mobile communication (GSM). A medical application on server can be programmed to immediately notify the nearest nurse, physician, caregiver or ambulance of critical conditions, in order to facilitate aid to the patient. As well, a medical storage server can collect the data for future research or follow-up. The medical application will also notify the patient or any one in attendance when emergency conditions arise and the physician or nurse is too far away from the patient. In case of an accident, the health monitoring system can immediately relay the patient's health status to the hospital. In addition the health monitoring system can also assist to choose which physician should visit the patient ahead of time.

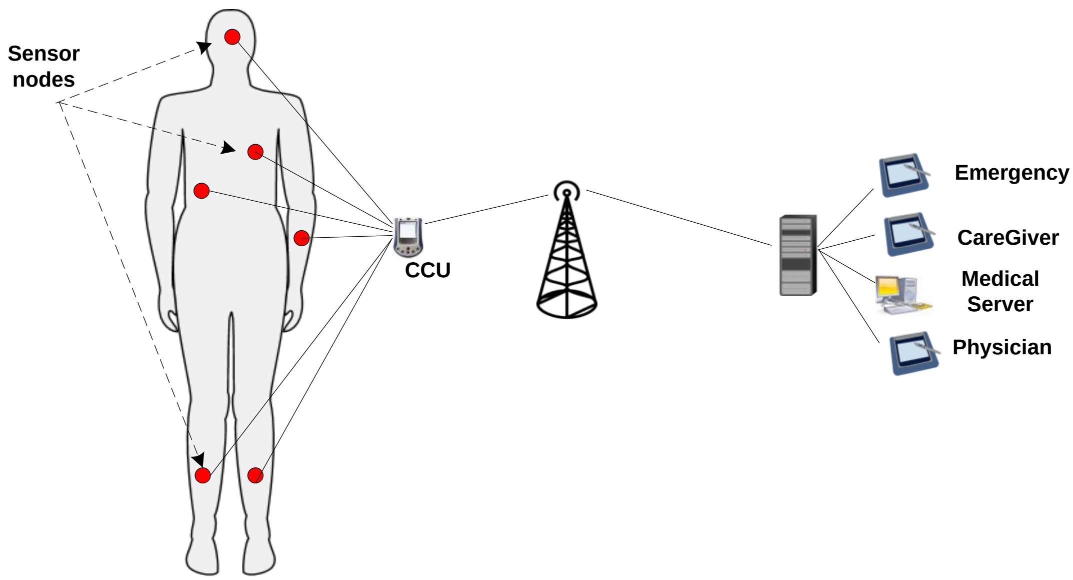

Figure 1.2 Illustration of BSN sensor nodes, CCU

BSN has been used in many applications like [31]:

- Healthcare applications such as the monitoring of physiological signals of patients, obstetrics(pregnancy) and new-born babies who are threatened by sudden infant death syndrome
- Emergency or life-critical scenario (disaster relief operation, firefighters)
- Entertainment scenario (game systems)
- Sport scenarios (sport training, sport studies and fitness)
- Human to computer interaction (HCI) [24]

In this work we focus on healthcare scenarios. In healthcare scenarios, the sensors and the CCU are connected using Zigbee [26, 38] standard and unified to a medical application by other wireless connection standards like WiFi or GSM [15, 22].

1.2 Technical Challenges

A normal-sized device as a CCU can easily be recharged or repaired. Most of the challenges in BSN can be seen in the sensor node's design and production, including the transmission rate, transmission latency and energy consumption. Implantable sensor nodes are more comfortable than removable sensor nodes since implantable sensor nodes are easily implanted beneath the skin providing more freedom to patients and less maintenance. However, access to implantable sensors is difficult and they must have longer lifetime.

Technology developments in sensor production have resulted in smaller, lighter and more sensitive sensors. More sensitive sensors can measure vital parameters more accurately. Yet these advanced sensor nodes create more data which means more communications, resulting a higher power consumption. The BSN lifespan is mostly limited by the sensor nodes battery life. A node failure causes a network failure which renders the BSN unusable. In addition sensor nodes are not easy to access due to their miniature size and cannot carry rechargeable battery or recharging circuits. Patients must be returned to the hospital on first failure, to debug the BSN. Battery usage is one of the most challenging research topics in BSN [43]. Energy consumption is still the first concern for the BSN lifetime [23, 8].

Researchers are looking for energy saving solutions for the BSN. The majority of energy saving techniques is as follows:

- Physical (PHY) layer techniques including over-head reduction and radio wave approaches [2], [8], [10], [11], [16].
- Energy scavenging from external sources [9], [13].
- Data reduction by sampling rate adjustment [6] or sample resolution adjustment [36].
- MAC Layer protocol to reduce the communication energy [1], [3], [4], [5], [17], [18].

This work is motivated by the proposed methods in [1, 2, 3, and 6]. In those studies, communications are reduced in MAC layer by a decision tree. The proposed scheme in [1] introduces a polling algorithm based on data generation prediction, sensor priority and energy-fidelity. Each sensor has a priority number that rates it in the decision tree to transmit data based on its importance. Scheduling scheme determines the best transmission time for each node. This optimum scheduling satisfies the required minimum latency and the least average header. The network model in this research defines the cost with combination of latency and energy. However the overhead is a small fraction of traffic and its ratio to payload depends on the amount of payload which has to be sent.

Burst communication [2, 23] is a MAC overhead reduction scheme. This scheme tries to data accumulation and then a transmission burst instead of communication flow. The accumulation forms a larger packet which can save transmission energy due to two factors. First, the number of transmission startup energy required for each transmission is reduced significantly. Secondly, the numbers of header bits are reduced through the use of one header for more data.

Dynamic decision algorithm [3] reduces the sampling rate and expands the frame length to minimize the data generation based on previous samples processed in the CCU. This novel protocol lets the sensor nodes to sleep for a longer time due to lower communication and as a result, saves a considerable amount of energy. But this algorithm is running in a CCU and an abnormal detected sample may meet an unacceptable latency due to a longer sleep period already stated by CCU.

Rate-distortion based data reduction [6] tries to optimize the sample's resolution or bits per sample based on energy cost. This protocol considers the more significant distortions of analog phenomena and ignores the less important parts in the digitizer. This method's efficiency depends on measuring subject types but cannot be universally applied to all sensor nodes.

1.3 Thesis Contribution

This work addresses energy conservation by transmission reduction. First we propose a dynamic transmission thresholds scheme. This scheme evaluates the captured data in the sensor node. It determines the more important fraction of data according to caregivers demand. Then the node omits the low important samples and transmits the high value samples. The novelty of our transmission reduction scheme is processing the captured data before reduction. Data processing before omission prevents the omission of necessary data. It also maximizes the unnecessary data omission.

Our scheme applies to high traffic generator nodes which are subject to energy exhaust more than low traffic nodes. The burst communication method only applies to low traffic nodes. The sampling rate reduction [3] and online data execution [6] reduces the data accuracy based on previous data. They can miss valuable data in case of sudden change after a long stability.

1.4 Thesis Organization

This dissertation is organized into five chapters. The remaining chapters are briefly introduced here.

Chapter 2 presents related work on BSN and power saving approaches including PHY, MAC and energy harvesting techniques.

Chapter 3 presents the proposed method. Two new states in addition to conventional state are investigated. The state transition circumstances and protocols are discussed in this chapter.

Chapter 4 provides the experimental evaluations on the proposed method by OPNET simulation. We investigate the power saving percentage for different nodes.

Chapter 5 concludes the thesis and outlines future research directions.

Chapter 2 BACKGROUND

In this chapter we provide a state-of-the-art of review of Body Sensor Networks (BSN), particularly as it relates to energy conservation. We first briefly review the general aspects of BSN, such as its applications and Zigbee. We then review the techniques on energy savings, including the physical (PHY) layer approaches and the Medium Access Control (MAC) layer approaches.

Zigbee [26] is the commercial version of Personal Area Network (PAN) connection standards, defined in IEEE 802.15.4[27]. Low-power, low-rate, short-range and least complexity are outstanding characteristics of this standard [25]. Zigbee is defined by Zigbee alliance [26] adapted for commercial and industrial applications [26]. Health monitoring use of zigbee is known as the Body Sensor Network (BSN) or Body Area Sensor Network (BASN). The Zigbee network consists of 3 kinds of nodes [28]. The master node is called Zigbee Coordinator (ZC), the sensor node is named Zigbee End Device (ZED), and Zigbee Router (ZR). ZR connects other nodes over a longer distance or in a cluster-tree topology.

The PHY-layer energy saving approach has three main concepts. The first approach reduces the power consumption in radio by proposing new methods in transmission protocols, and electromagnetic wave collection improvement [11]. The second approach involves the transmission's power adjustment. It can deduct the energy consumption depending on reception's direction and location [47]. The third and final approach includes energy that could be harvested from wake-up signal to feed the listening circuit [44].

Much work on energy saving is done in MAC layer. Novel MAC protocols refer to data aggregation, contention methods, TDMA polling methods, latency versus energy, data accumulation and sleep/wake up duty cycle adjustment.

The remainder of this chapter is organized as follows: Section 2.1 details related works on the BSN, as well as reviews of the BSN applications and Zigbee. Section 2.2 specifically reviews energy saving solutions including PHY and MAC approaches. Section 2.3 discusses the reasons behind choosing the Time Division Multiple Access (TDMA) MAC rather than Channel Sense Multiple Access (CSMA) for this work.

2.1 BSN Applications

Measured samples by sensors need some processing in the sensor node before being entered into memory. Platform independent software like Signal Processing In Node Environment (SPINE) [39] is needed to function as Analog to Digital convertor (A/D), math aggregator and to create threshold-based alarms. SPINE2 is the newer version which is adapted to tiny OS and is more task-oriented.

BSN like any other networks needs a standard to define the communication between its nodes. Most popular wireless standards such as Wireless Fidelity (WiFi) are not suitable for BSNs. Zigbee standards are evaluated for medical devices and discusses why Zigbee is preferred to IEEE WiFi(802.11) and Bluetooth [19]. It demonstrates how WiFi and Bluetooth offer higher bandwidth which is not necessary in BSN while consuming valuable energy in remote nodes. Zigbee defines a sleep mode which saves energy thus can quickly wakes-up and re-access to the communication channel. WiFi (802.11) is commonly uses for network connections in hospitals. Using WiFi for BSN will cause more interferences than Zigbee. Zigbee is designed to co-exist with WiFi with less interference. Zigbee supports a data rate in a range from 20k to 250k bits per second [26].

One medical application runs several BSNs and classifies information for different users. Adaptive low-power design [22] proposes a multi-layer hierarchy architecture for BSN thus dividing the BSN into the following layers:

- A system layer which is a PC or server in hospitals managing the control path and the data path for the BSN by sending commands to the application layer and receiving data. Determining the lowest energy data path is the most important function of this layer.
- An application layer controlling all the sensor groups by sending commands and receiving data from them.
- A sensor group layer that includes several sensor nodes. The body area is divided to several sub-areas and each sensor group consists of sensors in one area.

- A sensor layer that includes only one sensor node receiving commands from a sensor group and sending the detected data to the sensor group.

Hierarchy architecture helps the spread of the BSN to a greater number of sensor nodes with the least changes in higher levels.

