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TAD-MAC: Traffic-Aware Dynamic MAC Protocol for Wireless Body Area Sensor Networks

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***Abstract*—A wireless body area sensor network (WBASN) demands ultra low power and energy efficient protocols. Medium access control (MAC) layer plays a pivotal role for energy management in WBASN. Moreover, idle listening is the dominant energy waste in most of the MAC protocols. WBASN exhibits wide range of traffic variations based on different physiological data emanating from the monitored patient. For example, electrocardiogram data rate is multiple times more in comparison with body temperature rate. In this context, we propose a novel energy efficient traffic-aware dynamic (TAD) MAC protocol for WBASN. The protocol relies on dynamic adaptation of wake-up interval based on a traffic status register bank. The proposed technique allows the wake-up interval to converge to a steady state for fixed and variable traffic rates, which results in optimized energy consumption. A comparison with other energy efficient protocols for three different widely used radio chips i.e., $cc2420$, $cc1000$, and $amis52100$ is presented. The results show that TAD-MAC outperforms all the other protocols under fixed and variable traffic rates. Finally, lifetime of a WBASN was estimated and found to be 3–6 times better than other protocols.**

***Index Terms*—Adaptive algorithm, dynamic MAC protocol, traffic-aware MAC protocol, traffic status register, wireless body area sensor networks, wireless sensor networks.**

NOMENCLATURE

WBASN	Wireless body area sensor networks.
ECG	Electrocardiogram.
WSN	Wireless sensor networks.
WUInt	Wake-up interval.
WUB	Wake-up beacon.
ACK	Acknowledgment.
WUTime	Wake-up-time.
TSR	Traffic status register.
X_1	First half of the status register.
X_2	Second half of the status register.
$N_{0,1}$	Number of zeros in first half.
$N_{1,1}$	Number of ones in first half.
$N_{0,2}$	Number of zeros in second half.
$N_{1,2}$	Number of ones in second half.
Nc_{01}	Occurrence of consecutive zeros in first half.
Nc_{11}	Occurrence of consecutive ones in first half.
Nc_{02}	Occurrence of consecutive zeros in second half.
Nc_{12}	Occurrence of consecutive ones in second half.
L	Length of the traffic status register.
α	Constant weighting factor.
μ	Update factor.
t_{ref}	Reference time (system/simulator).

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I. INTRODUCTION

A WIRELESS body area sensor network (WBASN) is a special purpose WSN that can be incorporated within different networks such as a wireless local area network (WLAN) to enable remote monitoring for various environments [1]. One of the applications of WBASN is health care monitoring, where a number of patients can be observed, diagnosed, prescribed remotely. WBASN can be classified as invasive (in-body) or non-invasive (on-body) networks [2]. Smart sensor nodes can be connected to various parts of the body or fabricated inside clothes to transmit the information to the base station [3]. Thus, WBASN has emerged as a promising alternative to traditional wired network systems for medical environment with significant impact on the rehabilitation and improved patients' quality of life along with minimum personal monitoring [4].

WBASN can be applied to different scenarios such as monitoring of an individual patient from home, monitoring of few patients from intensive care units (ICU) and monitoring of many patients from hospital wards.

Generally in these scenarios there is no requirement for large network; single-hop communications with star or clustered-based topologies are most popular in WBASN [5], [6]. In this context, energy consumption and latency are two important design constraints along with the miniature size of the sensor nodes. The nodes that are implanted inside the body require high energy efficiency, in other words the lifetime of the sensor nodes and network needs to be prolonged by the use of ultra-low power technologies and protocols [3], [7].

In a typical WSN platform, the radio transceiver consumes most of the power. Radio activity is controlled by the medium access control (MAC) layer, therefore it is necessary to design

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an ultra low power and energy efficient MAC protocol suitable for WBASN. In this regard, low duty-cycle protocols such as preamble sampling MAC protocols are very efficient because these protocols improve the lifetime of the network by reducing the unnecessary energy waste [8], but their performance in terms of energy efficiency is questionable under variable traffic environment.

