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Energy-saving MAC scheme with dynamic transmission thresholds for body sensor networks

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Abstract: Body sensor network offers a real-time remote monitoring of patients with minimum cost to the health care system. It gathers health parameters by wireless nodes attached on the body or implanted inside the body and relay the information to a medical application. The power source in BSN like any other mobile system is the major concern. The power source recharge is very difficult and inconvenient in most cases. Energy saving is critical to prolong the network lifetime. This work targets the expansion of network lifetime with a context-aware dynamic transmission scheme. Our proposed scheme reduces data transmission by a status awareness definition. We used another energy saving scheme called burst communications to compare methods. Burst communication reduces MAC overhead by a less number of headers for the same data. The simulation results show up to 90 percent reduction in transmission energy especially in high traffic generator nodes.

Keywords: Body Sensor Network, Dynamic Transmission Threshold, Energy Saving

1. Introduction

Body Sensor Network (BSN) presents a real time, reliable and continuous measurement and transmission solution to monitor and report health parameters. A BSN is formed by a number of sensor nodes and a Central Control Unit (CCU). Sensor nodes measure vital parameters from body's organs. Vital parameters in the human's body are electrocardiography (ECG), electroencephalography (EEG), glucose level, blood pressure, oxygen level in blood (SpO2), temperature and body movement. The sensors and the CCU are unified using Zigbee standard and connected to a medical application by other wireless connection standards like Wireless Fidelity (WiFi) or Global System for Mobile communication (GSM). Energy saving is one of the most appropriate approaches to prolong the network lifetime.

This paper addresses energy conservation by transmission reduction. 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. The caregiver can choose the more important fraction of data for transmission and less important fraction for omission. Our scheme applies to high traffic generator nodes which are subject to energy exhaust more than low traffic nodes. The rest of the paper is organized as follows. Related works are reviewed in Section 2. Problem definition and formulation is introduced in Section 3. Section 4 describes our dynamic transmission thresholds scheme. Operation algorithm and proposed MAC protocol are presented in Section 5. Transmission reduction and energy saving are evaluated in Section 6. Finally, conclusion is presented in Section 7.

2. Related Works

Due to pervasive demands for BSN, numerous literatures are done to prolong the BSN lifetime by different approaches. Four main approaches are: MAC approach, PHY approach, energy harvesting and data reduction.

Sidharth Nabar (2010) in [1] proposed a polling based algorithm to postpone the transmission as much as possible to make a larger packet. A larger packet reduces the MAC overhead and save the transmission energy. Hassan Ghasemzadeh (2010) in [2] and Vitali Loseu (2011) in [3] proposed a similar idea and called it *burst communication*. Burst communication 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 to one from several. Secondly, the numbers of header bits are reduced through the use of one header for more data.

Shuo Xiao (2009) in [4] proposed the radio wave power adjustment which 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. The human body can act as a medium to relay a radio wave. This propagated wave is known as a creepy wave. Adrian Sapio (2010) in [5] found that layer-1 transmitter and receiver are able to communicate through this new medium so communication energy will dramatically drop and battery life will increase.

Jerald Yoo (2010) in [6] delivered the power remotely to a group of electrocardiogram sensors with 54.9% efficiency by an adhesive bandage. Xiaoyu Zhang (2010) in [7] designed a passive radio-frequency (RF) receiver with energy harvesting ability. David Layerle (2011) in [8] proposed an integrated passive receiver in order to harvest wake-up signal energy. Harvested energy can trigger the receiver circuit.

Zhisheng Yan (2011) in [9] reduced the sampling rate and expanded the frame length to minimize the data generation based on previous samples processed in the CCU. This method lets the sensor nodes to sleep for a longer time due to lower communication and as a result, saves a considerable amount of energy. Adam T. Barth (2010) in [10] proposed a new protocol 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.

3. Problem Definition

Burst communication increases the delay and overflows the buffer. It demands a large buffer memory and only applies to such a situation that delay is not important. On the other hand, header bits are not comparable to data bits in high traffic sensor and savings are not considerable. Energy harvesting either applies only to small amount of energy such as trigger energy, or demands a huge source of energy very close to the sensor. Delivered power dramatically reduces with distance. More power source and more powerful waves are required to feed the nodes. Powerful remote feeding magnetic waves are suspected to cause cancer or brain damages in peoples. Data reduction by context-awareness can omit the unnecessary data before the transmission. On the other hand, reducing the sampling rate or sample resolution by the CCU's request can omit the necessary data before being processed. In node data processing guarantees the necessary data transmission.