When both the data source (e.g., BSN) and the destination (e.g., caregiver or physician) are two mobile nodes, an open source framework named SenseFace application [15] is proposed to connect them to each other. The destination is a social network such as fax, email, voicemail, short message (SMS), file attachment, Facebook, YouTube, LinkedIn, tweeter, etc

2.2 Energy Conservation

Energy can be remotely fed to the sensor nodes. Adaptive threshold rectifier (ATR) [9] is a remote method to deliver the energy to several small nodes such as electrocardiograph (ECG). This rectifier wirelessly feeds the sensor node by an adhesive bandage. Energy is delivered remotely by ATR with 54.9% efficiency. This method is not expandable for all nodes due to an extra bandage over each sensor and almost twice as much in extra power expanded. Other energy conservation methods are proposed on PHY and MAC layer.

2.2.1 Energy Saving and Harvesting in PHY Layer

Application-specific integrated circuit (ASIC) defines three different modes [20]. The first mode is the "active" mode in which nodes communicate with each other through the wireless channel. The second mode is the "active standby" mode in which the node listens for a wake-up signal so the receiver is ON and consumed energy is considered as waste. The third mode is "passive sleep" mode. Passive sleep mode derives an energy saving period when the node neither has data to transmit nor is waiting for a beacon signal. A passive radio-frequency (RF) receiver with energy harvesting ability is designated to wake-up the node in case of unexpected beacon or synchronization lost.

Wake-up signal carries some energy and that energy can trigger the receiver [13]. The radio circuit can have an integrated passive receiver for active standby mode to harvest that energy. Harvested energy feeds the active receiver circuit [44].

Radio wave power adjustment can be used to control the power consumption. Transmission power adjustments regarding the last transmission quality acknowledgment can optimize the tradeoff between quality of service and power consumption [10]. Another algorithm called feedback-based closed-loop [47], proposes the similar idea to dynamically adjust the transmission power. Some researchers believe that most of the power is consumed in the receiver. Optimizing the transmitter throughput [16] is another power saving method in PHY.

The human body can act as a medium to relay a radio wave. This propagated wave is known as a creepy wave. If the layer-1 transmitter and receiver are able to communicate through this new medium, communication energy will dramatically drop and battery life will increase by $1.5X10^5$ times [11].

2.2.2 Energy Saving in MAC Layer

MAC layer in IEEE 802.15.4 defines a super-frame [8]. A super-frame can contain up to three divisions. The first division is a beacon frame which synchronizes other nodes with the coordinator and informs them of the remaining of super-frame's structure. The second division is the active period including Contention Access Period (CAP) and Contention Free Period (CFP). Sensor nodes compete with each other in CAP in order to send data by Carrier Sense Multiple Accesses with Collision Avoidance (CSMA-CA) mechanism. In this mechanism each node listens to the channel. If channel is free it begins communication. Otherwise, the node attempts again after a back-off timer. Coordinator may allocate Guaranteed Time Slots (GTS) in CFP. Guaranteed time slots are assigned to sensor nodes according to their data priority. This assignment is usually called TDMA. In this section, different energy saving methods in both CSMA-CA and TDMA schemes are discussed.

Pulsed triggered wake-up radio signal was discussed in PHY methods [13]. Accordingly, Pulse-MAC (PMAC) is designed for as a matched MAC for layer-2 and aims to cover the idle channel listening as opposed to TDMA. A pulse interval encoding (PIE) is used as network address to specify which sensor is the target for wake-up signal. This coding is based on pulse width modulation technique. This technique lets the node to save the receivers' energy during the idle listening period.

Full TDMA frame structure and a priority-based polling algorithm were suggested in Convex Optimization [1]. This frame consists of beacon, normal data time slot and alarm sub-slots. Beacon informs transmission turn and assigned time slot to the sensor node according to the polling algorithm. Polling algorithm calculates the accumulated data in the sensor nodes' buffers and assigns a data time slot before over-flow. If two nodes reach the full buffer at the same time, the assigned priority determines which node communicates first. Transmission with the full buffer reduces the overhead and consequently reduces the transmission energy. Assigning alarm sub-slot to each node guarantees low latency for abnormal data delivery.

Data aggregation [5] is useful in a cluster-tree or mesh topology. This research defines the data header and network information aggregation. In this method each node tries to synchronize its data with received data from another sensor node which must be retransmitted to a Central Control Unit (CCU). Data aggregation refers to saving one header when node transmits two packets which are its own packet and relaying packet with one header. Transmission energy for second header and one start-up energy are saved in this method. Data aggregation is suitable for high traffic networks. Synchronizing two node's data is not always possible because of different data generation sequence. Mesh is not a suitable topology for the BSN due to low distance and sleep period in sensor nodes.

Context-Aware MAC (CA-MAC) [4] defines a hybrid MAC structure combined CSMA and TDMA. It defines a polling turn to handle TDMA normal data and a contention period for re-transmission of the failed packets. The idea behind this combination is to postpone the re-transmission. This delay gives the chance to other sensors to seize the channel if a sensor does not have a clean access to it due to its location, direction or noise. Another try may conclude a better access to the channel with lower noise due to better physical location. This time-out increases the probability of better access to the channel. Context-aware MAC protocol provides a schedule to poll data from different nodes regarding to patient's situation. This schedule decides on what situation requires lower latency and the priority for each sensor.

Express Energy Efficient Medium Access Control (EX-MAC) [17] implements a MAC protocol to preserve the energy efficiency of the BSN and transfer packets from source to destination with acceptable latency. The idea behind this protocol is to change the sleep-awake period dynamically according to the network load fluctuation. When the sensor node's traffic increases, listening times are more frequent in order to increase the duty cycle, as such sensor node has more chances to communicate. On the other hand, when traffic is low, less listening times save the energy. This research applies to the CSMA network design.

The Context aware MAC protocol [3] proposed a dynamically changeable TDMA-based MAC frame structure and a novel synchronization method. The CCU changes the frame structure and collects most valuable data depending on previously analyzed data. This means CCU processes the received data from all nodes and then decides which node must adjust sampling rate or transmission rate. Sensors relating to abnormal data recently received will be signaled in order to increase accuracy. Other nodes might be notified to mitigate their traffic to guarantee the low latency for objective sensors. The novel synchronization method defines a protocol which encapsulates the local clock from each sensor to the data packet. The CCU compares the received clock from each sensor node. If the offset meets the threshold, the CCU will encapsulates the offset to the ACK packet in order to adjust the sensor node's clock, otherwise the synchronization overhead is saved. Sensor node also saves the clock computing task energy and leaves it for the CCU.

Online data and execution [6] proposes tools, methods and framework to evaluate the tradeoff between energy and in-node data execution. In this method, data generation is supposed to be reduced to save the energy. Sampling rate reduction can be used to reduce the data rate, when the measured subject does not have fast changes and measured samples are close to each other. Number of quantization levels (data resolution) is a significant factor in data generation. If lower accuracy of data is acceptable, reduction in quantization levels can reduce a fair data bulk. This computation is power consuming. The research aims to evaluate the overall tradeoff between the computation energy and saved energy.

This work focused on tremor sensors used mostly for patients with Parkinson's disease.

Wireless Communication Selection [2] introduces the burst communication. This approach is to accumulate the data to achieve longer packet size and minimize the overall energy. Optimization function is defined to consider the tradeoff between the energy and latency. The impact of this method is compared in Zigbee, Bluetooth, WiFi and ultra wide-band (UWB). Bluetooth and Zigbee are more suitable for smaller packets while WiFi and UWB can handle larger packets. In conclusion, if the latency has not limited the burst communication, WiFi or UWB would be the alternative protocol for Zigbee. The same idea with consideration of buffer size is discussed in [23]. However this technique has limitations like accepted latency, synchronization lost and buffer size.

Preemptive slot allocation and Non-Preemptive transmission (PNP-MAC) [18] defines a protocol in order to form a flexible super-frame and dynamic slot allocation. Conventional frame in this work is a combination of TDMA and CSMA frame. There are three problems associated with GTS allocation to emergency data. The first problem is a limitation of only up to seven GTS in each frame. The second problem is the latency between the GTS requests in the contention access period until GTS period in the next frame. The third problem illustrates that the GTS allocation mechanism is not based on sensor priority and works only on first-come first-serve basis. An important GTS request can be delayed or ignored due to high GTS demands. The proposed super-frame in this research is divided to six parts:

- Advertisements broadcast the binging of the super-frame and notify the nodes that they can send data or alarm time slot request to the coordinator.
- CAP when sensor nodes compete with each other to send the guaranteed time slot from the coordinator.
- Beacon signal broadcasts the allocated time slots to succeeded nodes in priority based time slot allocation.
- Data Time Slots (DTS) allocated by the coordinator when nodes transmit normal data.
- Emergency Time Slots (ETS) allocated by the coordinator when nodes transmit emergency data
- Inactive periods when the coordinator can sleep to save energy or assign this period to extended contention period (ECAP) if energy is not limited in it.

The novelty of this method is allocating the guaranteed time slot based on nodes' requests and their priority.

2.3 Zigbee MAC

Two popular multi-accesses schemes for wireless sensor network MAC layer [29, 12] are TDMA and CSMA/CA. In this section we briefly discuss both and describe why we prefer TDMA for BSN.

TDMA scheme is based on assigning time slots by the coordinator to other nodes for their communications. Coordinator forms a super-frame and assigns time slot sequences, then broadcasts this super-frame structure to all nodes by a beacon packet [12]. Beacon packets carry other information such as synchronization. End nodes turn off the transceiver after receiving the beacon and turn it ON for the next beacon or just prior to their transmission time slot if one has been assigned. An alarm time slot may be defined in the frame and then each node has an alarm sub-slot. An alarm sub-slot is used for emergency data transmission only when detected. There is no collision feasibility in TDMA unless one node fails or losses the synchronization and transmits data in a non-assigned time slot. On the other hand, synchronization is very critical thus each node must listen to the beacon which is energy consuming for the receiver.

The CSMA/CA scheme allows the sensor nodes to change the transceiver to sleep mode and activate it periodically to listen to the channel [29]. There is no transmission turn for sensor nodes and each node can transmit the data if the channel is clear. The transmission mechanism is based on collision avoidance when each node listens to the channel before the transmission. If the channel is clear, the node starts the transmission process. Otherwise, the node waits while trigging a back off timer then tries again. A dynamic network which loses and adopts nodes frequently can converge very quickly by CSMA scheme. CSMA weaknesses are:

- Energy waste for unsuccessful listening
- Buffer overflow in the event of simultaneous transmission demand by many sensors
- Low channel utilization
- Unpredictable latency on high traffic channels even for emergency data

	TDMA	CSMA/CA
Power consumption	Low	High
Bandwidth utilization	Maximum	Low
Preferred traffic level	High	Low
Convergence	Slow	Fast

Table 2.1 Comparisons between TDMA and CSMA/CA

Table 2.1 compares two schemes and shows that CSMA is a proper protocol for networks with temporal data transmission, higher bandwidth channels and lower data bulk. TDMA is appropriate for networks which have predictable invariant data generation and lower channel bandwidth.

In body sensor networks, sensor nodes generate data at the CCU's request and data bulk is predictable, so the TDMA MAC is proper method for BSN. Only unpredictable transmissions constitute abnormal data which requires the alarm sub-slot.

As mentioned before, energy harvesting, PHY and MAC approaches are most targeted methods to prolong the network life. Energy harvesting is useful only for receiver circuit wake-up procedures, and due to hygienic reasons, it cannot be extended for all nodes power sources. Powerful remote feeding magnetic waves are suspected to cause cancer or brain damages in peoples. Power transmission efficiency dramatically reduces with distance and a huge power source is required to feed the nodes by this method. PHY approaches have an acceptable power reduction, although the PHY methods are mostly hardware dependant. The MAC is the most flexible layer in Zigbee standard thus each algorithm change in the node, requires a new MAC protocol. In comparison between two MAC schemes, TDMA-MAC is appropriate solution for BSN due to full predictable traffic flow.