Typically in WBASN, physiological data of various parts of the body are transmitted over the network. Different nodes connected inside or on the body have great variation in terms of data rate. For example, in an emergency room for heart patients, continuous monitoring of ECG, oxygen, body temperature, and blood pressure could be required. In such a case, the sensors connected for these purposes have huge variations in their data transmission rates as presented in [9]. Therefore, to accommodate these variations of traffic it is very important to design a dynamic MAC protocol that can adapt to various nodes according to their traffic requirements.

In this paper a novel traffic-aware dynamic MAC (TAD-MAC) protocol is proposed, which may be considered as an addition in the class of preamble sampling MAC protocols [8] for variable traffic and application dynamics that can occur in WBASN. The presented protocol targets both invasive and noninvasive body area networks by considering a hybrid network topology which includes star network for in-body and mesh network for on-body WBASN. In our proposed technique, every node adapts its WUInt dynamically with due account of the amount of traffic (i.e., data packets) it receives and consequently optimizes the energy consumption. In this regards, a traffic status register bank (TSR-bank) contains the traffic statistics is used to continuously update the WUInt of the receive node with respect to the transmit nodes data transmission rate.

For invasive network, as the implanted nodes communicate directly with the coordinator, the latter contains a TSR-bank for all the transmit nodes. For the noninvasive network all the nodes contain a TSR-bank of their neighbor nodes but majority of the communication only takes place with the coordinating node. The coordinator converges towards the best WUInt for each transmit node based on TSR. Important design parameters are the length of TSR, convergence speed and initial WUInt value. Results show that the WUInt converges to a steady state value after several wake ups (within 40 s) and the proposed algorithm also converges very fast (within 2 s) whenever the data rate changes due to the variations within the physiological data of monitored activity. Furthermore, the best values (in terms of convergence rate) for the length of TSR and initial wake-up interval are presented for variable traffic patterns. Software implementation of different energy efficient preamble sampling MAC protocols is presented. Time spent by various protocols in transmit *Tx*, receive *Rx* and *Idle* states are evaluated and energy consumption of three different widely used radio chips is estimated. Finally, the lifetime is evaluated using different protocols and different radio chips.

The rest of this paper is organized as follows. In Section II, state of the art is presented, followed by the design principles and main attributes of the MAC protocols in Section III. The main contribution of the paper concerning traffic-aware dynamic MAC protocol is presented in Sections IV and V. Finally, the paper ends with the conclusion and future works. A list of acronyms are presented in the appendix to help the readability.

II. State of the Art

In the context of energy efficient MAC protocols, three classes of MAC protocols are widely used in WBASN: the preamble sampling protocols, protocols with common active period and scheduled protocols. The channel polling approach, low power listening or cycled receiver protocols are part of a broader class of protocols called preamble sampling protocols [8]. These protocols are most popular in distributed asynchronous wireless sensor networks because there is no requirement of synchronization and they are easily adaptable to various applications. Preamble sampling category includes energy efficient MAC protocols such as Cycled Receiver i.e., RICER (Receiver Initiated Cycled Receiver) [10], TICER (Transmitter Initiated Cycled Receiver) [10], LPL (Low Power Listening) [11], BMAC (Berkeley MAC) [11], XMAC [12], WiseMAC [13], etc. These protocols reduce the cost of extra overheads (in comparison with schedule-based protocols) and synchronizations by having single or multiple preambles. In addition a protocol such as WiseMAC can efficiently adjust the duty cycle based on the "wake up time" of the neighboring nodes, which results in a great reduction of idle monitoring, preamble size, and probability of collisions [13]. On the other hand, protocols with common active period such as S-MAC [14], PMAC [15], and the T-MAC [16] introduce predefined fixed and variable periodic listening and sleep schedule to avoid collision, overhearing and also reduce idle listening. Finally, schedule-based protocols such as *IEEE 802.15.6* [17], SS-TDMA [18], PicoRadio [19], etc., achieve energy efficiency by having contention free time slots at an extra cost of synchronization.