Data generated Bytes (D_i) by each sensor (S_i) which depends on three elements. The first element is sampling frequency (F_i) and it depends on the measuring object's fluctuation rate. The second element, sample resolution (M_i), depends on the accuracy required on each measured object. More accurate measurements require more quantization levels and a larger digital sample resolution. The final element is the data update interval (T_i), as it depends on accepted latency for each measured object like electrocardiography (ECG), electroencephalography (EEG) and temperature. The longest accepted latency is determined by physician or care giver. Packet (P_i) consists of data generated by analog to digital convertor (A/D) in one interval plus one header by the Zigbee application. MAC header (O) can be from 9 to 25 Bytes in wireless in [10] personal area networks. Packet size can be shown by Equation (1).

$$\mathrm{P}_i = D_i + \mathrm{O} = F_i \,.M_i.T_i + \mathrm{O} \text{ (Bytes)} \qquad (1)$$

And average transmission rate (R_i) by S_i can be illustrated by Equation (2).

$$R_i = 8 * \frac{F_i \,.M_i.T_i + \mathrm{O}}{T_i} \quad (bits/s) \qquad (2)$$

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 and targeted in this research. When consumed energy is $\mathrm{E_0}$ (jule/bit) for each transmitted bit, the average transmitter power consists of data transmission power (E_D) and header transmission power (E_O) is shown in Equation (3).

$$P_i = E_0 * R_i = E_0 * 8 * \frac{F_i \,.M_i.T_i + \mathrm{O}}{T_i}$$

$$= E_0 * 8 * F_i \,.M_i + E_0 * 8 * \frac{O}{T_i} = E_\mathrm{D} + E_\mathrm{O}(J/s) \qquad (3)$$

In fact burs communication approaches [1, 2 and 3] aim to reduce MAC header transmission power(E_O). They try to accumulate more data and transmit them with one header. Data reduction approaches are based on the pay-load transmission energy (E_D) reduction. Sampling rate [9] adjustment tries to find minimum acceptable sampling rate. It adjusts the sampling rate based on the BSN's traffic. Sample resolution adjustment [10] tries to find minimum Byte per sample. It adjusts the sample resolution based on previous samples processed in the CCU.

4. Dynamic Transmission Thresholds

Sensor nodes measure vital parameters from body's organs. Vital parameters in the human's body are continuous phenomenon such as temperature and oxygen level in blood. These parameters can change between normal values and abnormal. A normal value indicates that the patient is in normal situation. 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 subject to heart beat monitoring. Physician needs 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, care givers may very well see the value in our ability to predict some alarms. 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. We can adjust the upper and lower transmission thresholds so any samples more than eighty or less than fifty five beats per minutes will warn that the patient is approaching abnormal parameters. These samples are exceeded samples. Alarm and transmission thresholds are illustrated in Figure 1.

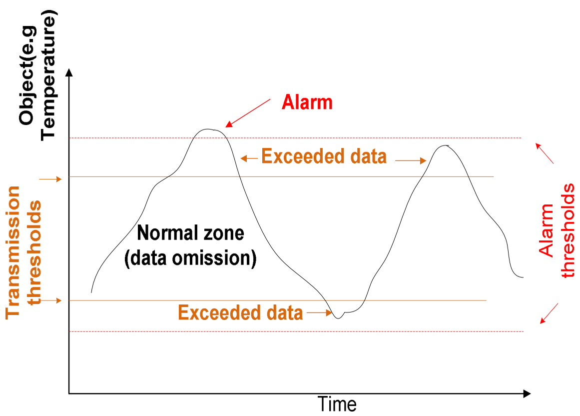

Figure 1. *Alarm and transmission thresholds for a typical object like temperature.*

We define the exceeded data ratio (D_r) as the number of exceeded samples divided by captured samples in each update interval (T_i). The exceeded data ratio depends on two factors. First factor is sample distribution pattern of the measuring phenomenon. Second factor is the transmission threshold distance from the mean sample. A lower variance in sample distribution and farther transmission thresholds from the mean causes lower bulk of exceeded samples. Exceeded data with different variance and transmission thresholds are shown in Figure 2.