2.4 Chapter Summary

In this chapter, we studied related works in BSN. Pervasive applications are becoming more popular nowadays. BSN can be integrated with other networks such as public health networks or social networks. We considered the energy consumption as the most significant challenge for the BSN. We also reviewed some studies about energy saving by the PHY techniques, the MAC techniques and energy harvesting. The most important techniques in MAC methods are, burst communication [1, 2 and 23], sampling rate reduction [6] and sample resolution reduction [36]. Finally, we discussed two different MAC schemes in IEEE 802.15.4 / Zigbee and chose the TDMA base scheme in our work.

Chapter 3 A NOVEL CONTEXT-AWARE MAC PROTOCOL FOR ENERGY SAVING IN BODY SENSOR NETWORK

In this chapter, a context-aware MAC is proposed to save the energy. In this MAC, three states are defined including conventional, burst communication and dynamic transmission states. In the conventional state, the measurement data is transmitted with the least latency. In burst communication state, the measured data is accumulated into one long packet and transmitted. In the dynamic transmission state (hereinafter: dynamic state), the data transmission is based on dynamic transmission thresholds. Both new states (the burst communication state and dynamic transmission state) try to reduce the transmission bits while preserving the network efficiency. Dynamic state omits the unnecessary data in sensor nodes based on the content and patient status. Burst communication state tries to reduce the overhead considering the trade-off between latency and energy.

This chapter is organized as followings.

Section 3.1 provides the problem definition and shows the energy consumption for sensor nodes in the BSNs.

Section 3.2 provides the sensor node's models on data generation and energy. Network models can assist the network designer in deciding.

In Section, 3.3 we define two new states and redefine the conventional state. We illustrate conditions and define states accordingly. We also define the start-up state and the transitions between states.

Lastly in Section 3.4, we provide the detailed network protocol for the proposed approaches.

3.1 Introduction

A body Sensor Network (BSN) contains one Central Control Unit (CCU) and n sensor nodes (S_i ,$1 \le i \le n$). The CCU is the BSN controller and connects the BSN to the application server. The CCU creates a beacon signal and broad-casts it to all sensor nodes in its network. The beacon carries information such as:

- Synchronization signal to sync sensor to the network
- Inform sensor nodes about their data sub-slot turn (${S^D}_i$)
- Inform sensor nodes about their alarm sub-slot turn (${A^L}_i$)
- Inter-node parameters adjustment like sampling rate

Each sensor node (S_i) takes ${S^F}_i$ samples per second by its sensor, utilizing an Analog to Digital (A/D) convertor to convert a sample to an individual measurement with resolution of M_i Bytes. Individual measurement resolution is the size of each sample after A/D which depends of the number of quantization levels. The processor compares the sample to the alarm thresholds and determines if an alarm has occurred. An alarm signal must be sent to the CCU in the first assigned alarm sub-slot (${A^L}_i$). Measured data (M_i) is accumulated waiting for the next transmission turn prompted by the beacon. A header is added to the accumulated data and forms a packet (${S^\mathrm{P}}_i$). This packet will be sent in the assigned time slot (${S^D}_i$). Table 3.1 shows the symbols used in this chapter.

Symbol	Parameter	Symbol	Parameter
S_i	The i^{th} sensor	T	Frame Length
M_i	Individual measurement resolution	O^v	MAC overhead
${S^F}_i$	Sampling rate	${A^{TR}}_i$	Average transmission rate
T_i	Accepted data latency	E	Transmitter energy consumption
A_i	Accepted alarm latency	T_D	Dynamic transmission state period
${S^{GD}}_i$	Generated data (after A/D)	T_B	Burst communication state period
${S^{\mathrm{P}}}_i$	Generated packet	T_C	Conventional state period
${S^D}_i$	Transmission time slot assigned	P	Transmitter Power consumption
${A^L}_i$	Alarm sub-slot		

Table 3.1 Notation table

BSN nodes communicate through 802.15.4/zigbee standard. Most important challenges in all wireless networks are the Signal to Noise Ratio (SNR) and coverage in layer-1, error control and transmission turn in layer 2, communication loss in layer 3, and power supply for stand-alone nodes. Transmission power in wireless nodes is much higher than wired and opt-fiber connected nodes. In this case transmission power must be enough such that the receiver in any direction is able to detect the data with a fair SNR. The BSN sensor node’s relative location to the CCU is unsteady therefore using the directional antenna is not possible. These nodes are so small that they are unable to carry several directional antennas with a multi-input multi-output (MIMO) design.

The lifetime of the sensor node is the main concern for BSN designer. First failure in the BSN causes a network failure that renders the patient unreachable. As a result of this failure patient must return to the hospital. Any consumption reduction like reducing the unnecessary communication helps to prolong the BSN lifetime. The physician may always ask for the least latency and more data regardless to the energy consumption. Later in this chapter we define the cost to illustrate the importance of normal data, alarm data and energy. Sensor nodes will save about 1/3 of transmission energy with our method, compared to conventional scheme. Network lifetime will be increased by proposed method.

3.2 Network Models

Data generation bulk in all nodes is known by the CCU. The CCU assigns the proper data time slot to sensor nodes in order to deliver data during acceptable latency. This assignment has to prevent the buffer overflow in sensor nodes. The CCU schedules the transmission turn for each sensor node depending on the BSN configuration.

3.2.1 Data Generation

Equation (3.1) shows the number of generated bytes (${S^{GD}}_i$) within an update interval by each sensor (S_i)in the BSN before the Zigbee application. The generated bytes depend on three elements. The first element is sampling rate (${S^F}_i$)and it depends on the measuring object's fluctuation rate. Sampling rate follows the sampling theorem. The second element, sample resolution (M_i), depends on the accuracy required on each measured object. More accurate measurements require more quantization levels thus a larger digital sample resolution. The final element is the data update period (T_i), which depends on accepted latency for each measured object like electrocardiography (ECG), electroencephalography (EEG) and temperature [1]. The longest accepted latency is determined by physician or care giver.

$$ {S^{GD}}_i = {S^F}_i \,.M_i \,.T_i \ \text{(Bytes)} \tag{3.1} $$

The data packet size is shown in Equation (3.2). A packet consists of data generated by A/D in one interval plus one header by the Zigbee application. Data packet MAC header is 9 to 25 Bytes in wireless personal area networks [8].

$$ {S^P}_i = {S^F}_i \,.M_i.T_i + O^v \ \text{(Bytes)} \tag{3.2} $$

Average transmission rate by S_i is given by:

$$ {A^{TR}}_i = 8 * \frac{{S^F}_i \,.M_i.T_i + O^v}{T_i} \ \ (bits/s) \tag{3.3} $$

The processor compares each sample to alarm thresholds and determines the alarm occurrence. The time of an alarm is not predictable but does not affect the normal data transmission. Alarm sub-slot is assigned to each slave node and is used if the alarm is detected or otherwise left blank.

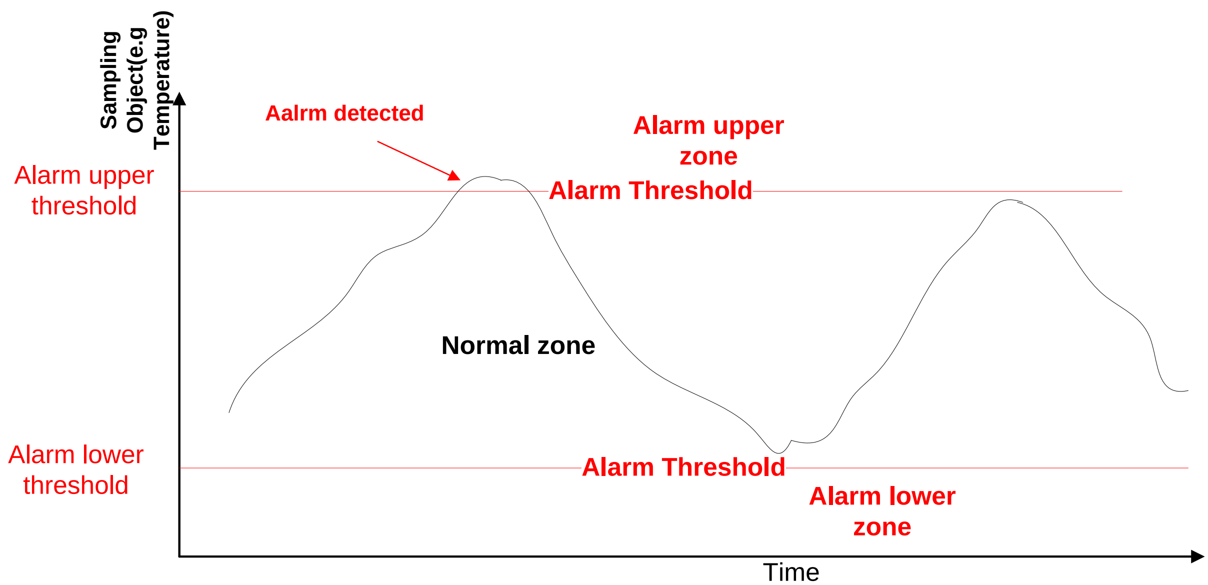

Figure 3.1 Alarm detection and threshold.

Alarm thresholds, as shown in Figure 3.1, are defined by the physician and stored in the sensor nodes as numbers, ranges or patterns. Matched samples are determined as an alarm. Alarms must be transmitted in designated alarm sub-slot ($A^L{}_i$) in the current frame. The processor accumulates normal data and waits for a transmission turn from the polling turn $S^D{}_i$ then transmits them it a header.

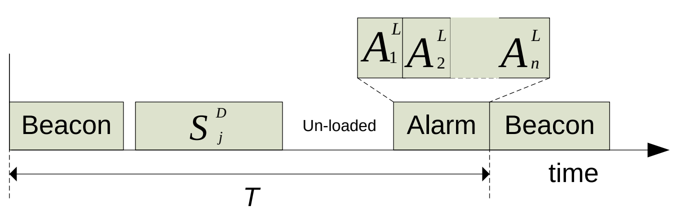

Figure 3.2 Normal data and alarm data stuffing in the super-frame

The conventional frame defined in [1] contains the beacon frame, the assigned data time slot for one sensor node, and the guaranteed alarm sub-slot for all sensor nodes. This super-frame is illustrated in Figure 3.2.

3.2.2 Power Consumption

Energy consumption in sensor node consists of three parts: transmitter energy, receiver energy and energy consumed in electronic circuit. Transmission energy is a top energy factor, thus it is used in this research through the MAC and application layers.

When the consumed energy is E_0 (Joule/bit) for each transmitted bit, the average transmitter power is given by

$$P_i = E_0 * A^{TR}{}_i = E_0 * 8 * \frac{S^F{}_i.M_i.T_i + O^v}{T_i} \quad (J/s)(Watt) \tag{3.4}$$

3.3 The Proposed Context-Aware Data Transmission Scheme

In this section we discuss two approaches to reduce the transmission energy. The first approach is to reduce unnecessary data in order to lower the transmission bits. The second approach is to reduce the overhead bits such as the header. Reducing the number of headers is possible by accumulating the data and sending more data with one header. Reducing the number of data bits is very challenging. Data accuracy and data integrity should be considered.

The BSNs can be used for three main purposes. Its first purpose is for health administrators and therapists who want to monitor their patients and be notified of life threats in real time. Normal data measured from their subjects is not needed. Instead alarm data is needed mostly for scenarios like critical care patients and senior monitoring applications. The BSN applications discard normal data after has its arrival, surplus transmission procedure is wasted. We refer to the use of the BSN in this manner as dynamic transmission thresholds. Its second purpose is to do sports research and monitor exercise effects. Sensors are either attached or implanted to an athlete’s or a volunteer’s body. These sensors measure and transmit all outcomes regarding physical exertion testing within a controlled environment such as a laboratory [14]. Latency is not important in such cases. We refer to this use of BSN as burst communication.