With regards to MAC protocols for WBASN, various studies exist in the literature. For example various proposals from different research centers and companies are presented to *IEEE 802.15.6 TG6* (WBAN Task Group) in [20]. Similarly, [6] presents an improved *IEEE. 802.15.4* MAC protocol with an adjustment of beacon traffic according to packet arrival rate. The presented scheme performs better in terms of energy consumption with regards to classical *IEEE. 802.15.4*. The energy efficient MAC protocol for WBASN presented in [5] is based on multichannel and centrally controlled synchronized protocols. In this paper, master–slave-based network topology is used, where master is synchronized with slave based on time slots for fixed traffic. The protocol is efficient only for very low static traffic and it is completely synchronous.

Very few papers in the literature explore the variations in the traffic. In this regard, [21] which is one of the proposal presented to WBAN Task Group, proposes a traffic-based secure WBAN MAC protocol. This proposal considers three traffic variations i.e., normal, on-demand, and emergency traffic. Further the body network coordinator (BNC) adjusts its wake-up schedule based on wake-up patterns from low traffic to high traffic and vice versa, moreover it utilizes wake-up radio for on-demand

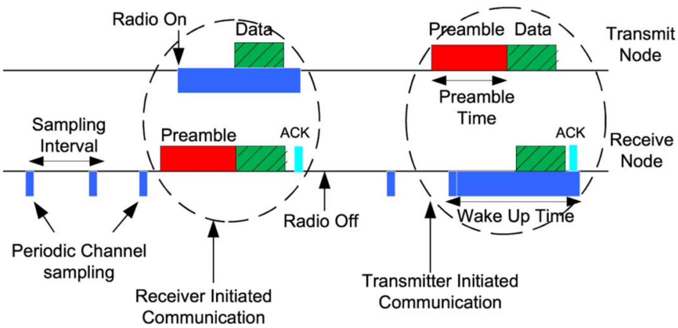

Fig. 1. General mechanism of preamble sampling protocols. Communication can either be initiated by receive or transmit node.

and emergency traffic. This proposed technique leads to extra hardware cost by adding wake-up radio and second, it does not specify any mechanism for the coordinator to adapt to the variable traffic. Therefore, there exists a strong requirement for a novel energy efficient traffic-aware dynamic MAC protocol design for WBASN to deal with the all types of variable traffic that can reduce the energy consumption.

III. MAC Protocols Design Principles

This section presents different design aspects of the MAC layer from the point of view of energy consumption. Further it explains various network and application perspectives of the WBASN. Medium access control (MAC) is the ability of a sensor node to efficiently share the wireless medium with the other nodes in the network [8]. The main objective of the MAC layer is to keep the energy consumption low by turning off the radio module as often as possible. In the context of energy efficient WSN/WBASN protocols, the preamble sampling method is an attractive option for light traffic [8].

Preamble sampling MAC protocols are based on nonscheduled mechanisms without any synchronization among the nodes, which means that each node is completely independent of its own active/sleep strategy. The general mechanism of a preamble sampling protocol is shown in Fig. 1. The initialization of the communication between sensors can be initiated by either a transmit or a receive node (depending upon the specific protocol being used). If the communication is initiated by the receiver, the receive node will send the preamble to the transmit node and the transmit node will respond with the data packet, whereas if it is initiated by the transmitter then the preamble will be sent by the transmit node followed by the data packet. The receive node wakes up periodically with fixed interval (that is selected according to the application) to sense the channel activity and if it does not find any preamble it goes to sleep mode immediately. It is to be noted that preambles have to be long enough such that the intending receive/transmit node can be able to receive the preamble on the wake up and further to keep the radio on for receiving the subsequent data packet.