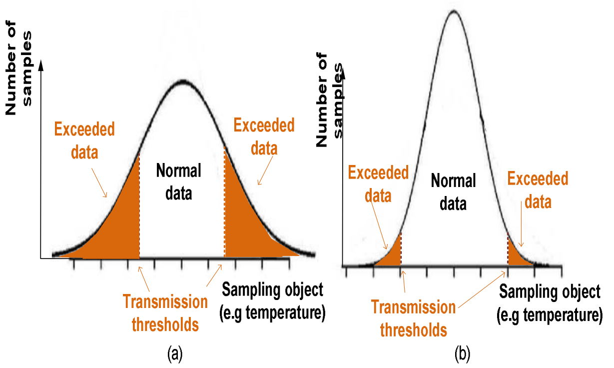

Figure 2. *Determining exceeded data and normal data: (a) higher variance and closer transmission thresholds to mean, (b) lower variance and farther transmission thresholds to mean.*

5. Proposed MAC Protocol

In this section, a context-aware MAC protocol is proposed. In our scheme, CCU carries three main duties in a BSN. Its first duty is receiving acceptable alarm latencies, alarm thresholds and transmission thresholds from medical application. Its second duty is to form a Time Division Multiple Access (TDMA) frame including beacon and broadcast it into the BSN. CCU's third duty is running the data polling algorithm to poll data from nodes and transmitting collected data to medical application.

Accepted alarm latencies are determined by the caregiver. Shortest latency in the BSN is assumed as frame period (T). The CCU forms a super-frame with 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 transmission (D_j, D_k) and alarm time-slot which is sub-slotted equally among all sensor nodes in the BSN, as shown in Figure 3.

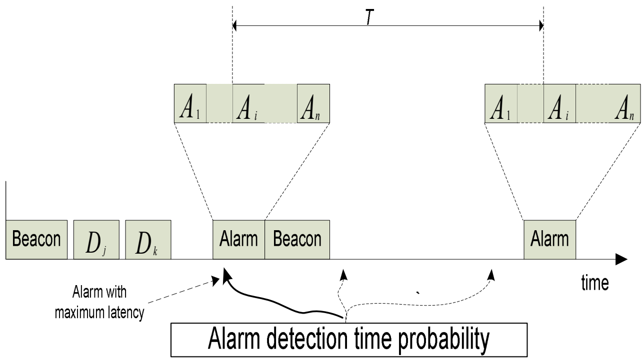

Figure 3. *Alarm latency and super-frame structure.*

The beacon carries mandatory data to sensor nodes. These data are assigned data time-slots, alarm time-slot and CCU clock. CCU broadcasts the beacon to all nodes. Each node synchronizes its internal clock with the CCU clock. Then it finds its alarm sub-slot. The node also determines its data time slot if assigned. All nodes turn off the radio until next beacon unless the nodes have an assigned time slot. If new thresholds are delivered by beacon, the sensor stores them. Sensor nodes keep ON or turn ON the radio to transmit the accumulated data. They attach the MAC header to the accumulated data. A low battery alert is included in MAC if occurred. Sensor nodes turn OFF the radio after transmission. If an alarm is detected during the frame, sensor node turns ON the transmitter at its alarm sub-slot, transmits the alarm and turns OFF the radio. All sensor nodes turn ON the radio at beacon time. The sensor node's processor task is shown in Figure 4.