The BSN’s third purpose is for the scenario when the subject must be under close observation and all measured data including normal data and alarm data must be transmitted. An example of such scenario is a patient after a surgery or critical health threat. This is the conventional state when the BSN continually transmits all pertinent data including alarm and normal samples.

Traditional BSN Frame defines one rule which carries all alarm data in the first frame and normal data in a polling turn specified by the CCU. We want to define three different situations. In each situation one or two type of data must be transmitted. Unnecessary data may be omitted in sensor node before transmission.

3.3.1 Dynamic Transmission State

In some cases, physician and care giver don’t need all measured data as they are simply looking for abnormal samples. For example, if a patient is released from hospital after heart surgery, the patient must be kept under close surveillance for two weeks which requires the conventional state BSN. The caregiver doesn’t need all measured parameters after two weeks. They need only abnormal samples especially from ECG sensor. Transmitting all usual samples is unnecessary. We want to ignore the normal samples and focus on abnormalities. On the other hand, caregivers may very well see the value in our ability to determine low and high value data. For example, heart-beats more than ninety beats per minute or less than fifty beats per minute are defined as alarms in the conventional BSNs as shown in Figure 3.3. We can adjust the upper and lower transmission thresholds so any samples more than eighty or less than fifty five beats per minutes will inform the care giver that the patient is approaching abnormal parameters. These samples are called exceeded samples.

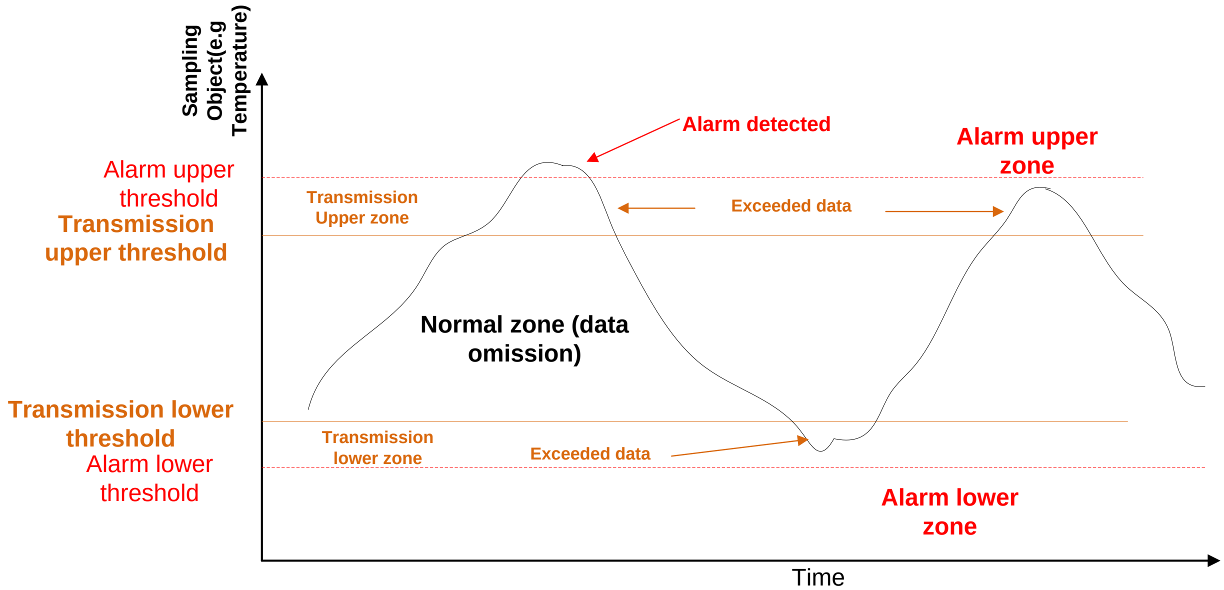

Figure 3.3 Transmission thresholds for dynamic state

Because the patient is not hospitalized, low alarm latency is required. We suggest omitting normal samples from sensor node's memory and retaining the exceeded data. The sensor node will only send samples higher than the transmission upper threshold or lower than the transmission lower threshold. Average transmitted bits are lower and energy saving is high.

3.3.2 Burst Communication State

In other cases, physician and caregivers don't need alarms because the subject is under a close observation [2] such as evaluating a new training theory. For example, a group of professional baseball players and volunteers are chosen for research on baseball swing training [14], in order to evaluate exercise and supplement effects. They take supplements three times a day and follow an exercise program. Researchers do not need alarm data since the subjects are inside the research institute. However, all details on normal data are required. On the other hand, outside the research institute, only alarm data might be needed by the physician for observing any incident or other accidental events. In similar cases, the subject is under close observation. Physicians or researchers need to collect information about vital parameters such as a medicine reaction (e.g. reaction to a heartbeat decelerator), an exercise effect such as breathing rate after a 100-meter running, brain signal changes after excitement. Data reduction in this state is based on burst communication in which the measured data is accumulated for a longer period and then transmitted with one common header. We use the burst communication method as complementary saving for low-traffic nodes.

3.3.3 Conventional State

In some cases, the physician or health supervisor needs to have all measured parameters. These parameters include normal and alarm samples. The CCU sets the sensor-nodes up conventional state. In this case we cannot reduce the number of transmitted bits. Normal data sub-slot in each frame is assigned to only one sensor in conventional BSN MAC [1]. In this situation, we suggest placing more than one sensor node's transmission turn in normal data sub-slot as long as the separator gap can distinguish two consecutive signals. The number of sensor nodes which can transmit normal data in one frame depends on normal data time slot length, packet sizes, and required gaps between them to clear the channel from PHY conflict between transmitters.

3.3.4 Start-up and Transition

BSN might be turned ON for several times before it is properly configured for test or other purposes. The BSN must function properly but conserve energy in case of a start-up test or left unattended. We suggest setting dynamic transmission state as the default state and set transmission thresholds as alarm thresholds. This default setting can save power consumption and yet recognize and transmit the alarm upon a start or restart. This default state guarantees lower power consumption when the BSN is turned ON and before it is fully configured as shown in Figure 3.4. State transition can be defined by a combination of alarm detection, time, location, prescribed medication, and battery status.

Alarm detection is the most important event. Upon alarm detection in dynamic transmission state or burst communication state, the BSN changes the state to conventional state in order to collect data and alarm as much as possible. Time is another parameter in state change decision as well as location. Location is determined by global positioning system (GPS) and can assist the care giver in deciding the BSN state. Taking a medicine might require more burst communication in order to study the body’s reaction. Low battery occurrence in the burst communication or in the conventional states automatically changes the state to dynamic transmission state, which prolongs the node’s life time while the remainder of battery is used only for alarm transmission. Sensor node processes samples to recognize the alarm regardless of the state and will inform alarm occurrence in the first assigned alarm sub-slot. It sends low battery notification in first transmitting header to the CCU which means asking for state change.

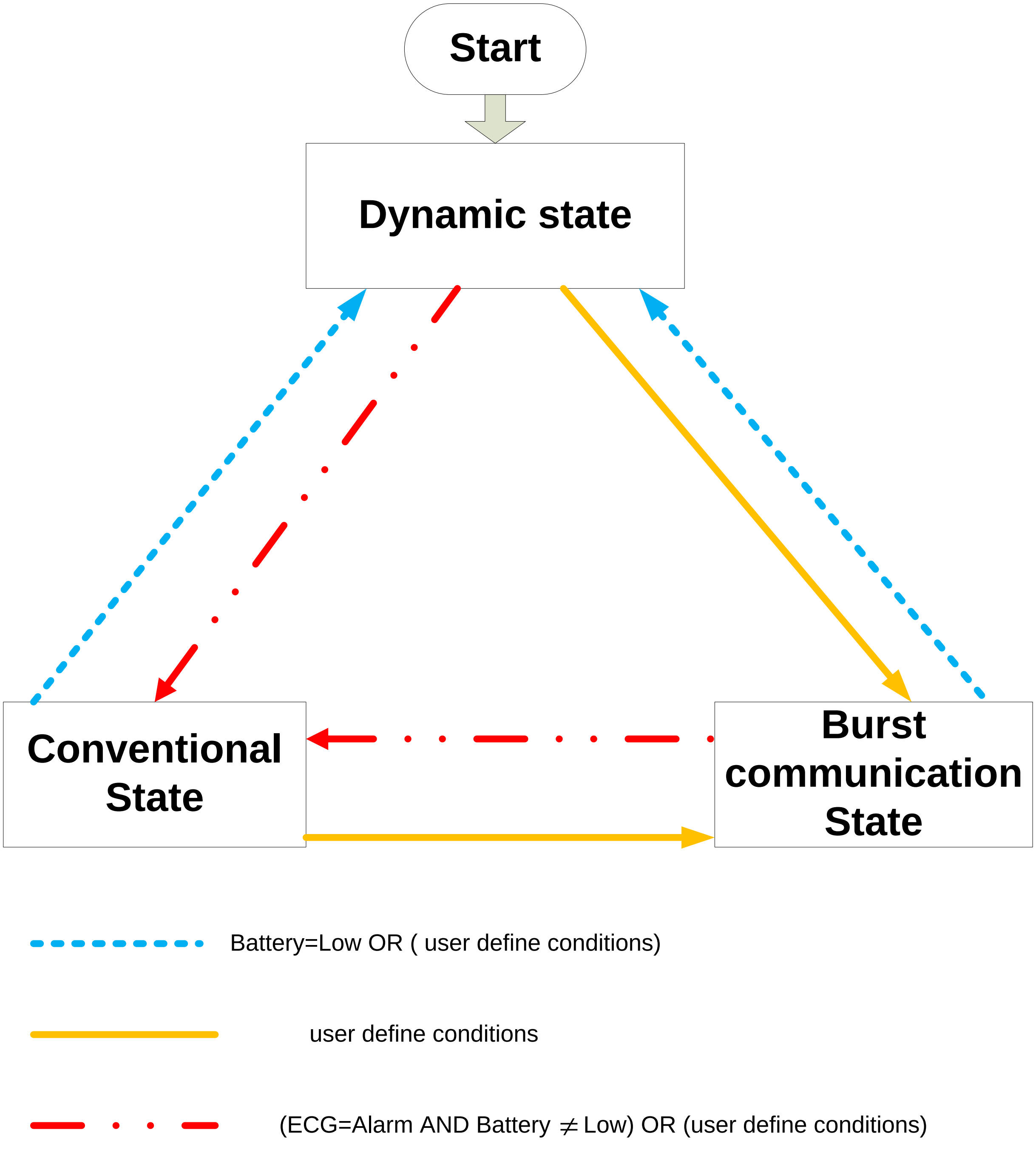

Figure 3.4 Start-up and state transitions

3.4 Proposed MAC Protocol

In this section, a context-aware MAC protocol is proposed to combine the three states for the BSN. CCU carries three main duties in BSN which are: 1) forming a TDMA-BASE frame, 2) determining the state for nodes, and 3) running the data polling algorithm to poll data from nodes.

Accepted alarm latencies are determined by the caregiver. The shortest latency in the BSN is assumed as frame period *(T)* as shown in Figure 3.5.