A. Energy Efficient MAC Design

Idle listening, overhearing, overheads, unnecessary beacon transmissions and collisions are the major sources of energy waste in WSN/WBASN. Idle listening occurs when a sensor node is waiting for the receive node to wake-up (and to send the beacon) such that the transmit node transmits its data as reflected by receive node initiated communication mechanism in Fig. 1. In the receive node initiated communication, it is the transmit node which wastes the energy due to idle listening. Moreover, the possibility of two nodes transmitting to the same receive node at the same time will result in collision. In this regard, previous work [22] showed that transmit nodes energy consumption can reach 100 times more in comparison with receive node. Though there is no overhearing cost as the transmit node sends data to the specific destination on the reception of a beacon, further this way of communication reduces the long preambles and uses less overheads.

On the other hand, if the communication is initiated by the transmit node, it appends long preambles with the data, which introduces no idle listening at the start before transmitting but it has to wait for a long duration in idle listening for the response (in the form of acknowledgment) from the receive node. It results in a significant energy waste due to overhearing as all the neighboring nodes receive the preambles and the cost of transmitting long preambles (overheads) is also very high. This style of communication also impacts on the channel occupation and results in long delays in transmission.

To conclude, if the transmit node adapts its transmission according to the wake-up schedule of the receive node (as it is the case in WiseMAC), the transmit node can reduce idle listening and long preamble transmissions. WiseMAC is effective in static network and for fixed traffic, but in the case of variable traffic environment the receive nodes wake-up schedule should also be adaptable and there is a need of modification in WiseMAC. Whereas, in the case of receive node initiated communication, idle listening and collisions can be avoided by introducing adaptive wake-up interval as proposed in this paper.

B. Application Scenarios and Network Configuration

Typically in WBASN physiological data of various parts of the body are transmitted through the network. Different sensor nodes connected inside or on the body have great variations in terms of sensing rate. These variations can be due to the monitoring of different physiological data such as ECG, oxygen, body temperature, blood pressure, etc., and also each sensor itself can have significant variations according to the state of health of the patient Thus, the sensors connected for these monitoring have huge variations in their data transmission rate as presented in [9]. Therefore, to accommodate these variations of traffic it is important to design an adaptive MAC protocol that can adapt to various nodes according to their requirements.

Network configuration is another important design attribute of WBASN. For invasive sensors, it is difficult to communicate with each other due to the complexity of the human body, therefore, surgeon avoids in-body communication between sensors. Typically, a star topology is used for invasive WBASN, where all the in-body sensors are connected to a coordinating node which has more battery power and processing capabilities with regards to the implanted nodes. For the case of noninvasive sensors various options can be selected depending upon the intercommunication among the nodes, number of nodes and patients. For monitoring home-based or intensive care units where few

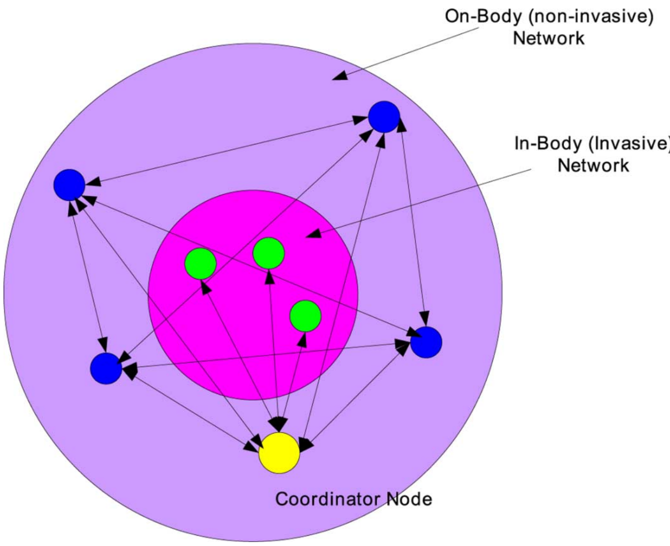

Fig. 2. Hybrid network topology: invasive sensor nodes are connected with a coordinator through star network, whereas, noninvasive nodes are configured through mesh topology.

nodes are on every patient body, star or mesh network is suitable and multiple coordinating nodes can even be configured. On the other hand, for hospital wards multiple coordinators or multihop-based routing mechanisms are necessary. In this context a hybrid network topology as illustrated by Fig. 2 seems to be the most suitable configuration for WBASN.