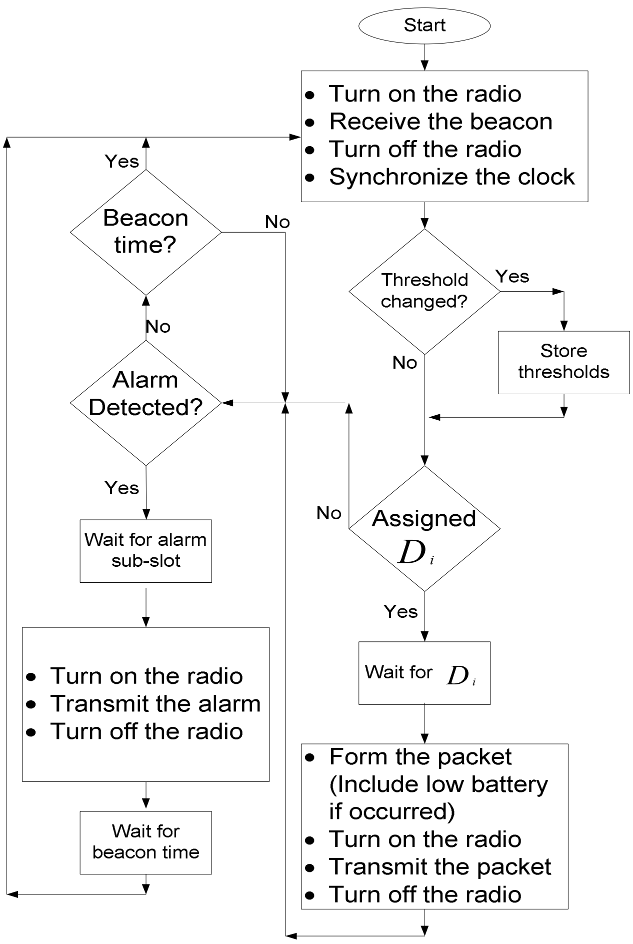

Figure4. *Sensor node working flowchart*

Data packet MAC header is shown in Figure 5-a. 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). An acknowledge packet (ACK), as shown in Figure 5-b, will be returned as respond. The ACK frame contains two octets of frame control, one octet of sequence number and two octets of frame check sequence. Data transmission and ACK sequences are shown in Figure 6-a. If a sample is detected as alarm, the node turns ON the radio before its first alarm sub-slot and transmits the alarm signal without details. CCU returns an ACK and then orders the node to remove the transmission thresholds and transmit all captured data. The node returns the ACK and starts to send all captured data as shown in figure 6-b. Alarm sub-slots are unloaded when patient is in normal status. A transmission thresholds change command according to transition conditions might be sent to one or all nodes. The MAC header for command is shown in figure 5-c and 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 ACK and change the transmission thresholds according to command. Transmission thresholds change sequences are shown in Figure 6-c. A low battery must be reported to CCU in the first transmitted packet. The CCU will decide to change the node's transmission thresholds according to other parameters. If the CCU agrees to change the thresholds, it sends a "maximize the transmission thresholds" command as shown in figure 6-d.

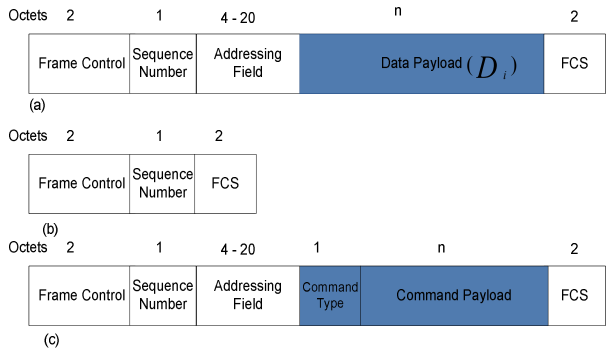

Figure 5. *Proposed MAC structure: (a)-data packet, (b)-ACK. Packet and (c)-command packet(transmission thresholds change).*