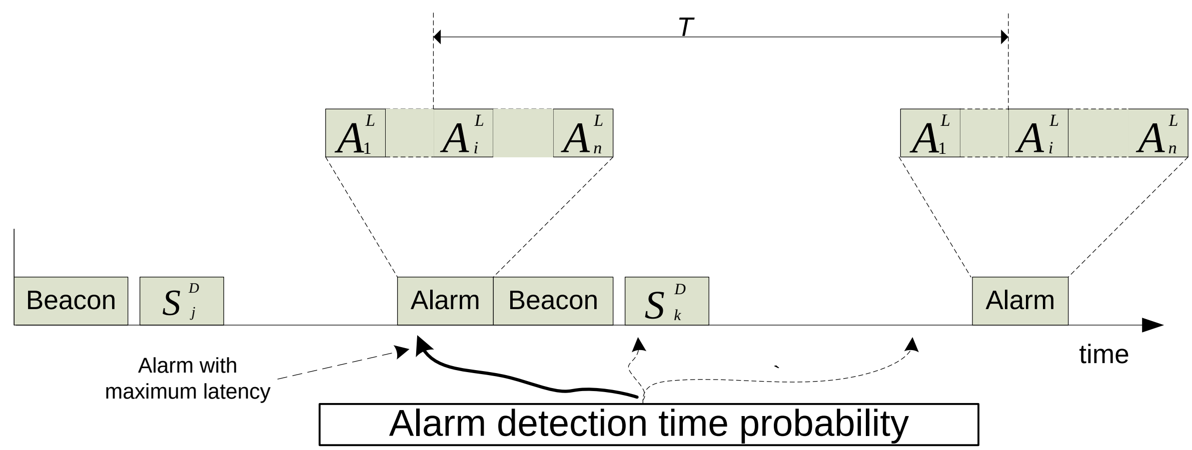

Figure 3.5 Alarm latency

Alarm latency is the period from the time when a sample is detected as an alarm sample to the first alarm transmission time, as shown in Figure 3.5. Maximum alarm latency occurs when the alarm is detected right after alarm sub-slot is started. The CCU forms a super-frame with the shortest acceptable alarm latency as frame period *(T)*. Then, the CCU divides the super-frame into: a beacon frame which is a down-stream transmission, normal data time-slot which can be divided into more than one up-stream data transmissions and alarm time-slot which is sub-slotted equally among all sensor nodes in the BSN, as shown in Figure 3.6.

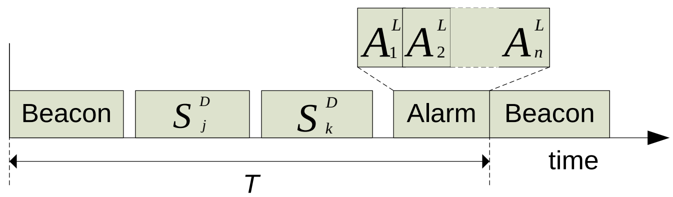

Figure 3.6 MAC frame structure

A beacon is formed by two sections. Universal section contains Synchronization (clock) and frame structure including alarm time-slot to all sensor nodes in the BSN. Second section carries data time slot, state change command and ACK to demanded sensor nodes. Beacon structure is shown in Figure 3.7.

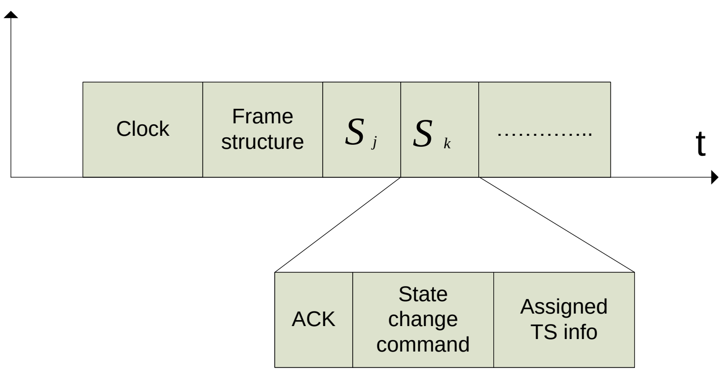

Figure 3.7 Beacon structure

The CCU broadcasts the beacon to all nodes. Each node synchronizes its internal clock with the CCU clock, finds its alarm sub-slot and data time slot if assigned. All nodes turn off the radio until next beacon, unless the nodes have an assigned time slot. They keep the radio ON or turn the radio ON to transmit the accumulated data with proper MAC header, as shown in Figure 3.8. This MAC contains two octets of frame control, one octet of sequence number, four to twenty octets of addressing field, data payload, and two octets of frame check sequence (FCS). Polling algorithm [1] is responsible for data time slot assignment based on node priority and data generation.

Octets	2	1	4 - 20	n	2
	Frame Control	Sequence Number	Addressing Field	Data Payload (S_i^{GD})	FCS

Figure 3.8 MAC data frame

If a sample is detected as alarm, the node turns ON the radio before its first alarm sub-slot and transmits the alarm signal. CCU returns an ACK which instructs the node to change to conventional state to collect all data. The node returns the ACK and starts to run in its conventional state, as shown in Figure 3.10(b). Alarm sub-slots are unloaded in most of the times.

A state change command according to transition conditions might be sent to one or all nodes. The MAC header for this command is shown in Figure 3.9 and it contains two octets of frame control, one octet of sequence number, four to twenty octets of address field, one octet of command type, *n* octets of command payload and two octets of frame control sequence. Recipient nodes will return an ACK and change the state according to command. State change sequences are shown in Figure 3.10©.

Octets	2	1	4 - 20	1	n	2
	Frame Control	Sequence Number	Addressing Field	Command Type	Command Payload	FCS

Figure 3.9 MAC state change command

A low battery must be reported to CCU in the first transmitted packet. The CCU will change the node’s state based on the other parameters. If the CCU decides to change the state, it sends a state change command as shown in Figure 3.10(d).

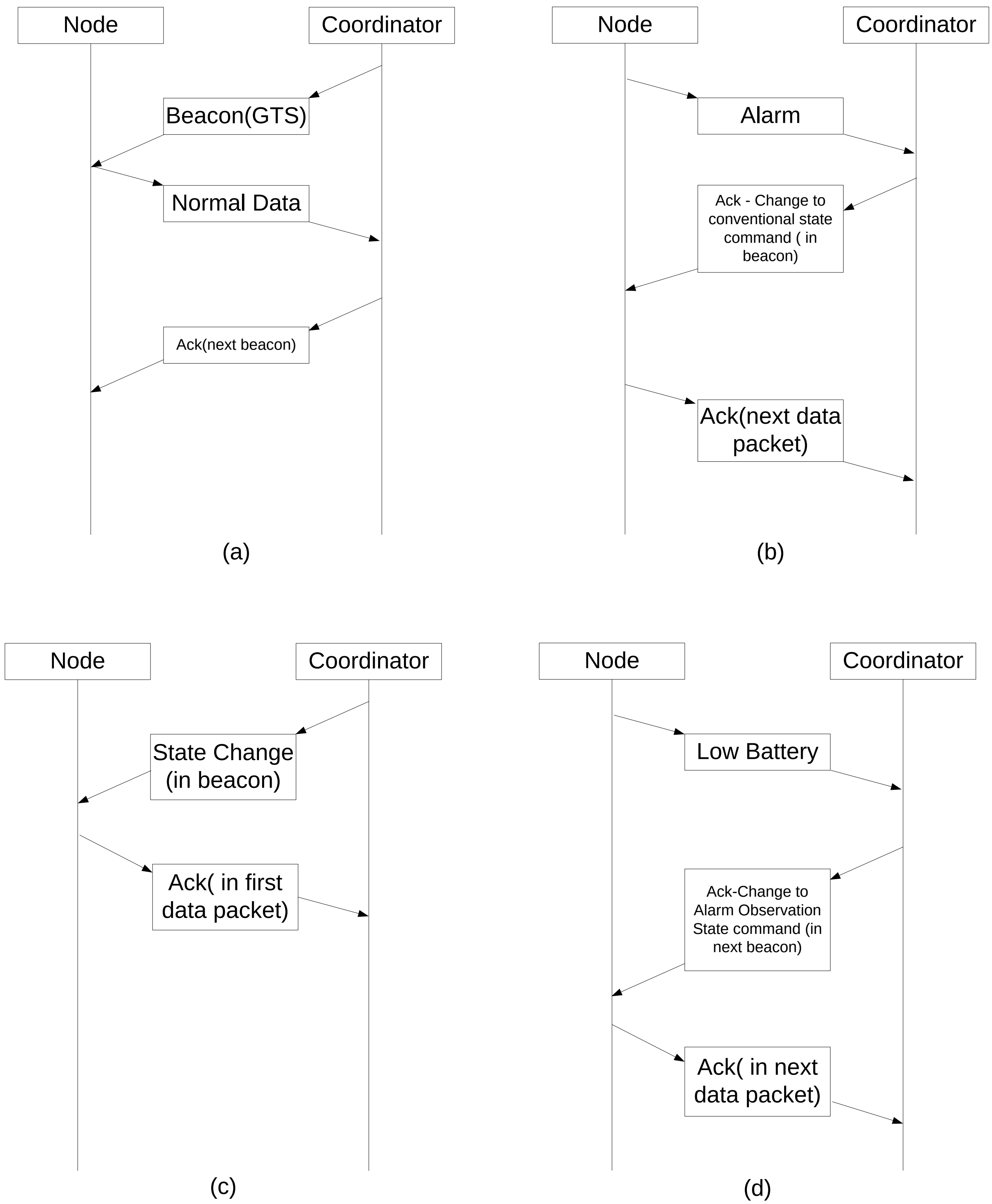

Figure 3.10 Context-aware MAC flow chart: (a) normal data transmission, (b) alarm data transmission, (c) state change by CCU, and (d) low battery detection by the sensor node

3.5 Chapter Summary

In this chapter we proposed a novel energy-saving MAC scheme with dynamic transmission thresholds consisting of three states: dynamic transmission state, burst communication state and conventional state. Dynamic transmission state is the key part for data reduction. Dynamic transmission thresholds are defined for this state. Dynamic transmission state lets the caregiver to choose the necessary data depending on time, patient's status and location. In-node data processing outranks other data reduction methods since it determines the value of data before transmission or omission. Our method omits data only after analog to digital conversion and comparison to thresholds. Burst communication state applies to cases without low latency requirement. Proposed MAC protocol guarantees required latency and conserve the energy with contention free TDMA-base scheme. Transition mechanism defines the switching between three states. This mechanism can switch the state according to peripheral, network and patient parameters. These parameters are patient's status, time, location, low battery and detected alarm. The network model shows that the transmission energy is a linear function of transmitting bits. So every transmission reduction results associated transmission energy saving.

Chapter 4 EXPERIMENTAL EVALUATION

In this chapter, the proposed context-aware transmission schemes are evaluated in OPNET simulations. In section 4.1, we set up simulation setting including data generation parameters and network parameters. In section 4.2, simulation results are given. In section 4.3, we discuss the power consumption reduction. Section 4.4 summarizes this chapter

4.1 Simulation Setup

A Body Sensor Network (BSN) is set_up by OPNET IT modeler simulation application with one Central Control Unit (CCU) and eight Zigbee end devices (sensor nodes). To compare the proposed context-aware MAC protocol with the conventional mode [1], we set_up two sensor nodes for each object. The first sensor node functions in conventional mode, while the second sensor node follows the proposed protocol. Objects are electrocardiogram (ECG, denoted as S_1), accelerometer (denoted as S_2), blood oxygen sensor (SpO2, denoted as S_3), and temperature (denoted as S_4). A typical patient daily schedule assumed in Figure 4.1 is used to evaluate the context-aware MAC protocol. However, other scenarios are evaluated in section 4.3. In this scenario, the caregiver asked to have alarm and exceeded data between 12:00 am to 08:00 am as the patient is at home and no normal data is needed. The patient leaves home at 08:00 am. Global Positioning System (GPS) shows the actual exit. The caregiver needs all the data from patient due to unexpected events possibility while the patient is driving. After the subject arrives the work place (detected by GPS), only samples which exceed the transmission thresholds are needed. When the patient leaves work at 5:00 pm, all data are required while the patient is out of work and home. Normal data can be ignored when patient is at home. Furthermore, if the patient takes a medication and sleeps about 9:30 pm, the caregiver will need to collect all order to study the reaction from medication for 2:30 hours. Accelerometer movement indicates an unusual event between 9:30 pm to 8:00 am. In this case, care giver needs all captured data. Table 4.1 illustrates this schedule.