It is necessary that MAC layer incorporates in its design phase various dynamics of application scenarios and network configurations as explained above. In this paper, an adaptive MAC protocol based on different application scenarios and a hybrid network topology is presented.

IV. Traffic-Aware Dynamic Energy Efficient MAC Protocol

Wake-up interval is the most important design parameter in preamble sampling class of MAC protocols. For periodic sensing, variable sensing or even event driven applications it is usually kept fixed, which results in degrading the performance as well as the energy efficiency. In our previous research work on scenario-based hybrid energy model [22] for preamble sampling category of MAC protocols, it was concluded that adaptive wake-up interval can help to optimize the energy consumption by reducing idle listening (which can consume up to 100 times more energy in comparison with the rest of a complete communication between transmit and receive nodes) and generally it is the most significant energy waste in asynchronous sensor networks [22].

In this paper, a dynamic MAC protocol (called traffic-aware dynamic MAC i.e., TAD-MAC) is proposed which adapts the wake-up interval based on the traffic variations. The proposed protocols can further be applied to other low power asynchronous MAC protocols (with some modifications as for instance explained in Section V-B) such as B-MAC [11], X-MAC [12], WiseMAC [13], CyclED Receiver [10], RI-MAC [23] to reduce their energy consumption.

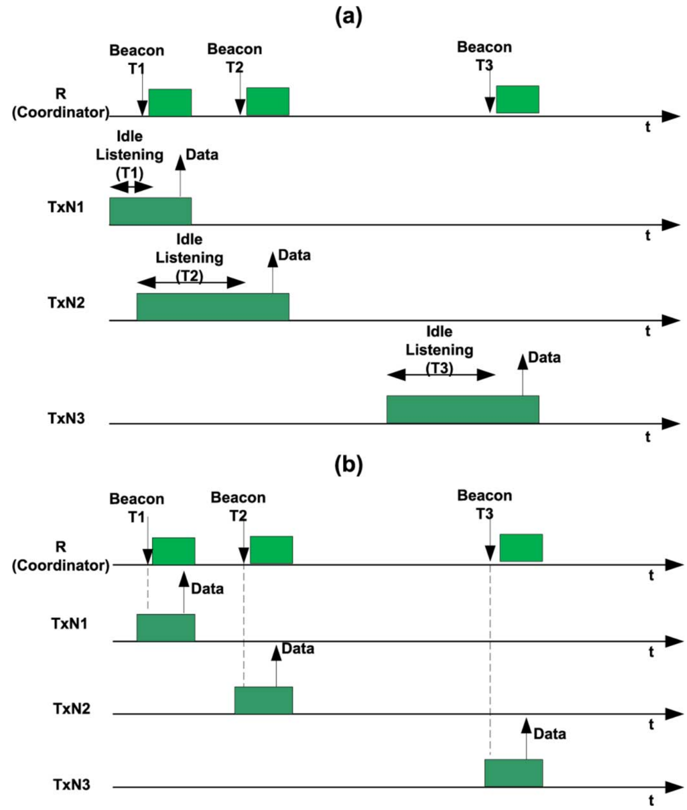

Fig. 3. Traffic-aware dynamic MAC protocol is divided into two phases: (a) the evolution phase which is before convergence and (b) steady state phase which is after convergence. It is important to note that in the second phase the receive node (coordinator) has adapted its WUInt schedule as such that the idle listening is minimized.