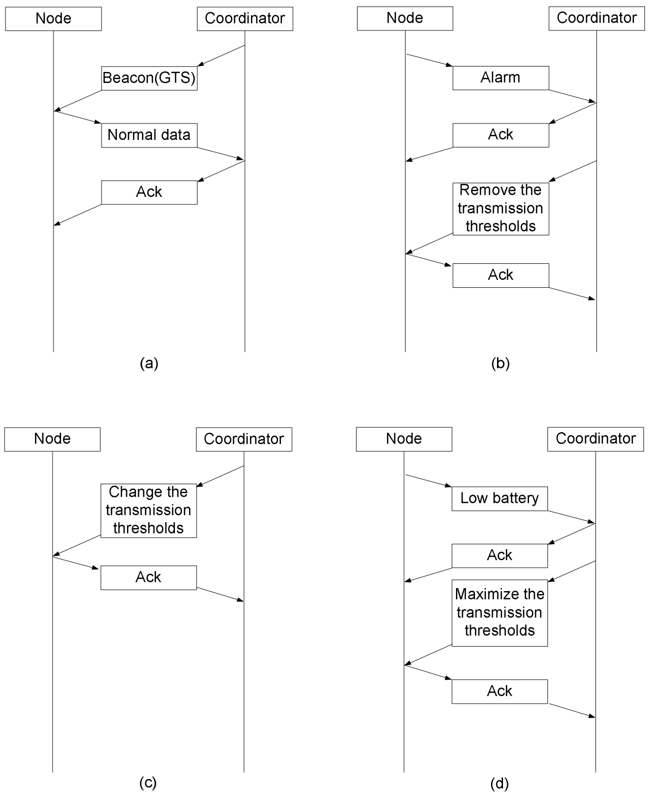

Figure 6. *Context-aware MAC sequences: (a)-normal data transmission, (b)-alarm data transmission, (c)-transmission thresholds change by CCU and (d)-low battery detection by sensor node.*

6. Evaluation

In this section we evaluate our novel scheme for different nodes and compare the savings to the burst communication method. Table 1 shows assumed parameters in a typical BSN in [1]. We choose ECG as a high traffic generator node with very high sampling rate, large sample resolution and short update interval. Temperature as a low traffic generator node has slowest sampling rate, small sample resolution and long update interval. Header is allowed in [11] between nine to twenty five Bytes and according to reference [1] is assumed 15 Bytes.

Table 1. Sensor nodes typical parameters

Name	F_i (samples/s)	M_i (Byte)	T_i (second)	D_i (Byte/s)
ECG	256	4	8	1024
Temperature	1	1	50	1

6.1. Transmission simulation by OPNET

A BSN network is setup by OPNET IT modeler simulation application with one Central Control Unit (CCU) and two Zigbee end devices (sensor nodes). To compare dynamic alarm thresholds with burst communication method, we setup two sensor nodes for each object. The first sensor node functions in dynamic alarm thresholds protocol, while the second sensor node follows the burst communication method. Objects are electrocardiogram (ECG), and temperature. Simulation is run for ratio of exceeded data to captured data (D_r) from 100% to 10% in dynamic transmission thresholds protocol. Figure 7 shows the transmission reduction in our protocol. This protocol reduces the transmission rate in ECG from 1024 bits per second (bps) to 103 bps when D_r equals 10% (figure 7-a). Transmission rate is reduced from 1.3 bps to 0.4 bps (figure 7-b). Reduction is not equal to 10% due to considerable amount of header in comparison with data.

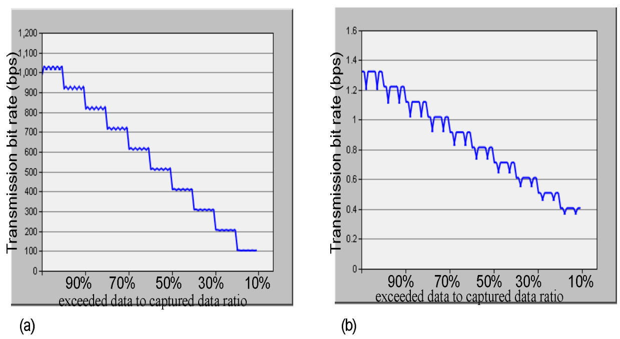

Figure 7. Transmission rate in dynamic transmission thresholds: (a)-ECG, (b)-temperature.

Delay is multiplied by 1 to 10 times for burst communication method. Figure 8 shows the transmission reduction in the burst communication method. This method reduces the transmission rate in temperature from 1.3 bps to less than 1bps when delay is multiplied by 1 to 10 (figure 8-b). We used the average bit rate due to fluctuation in transmission shape. Transmission rate is not reduced significantly for ECG due to unnoticeable amount of header in comparison with data (figure 8-b).

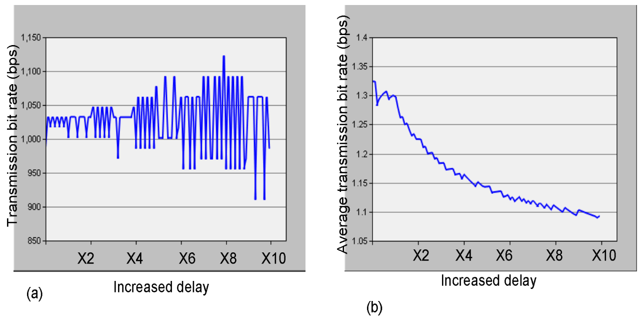

Figure 8. Transmission rate in burst communication: (a)-ECG, (b)-temperature.