Time	Conventional (all data)	Dynamic transmission (exceeded data)	Burst communication (all data with 10x delay)
12:00 am to 8:00 am	If accelerometer indicates movement	Default	
8:00 am to 8:30 am	Default	If GPS indicates indoor	
8:30 am to 5:00 pm		Yes	
5:00 pm to 5:30 pm	Default	If GPS indicates indoor	
5:30 pm to 9:30 pm		Yes	
9:30 pm to 12:00 am	If accelerometer indicates movement		Default

Table 4.1 Typical patient daily schedule and required data

The state transition conditions for the patient are shown in Figure 4.1.

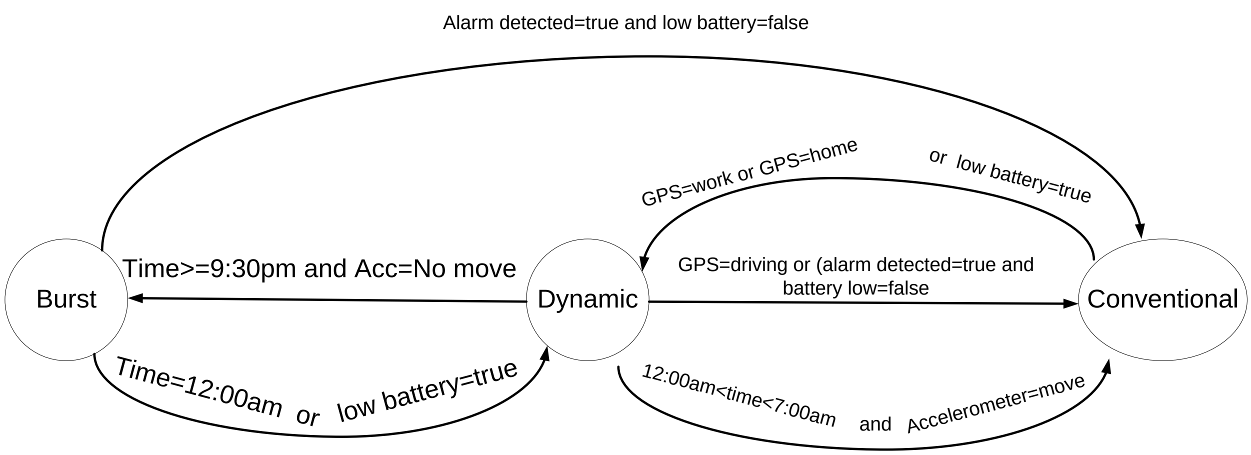

Figure 4.1 Transition diagram

Accelerometer and blood oxygen sensor (SpO2) have lower sampling rates and smaller sample resolutions due to their slower changes and less variations. Temperature is a slowly varying, and one sample every fifty seconds provides sufficient data. One Byte is enough to report a temperature sample. We assume that the header is 15 Bytes for every packet [1, 8].

Each packet consists of data generated by sensor plus one header. Data generated by sensors, packet sizes and average bit-rates are calculated based on Equations (3.1), (3.2) and (3.3) with the typical values from [1], as shown in Table 4.2.

S_i	Name	${S^F}_i$ (samples/sec)	M_i (Bytes)	${S^{GD}}_i$ (Bytes/sec)	T_i (seconds)	${S^P}_i$ (Bytes)	${A^{TR}}_i$ (bps)
S_1	ECG	256	4	1024	8	8207	8207
S_2	Accelerometer	50	2	100	8	815	815
S_3	Sp O2	20	1	20	20	415	166
S_4	Temperature	1	1	1	50	65	10.4

Table 4.2 Parameter values for different sensors

Transmission rates can be simulated by packet size and transmission interval in each Zigbee end device's traffic properties.

In burst communication state of ECG sensor node, buffer size limitation is a1 concern and extra latency is not tolerated by the physician or caregiver. We assume the buffer size to be 80 kBytes (81,920 Bytes). Based on Equation (3.2), T_i is given by

$$T_i = \frac{{S^P}_i - O^v}{{S^F}_i . M_i .} = \frac{81{,}920 - 15}{256 * 4} = 79.985 \text{ seconds}$$

It means data latency can be extended by 10 times (from 8 to 80 seconds). Accelerometer, SpO2 and temperature sensors are slower-varying nodes and accumulating the data is not very noticeable compared to ECG nodes. Due to their low importance, update intervals can be expanded to a large value. We multiply their update interval by 10 for a fair comparison with the ECG.

In the dynamic state, each sensor node will send only exceeded samples in each update interval. We assume five percent of all samples are exceeded according to transmission thresholds. Normal data has been omitted in the dynamic state and each packet consists of five percent of samples and 15 Bytes header.

4.2 Simulation Results

Each simulation was run for 24 hours according to daily schedule stated in Section 4.1. The ECG had a high sampling rate due to its fast changes and large sample resolution because of numerous measuring levels which required more quantization levels. It also had a short transmitting period because of its vital importance. These ECG parameters cause a high traffic generation.

Burst communication state does not show a significant transmission reduction, as shown in Figure 4.2 between 9:30 pm and 12:00 am. Dynamic transmission state has reduced the transmission rate between 12:00 am to 8:00 am, 8:30 am to 5:00 pm and 5:30 pm to 9:30 pm.

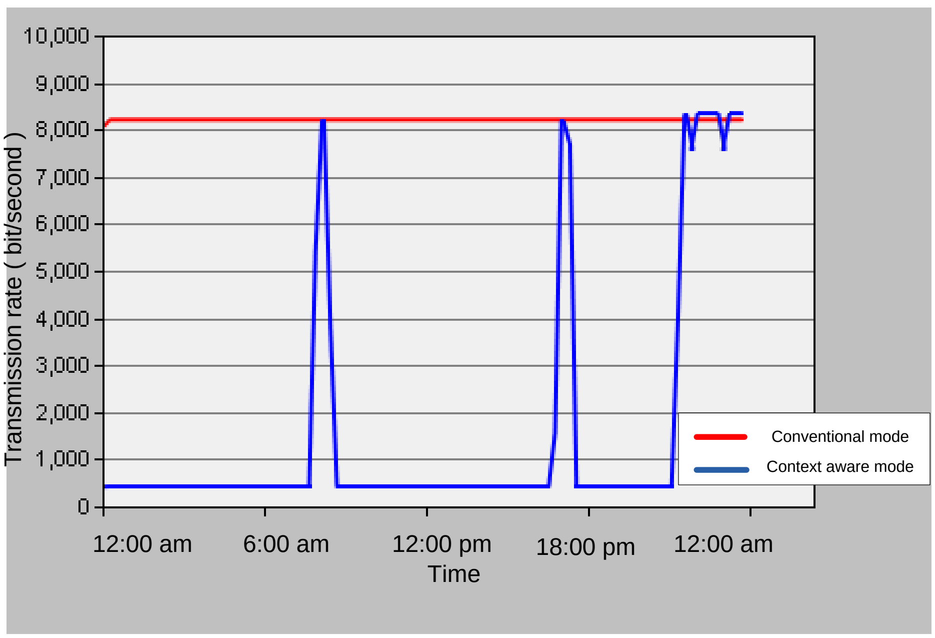

Figure 4.2 Transmissions of ECG data

The transmission rate of the ECG was 8207 bits per second (bps) in conventional state (Table 4.2). We can calculate the average rate for burst communication state and dynamic transmission state by Equation (3.3) when ${S^F}_1 = 256$ samples/second, $M_1 = 4Bytes$, $T_1 = 80\ seconds$ (Burst communication) and data ratio=5% (Dynamic transmission).

$$A^{TR\,D}{}_1 = 8 * \frac{S^F{}_1 .* M_1 * \ T * 0.05 + \ O^v}{T} = 8 * \frac{256 * 4 * 8 * 0.05 + \ 15}{8} = 424.6 \ bps$$

$$A^{TR\,B}{}_1 = 8 * \frac{S^F{}_1 .M_1.T_1 + \ O^v}{T_1} = 8 * \frac{256 * 4 * 80 + \ 15}{80} = 8193.5 \ bps$$

Burst communication state shows a minor transmission reduction, as shown in Figure 4.3 between 9:30 pm and 12:00 am. Dynamic transmission state transmission reduction is equal to ECG.

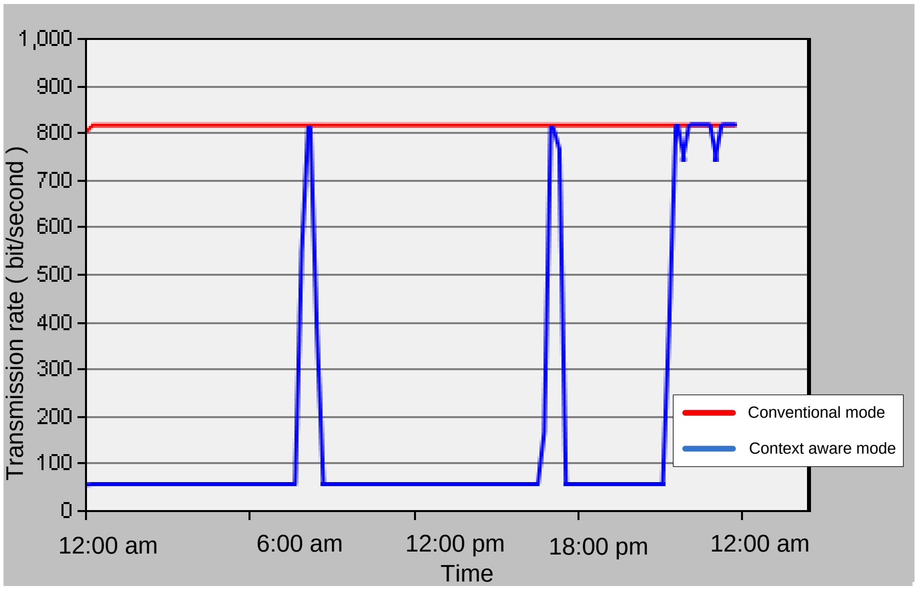

Figure 4.3 Transmissions of accelerometer

The transmission rate of the accelerometer was 815 bps in conventional mode. We calculated the average rate for burst communication state and dynamic transmission state by Equation (3.3) when $S^F{}_2 = 50$ samples/second, $M_2 = 2Bytes$, $T_2 = 80 \ seconds$ (Burst communication) and data ratio=5% (Dynamic transmission).

$$A^{TR\,D}{}_2 = 8 * \frac{S^F{}_2 .* M_2 * \ T * 0.05 + \ O^v}{T} = 8 * \frac{50 * 2 * 8 * 0.05 + \ 15}{8} = 55 \ bps$$

$$A^{TR\,B}{}_2 = 8 * \frac{S^F{}_2 .M_2.T_2 + \ O^v}{T_2} = 8 * \frac{50 * 2 * 80 + \ 15}{80} = 801.5 \ bps$$

Burst communication state shows more fluctuation in transmission shape due to data accumulation and flooding, as shown in Figure 4.4 between 9:30 pm and 12:00 am. Dynamic transmission state transmission reduction is similar to ECG.