A. Protocol Description

The basic principle of the proposed protocol which is initiated by the receive node is shown in Fig. 3. The figure is divided into two phases (i.e., before convergence and after convergence), that sketch the results for the nodes attempting to transmit data (TxN1 to TxN3) to a receive node R. During the evolution phase [shown in Fig. 3(a)] before reaching a steady state, each transmit node (TxNi) waits for the beacon signal from the coordinator before sending its data to the coordinating node (as is the case for invasive sensor nodes). The beacon transmitted from the coordinator contains the specific node ID (identifier). Other intending transmit nodes continue to wait for the next beacon if the next wake-up time is very close, otherwise they can go to sleep mode and wake-up just before the next WUB. The next wake-up time is embedded inside the beacon frame that all the transmit nodes receive, but only the specified node will respond with the data.

After several wake-ups of the coordinating node for various transmit nodes, the coordinator will adapt its WUInt based on the statistics of the traffic it receives from each individual node. For that matter all the receive nodes including coordinator contain a traffic status register bank. The second phase after the convergence [shown in Fig. 3(b)] indicates that the receive node (coordinator) has adapted its WUInt schedule in such a way that idle listening is minimized. In order to cater for the clock drift and hardware latencies the receive node sends the WUB slightly after its scheduled time to ensure that the intending transmit

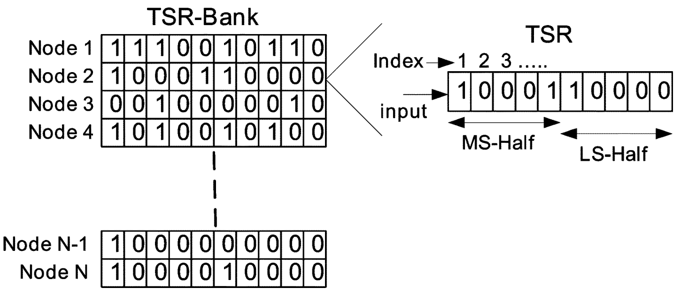

Fig. 4. Traffic shift register bank: it contains N registers for N neighbor nodes. If the receive node receives data the register (of that specific node) is filled with $'1'$ and if it does not receive data TSR filled with $'0'$. The new data (either 1 or 0) is filled in the first index of the register. The register contents are shifted one bit right before inserting a new data.

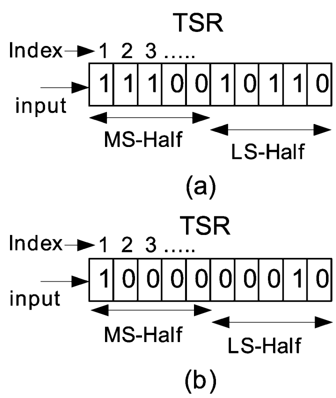

Fig. 5. Different TSR patterns are possible in the register depending upon the variations in traffic and position of the nodes.

node is already awake. For the case of noninvasive sensor nodes, which are configured through mesh topology, each node contains a TSR-bank to adapt its WUInt with respect to all the neighbor nodes which are within the radio range.

For the adaptation of WUInt, each node contains a traffic status register bank as shown in Fig. 4 to keep the traffic status of all the neighbor nodes. Each register corresponds to a node and is updated on the reception of data in response to the wake-up beacon sent by the receive node. If the receive node receives data at time t_i, the register (of that specific node) is filled with a $'1'$ and if it does not receive data, TSR is filled with a $'0'$. The new status (either 1 or 0) is filled in the first index of the register. The register contents are shifted one bit right before inserting a new status. The receive node wakes up and sends its beacon to the node which has the nearest WUInt time. This beacon contains the information about the specific node ID which should transmit its data.

Wake-up interval for an individual node is estimated based on the traffic status register shown in Fig. 5. TSR receives one as an input if a node wakes up and receives a data otherwise it contains zero. Register is divided into two halves in order to consider dominant impact from the most recent traffic (which resides in the *least significant* (LS) half) in comparison to relatively old traffic (which is in *most significant* (MS) half). TSR can have different patterns depending upon the variations in the traffic and position of the node. Further, it is used to evaluate the next

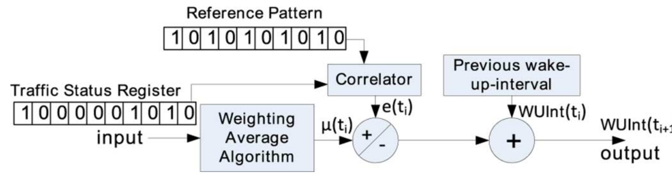

Fig. 6. Adaptive wake up interval algorithm.

wake-up interval and helps to reduce the unnecessary wake-up beacon or preamble transmissions.