6.2. Power Consumption Evaluation

As we defined in the section 2, transmission power is a linear function of data and header bits. We proposed dynamic transmission thresholds in order to deal with data bulk whereas burst communication was designed to deal with header bulk. We can calculate power consumption with the Equation (3) and assumed parameters. We define the power ratio (W_i) by reduced power consumption after each improvement divided by power consumption without improvement.

6.2.1. Burst Communication Evaluation

When the increased latency in burst communication F_i method is L_i , the power ratio can be formulated by:

$$W_i = \frac{E_0 * 8 * F_i \,.\, M_i + E_0 * 8 * \frac{O}{L_i}}{E_0 * 8 * F_i \,.\, M_i + E_0 * 8 * \frac{O}{T_i}} = \frac{F_i \,.\, M_i + \frac{15}{L_i}}{F_i \,.\, M_i + \frac{15}{T_i}}$$

If we increase the latency by 10 times, maximum power consumption ratio for ECG and temperature are:

$$W_1 = \frac{F_1 \;.\, M_1 + \frac{15}{L_1}}{F_1 \;.\, M_1 + \frac{15}{T_1}} = \frac{256 * \; 8 + \frac{15}{80}}{256 \;.* \; 8 + \frac{15}{8}} = 0.999$$

$$W_2 = \frac{F_2 \,.\, M_2 + \frac{15}{L_2}}{F_2 \,.\, M_2 + \frac{15}{T_2}} = \frac{1 * \; 1 + \frac{15}{500}}{1 * \; 1 + \frac{15}{50}} = 0.792$$

It shows that burst communication can reduce the power consumption up to 21% for temperature but almost zero for ECG.

6.2.2. Dynamic Transmission Thresholds

Power ratio in dynamic transmission can be calculated by when D_r is applied to Equation (3) and results Equation (4).

$$W_i = \frac{E_0 * 8 * F_i \,.\, M_i . D_r + E_0 * 8 * \frac{O}{T_i}}{E_0 * 8 * F_i \,.\, M_i + E_0 * 8 * \frac{O}{T_i}} = \frac{F_i \,.\, M_i . D_r + \frac{15}{T_i}}{F_i \,.\, M_i + \frac{15}{T_i}} \qquad (4)$$

Equation (4) is drew in Figure 9 when the exceeded data to captured data ratio (D_r) is change from 100% to 10% in our method. Dashed lines represent the burst communication power consumption percentage in comparison with conventional BSN. The figure shows when the burst communication saves up to 80% of energy only on temperature node, dynamic transmission saves up to 30% energy on temperature and up to 90% on ECG sensor node.

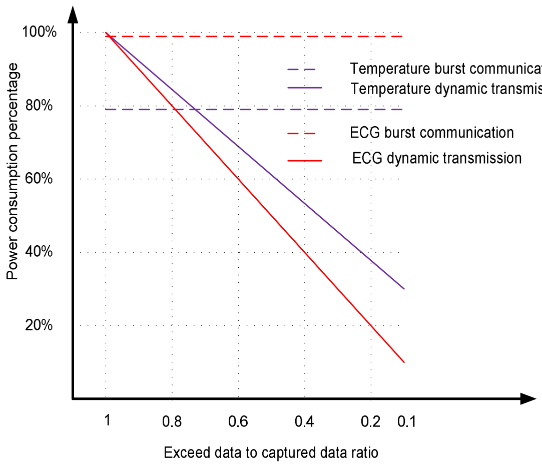

Figure 9. *Power consumption percentage in burst communication and dynamic transmission.*

7. 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 omit. In node data processing by dynamic transmission thresholds evaluates the data before the execution. Simulations results show that ours schemes 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 is only effective for low traffic nodes. It saves up to 19% transmission energy in these nodes. This method loses the efficiency as traffic generation increases and header to data ratio reduces. Sampling rate reduction [9] and sampling resolution reduction [10] 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 30% energy on low traffic nodes and up to 90% energy on high traffic nodes.

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