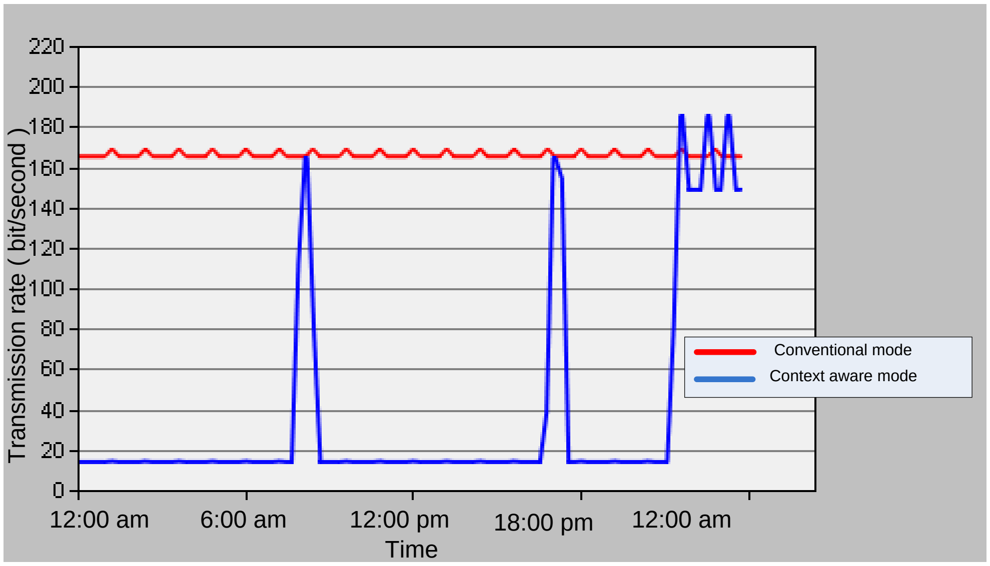

Figure 4.4 Transmission of SpO2

The transmission rate of the SpO2 was 166 bps in conventional mode. We can calculate the average rate for burst communication state and dynamic transmission state by Equation (3.3) when $S^F{}_3 = 20$ samples/second, $M_3 = 1Bytes$, $T_3 = 200\ seconds$ (Burst communication) and data ratio=5% (Dynamic transmission).

$$A^{TR\ D}{}_3 = 8 * \frac{S^F{}_3 .* M_3 * T * 0.05 + O^v}{T} = 8 * \frac{20 * 1 * 20 * 0.05 + 15}{20} = 14\ bps$$

$$A^{TR\ B}{}_3 = 8 * \frac{S^F{}_3 .M_3.T_3 + O^v}{T_3} = 8 * \frac{20 * 1 * 200 + 15}{200} = 160.6\ bps$$

Burst communication state significantly reduced the transmission rate as shown in Figure 4.4 between 9:30 pm and 12:00 am. Dynamic transmission state transmission reduction is lower than ECG.

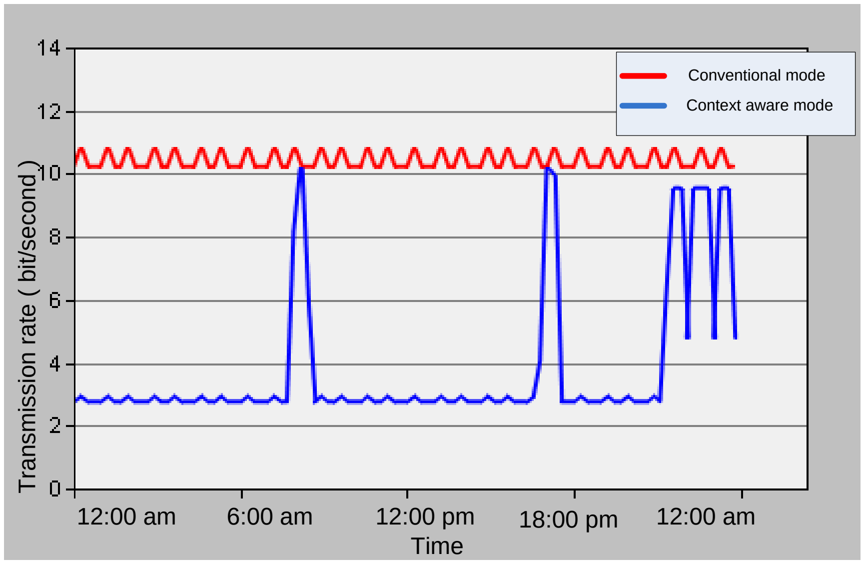

Figure 4.5 Transmission of temperature

The transmission rate was 10.4 bps in conventional mode. We can calculate the average rate for burst communication state and dynamic transmission state by Equation (3.3) when ${S^F}_4 = 1$ samples/second, $M_4 = 1Byte, T_4 = 500\ seconds$ (Burst communication) and data ratio=5% (Dynamic transmission).

$$ {A^{TR\,D}}_4 = 8 * \frac{{S^F}_4 .* M_4 * \ T * 0.05 + \ O^v}{T} = 8 * \frac{1 * 1 * 50 * 0.05 + \ 15}{50} = 2.8\ bps $$

$$ {A^{TR\,B}}_4 = 8 * \frac{{S^F}_4 .M_4.T_4 + \ O^v}{T_4} = 8 * \frac{1 * 1 * 500 + \ 15}{500} = 8.24\ bps $$

The average transmission during the day (over three states) are taken from the "OPNET top object results" and shown in Table 4.3. This table shows the average transmission rate is reduced from 8207 bps (bit per second) to 1562 bps for ECG, from 815 bps to 166 bps for accelerometer, from 166 bps to 36 bps for SpO2, and from 10.4 bps to 3.7 bps for temperature sensor. It means 81% transmission reduction for ECG, 80% for accelerometer, 78% for SpO2, and 64% for temperature sensor.

op Objects Report: ZigBee Application.Traffic Sent (bits/sec)

Rank	Object Name	Minimum	Average	Maximum
----	---	--------------	--------------	--------------
1	ECG-conventional	8,055.0	8,207.0	8,207.0
2	ECG-context-aware	416.8	1,561.9	8,345.2
3	Accelerometer-conventional	799.9	815.0	815.0
4	SpO2-conventional	165.2	166.0	169.1
5	Accelerometer-context-aware	54.0	166.0	816.3
6	SpO2-context-aware	13.9	35.6	185.9
7	Temperature-conventional	10.2	10.4	10.8
8	Temperature-context-aware	2.8	3.7	10.2

Table 4.3 Comparing traffic generation in conventional mode and context aware mode

Table 4.4 evaluates transmission savings and increased latency for each state. This information is gathered from table 4.3, assumed latency and calculated transmission rate based on equation 3.3.

	Conventional	Dynamic transmission thresholds		Burst communication		
Name	Average bit-rate (bps)	Average bit-rate (bps)	Transmission saving (percent)	Average bit-rate (bps)	Latency multiply	Transmission saving (percent)
ECG	8207	424.6	94.8	8193.5	10	0.16
Accelerometer	815	55	93.2	801.5	10	1.6
Sp O2	166	14	91.5	160.6	10	3.2
Temperature	10.4	2.8	73	8.24	10	20.7

Table 4.3 Transmission saving and latency

Transmission rate shows from 95 percent to 73 percent saving in the dynamic transmission thresholds state with our assumptions. It has from less than 1% to 21% saving in burst communication state with 10 times latency.

4.3 Power Saving

Consumed transmission energy per bit (E_0) is assumed to be 0.296 mJ/Kb [2]. The transmission power is then given by

$$P_{\mathrm{i}} = E_0 * A^{TR}{}_i \text{ (J/s)} \tag{4.1}$$

Let $P^{\mathrm{tC}}{}_i$, $P^{\mathrm{tD}}{}_i$ and $P^{\mathrm{tB}}{}_i$ represent the average power in conventional, dynamic transmission thresholds, and burst communication states, respectively. For example, at ECG sensor, $P^{\mathrm{tC}}{}_i$, $P^{\mathrm{tD}}{}_i$ and $P^{\mathrm{tB}}{}_i$ are given by

$P^{\mathrm{tC}}{}_1$ = 8207*2.96E-7=2.43E-03 J/s

$P^{\mathrm{tD}}{}_1$ = 424.6*2.96E-7=1.26E-04 J/s

$P^{\mathrm{tB}}{}_1$ = 8193.5*2.96E-7=2.43E-03 J/s

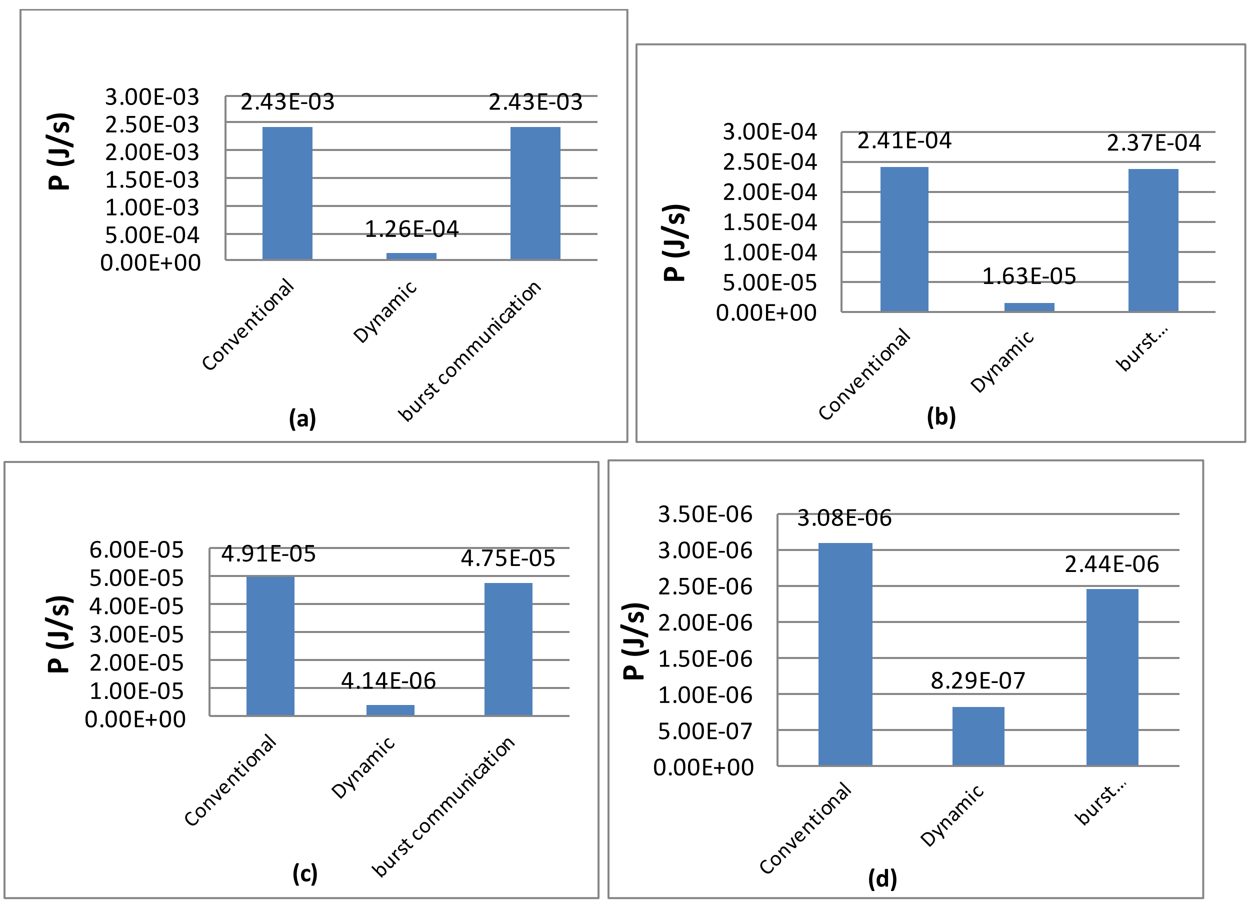

Figure 4.6 Average transmission power consumption in three states at different sensors: a) ECG, b)accelerometer, c)SpO2, and d)Temperature

Transmission power consumption depends on transmitted bits. We can see a significant power saving on dynamic transmission thresholds state for all sensors. Burst communication state is effective for lower data transmitting sensors. Figure 4.6(a) shows the power consumption in ECG node. Figure 4.6(b), (c) and (d) show the power consumption for accelerometer, SpO2, and temperature respectively.

4.3.1 Saving on Different Traffics

As illustrated in simulation results and power saving, burst communication state and dynamic transmission state acts differently on different traffics. Figure 4.7 compares the energy saving percentage on different nodes.

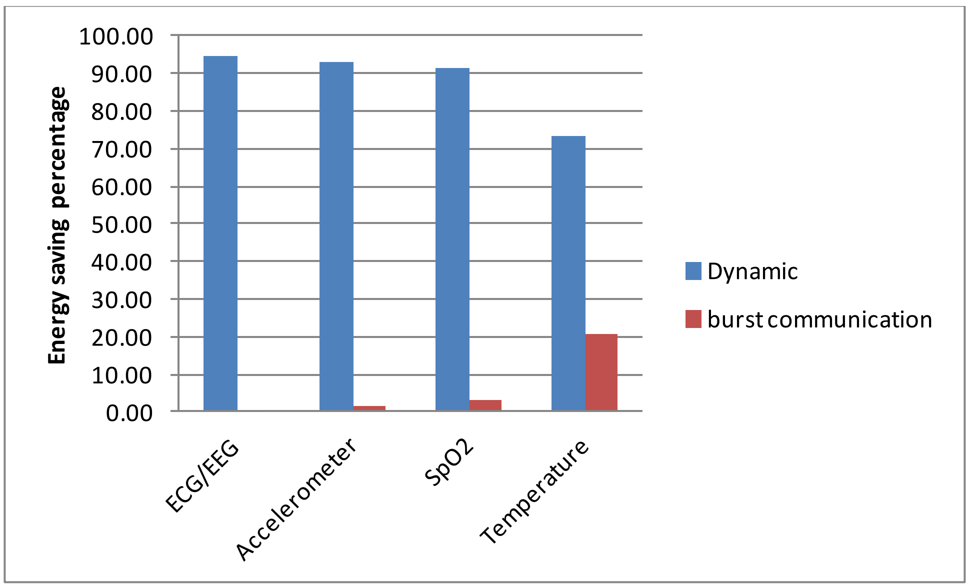

Figure 4.7 Transmission energy saving percentage on different nodes.

Dynamic transmission state saves from 94 percent energy on high traffic nodes to 73 percent on low traffic nodes. Burst communication saves from 0.1 percent energy on high traffic nodes to 20% on low traffic nodes.

4.3.2 Combination of Three States

We saved different amounts of energy on each sensor in burst communication and dynamic transmission states. Now we show the overall energy saving when combining three states. We examine the power saving with different combinations of three states. We use T_D, T_B and T_C to represent the percentage of time for the dynamic transmission, burst communication, and conventional states, respectively. We have:

$$T_D + T_C + T_B = 1 \ , 0 \leq T_D \leq 1 \quad , 0 \leq T_C \leq 1 \quad , \quad 0 \leq T_B \leq 1$$

Then consumed power (P_i) at each sensor is given by:

$$P_1 = 2.96\text{E} - 7 * (T_D * 424.6 + T_C * 8207 + T_B * 8193.5) \ \text{J}$$

$$P_2 = 2.96\text{E} - 7 * (T_D * 55 + T_C * 815 + T_B * 801.5) \ \text{J}$$

$$P_3 = 2.96\text{E} - 7 * (T_D * 14 + T_C * 166 + T_B * 160.6) \ \text{J}$$

$$P_4 = 2.96\text{E} - 7 * (T_D * 2.8 + T_C * 10.4 + T_B * 8.24) \ \text{J}$$

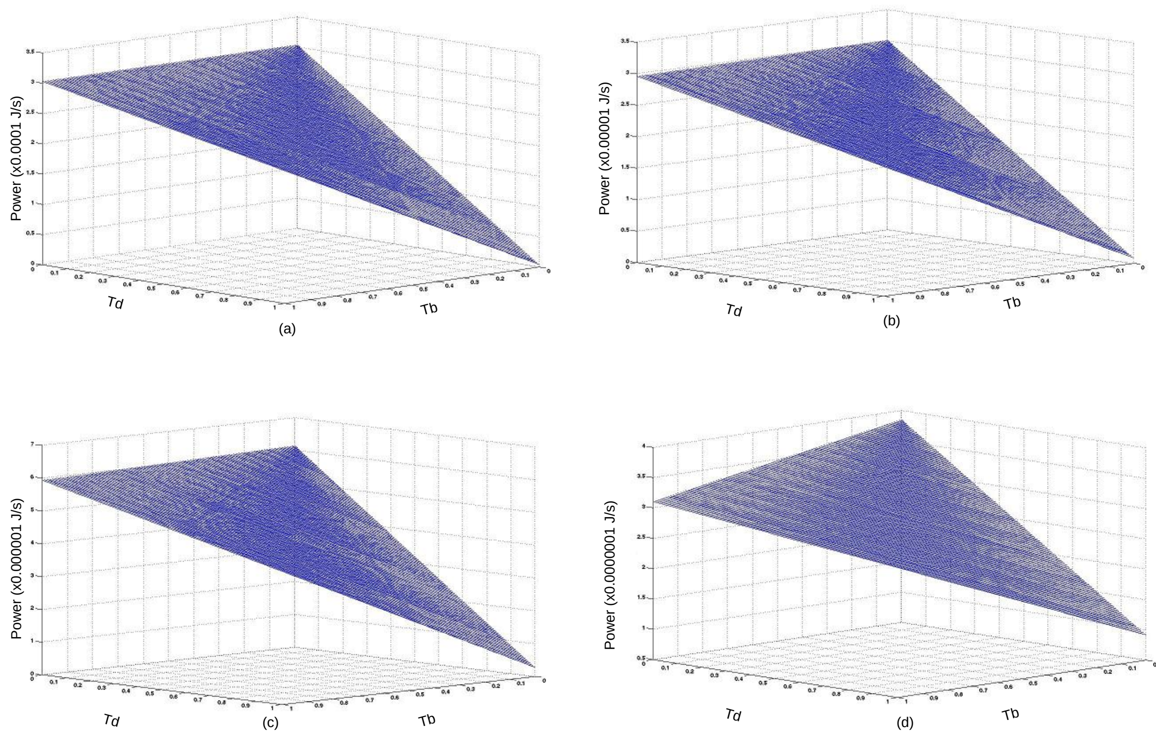

Figure 4.8 Transmission power consumption on different combination of states at different sensors: (a) ECG, (b) accelerometer, (c) SpO2, and (d) temperature.

Figure 4.8 illustrates power consumption with different combinations of states. At ECG sensor, the difference between burst communication and conventional states is not noticeable as the left side of graph in Figure 4.8(a) is almost flat. But the ECG power consumption is much lower in the dynamic state. We see the right side of the graph rapidly decreased to almost zero. In Figures 4.8(b) and 4.8(c), accelerometer sensor and SpO2 sensor save the energy in the dynamic state almost the same as ECG plus a minor improvement in burst communication as we note the left edge of the graph which demonstrates a slight visible slope. Figure 4.8(d) demonstrates the burst communication state can improve power consumption as represented by 20% slope, but the slope in right edge is much lower than other sensor nodes and never diminishes to lower than $9x10^{-8}$J/s which is mostly headers.

4.4 Chapter Summary

Based on the evaluations provided in this chapter, context-aware scheme with assumed scenario saves from 64% to 81% of transmission energy in different sensor. We conclude that the energy saving percentage in different approaches depends not only on the network parameters such as header or data reduction but also on the node's traffic generation. Burst communication reduces the output traffic at low traffic nodes. In these nodes overhead is comparable to data bulk and reducing the number of headers is valuable. Omission of unnecessary data saves the energy much better than header saving in high traffic nodes. Dynamic transmission thresholds are considered to be a good approach for data omission.

Chapter 5 CONCLUSION AND FUTURE RESEARCH DIRECTIONS

In this chapter we conclude our work and provide additional directions for future research.

5.1 Conclusion

In this research, energy-saving MAC scheme with dynamic transmission thresholds for body sensor networks is proposed. Dynamic transmission thresholds can limit the transmitted data. The more valuable fraction of captured data is transmitted. Negligible data are subject to omission. In node data processing by dynamic transmission thresholds evaluates the data before the execution. Simulations results show that our scheme is effective in all nodes. It reduces the data transmission as caregiver's request. Our method outranks three other schemes in transmission reduction. Burst communication method [1,2 and 23] is only effective for low traffic nodes. It saves up to 21% transmission energy in these nodes. This method loses the efficiency as traffic generation increases and header to data ratio reduces. Sampling rate reduction [6] and sampling resolution reduction [36] may cause a valuable data loss before they have an evaluation chance. Our novel protocol omits data only after analog to digital conversion and comparison to thresholds. It saves up to 73% energy on low traffic nodes and up to 95% energy on high traffic nodes.

5.2 Future Research Directions

Due to a very limited power supply, energy saving is a critical problem in the BSN. In this section, additional ideas are introduced for future works.

Transmission thresholds are one of the most important BSN parameters which can be used to determine the amount of alarm data in dynamic transmission thresholds state.

Dynamic transmission thresholds can permit the supervisor to keep the BSN in the dynamic transmission state for a longer period. Dynamic transmission thresholds can be done by two approaches. First, the differential value of one measuring object indicates the object's changing slope, and it can be used to predict the alarm occurrence. The second approach is to study the objects' samples and find the patterns which are not still alarms but statically would be heading to an alarm. The first approach can be applied to simple objects like temperature and blood oxygen level (SpO2), and the second approach can be applied to the more complicated objects like electrocardiogram (ECG).

Directional antennas consume less energy compared to omni antennas. If antenna production technology could offer micro-directional antennas with 1/8 of space coverage, transmission data by one of these 8 antennas would consume 1/8 energy in comparison with an omni antenna. A Multi Input, Multi Output (MIMO) scheme can find the best directed antenna in each interval by calculating the received signal strength from each antenna. This scheme works on layer-3 but is based on layer-1 measured parameters. Even if additional energy is consumed to find the best directed antenna with a MIMO scheme, much energy can be saved due to directional transmission.

Each transmission consumes some energy for start-up regardless of the number of transmitted bits. Reducing the number of transmissions can reduce the energy consumption. The burst communication state reduces the number of transmissions, but in this research, we chose to ignore this saving and left it for future works. Expanding the frame length can reduce the number of transmissions. Start-up energy can be included in network modeling and delivery cost to introduce the trade-off between this saving and latency.

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