As the node wakes up, it sends the wake-up beacon and then it computes the next wake-up interval based on the TSR. Wake-up interval is updated for the time instant $(t_i + 1)$ based on the values of WUInt, μ and e at time instant (t_i) as

$$\mathrm{WUInt}(t_{i+1}) = \mathrm{WUInt}(t_i) + (\mu(t_i) + e(t_i)) \cdot t_{\mathrm{ref}}. \tag{1}$$

In order to have unique reference of time among WUInt, μ, and e, t_{ref} is multiplied with μ and e, and it is defined with reference to the system/simulator clock. The update factor $\mu(t_i)$ is calculated based on most significant $(X_1(t_i))$ and least significant $(X_2(t_i))$ halves computations along with constant weighting factor α as

$$\mu(t_i) = \alpha \cdot X_1(t_i) + (1 - \alpha) \cdot X_2(t_i) \tag{2}$$

where $X_1(t_i)$ and $X_2(t_i)$ are

$$X_1(t_i) = \frac{N_{0,1}}{\frac{L}{2}} \cdot Nc_{0,1} - \frac{N_{1,1}}{\frac{L}{2}} \cdot Nc_{1,1} \tag{3}$$

$$X_2(t_i) = \frac{N_{0,2}}{\frac{L}{2}} \cdot Nc_{0,2} - \frac{N_{1,2}}{\frac{L}{2}} \cdot Nc_{1,2} \tag{4}$$

where $N_{0,1}$, $N_{1,1}$, $Nc_{0,1}$, and $Nc_{1,1}$ are the number of zeros, number of ones, occurrence of consecutive zeros, and occurrence of consecutive ones in X_1, respectively, whereas, $N_{0,2}$, $N_{1,2}$, $Nc_{0,2}$, and $Nc_{1,2}$ are the number of zeros, number of ones, occurrence of consecutive zeros, and the occurrence of consecutive ones in X_2, respectively. The optimization parameter L is the length of the TSR.

The adaptive wake-up interval algorithm is illustrated in Fig. 6. After the weighting average algorithm computation of the wake-up interval $\mu(t_i)$ through (2)–(4), a cross correlator is used to smooth the output of the weighting average algorithm. The correlator is fed with the current contents of TSR and it computes a correlation error after a comparison with the reference patterns that can be either $[10101010\cdots]$ or $[11111111\cdots]$. The correlator provides the output error either positive (which means that the TSR sequence contains more zeros than ones, hence, the correlator output should contribute to increase the wake-up interval) or negative (which means that the TSR sequence contains more ones than zeros, hence, the correlator output should contribute to decrease the wake-up interval). Consequently, it guides the adaptation of wake-up interval towards the desired sequence. Finally, the previous wake-up interval value is added with $\mu(t_i)$ and $e(t_i)$ to compute the next wake-up interval at the output.

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In the proposed algorithm, the most influential parameter is Nc (occurrence of consecutive zeros or ones). Even though there are multiple ones or zeros in the TSR they will not make an impact on the update value of wake-up interval until there are back-to-back zeros or ones. Multiple consecutive zeros employ that the next wake-up interval should be increased in comparison to the previous value, whereas multiple consecutive ones imply that the next wake-up interval should be decreased.

Proof of Concept

In this section, simulation results of the proposed adaptive wake-up interval algorithm are presented for fixed and variable traffic. Let us consider a typical body area network with five nodes connected on the body including a coordinating node. The coordinating node act as a receive node for all the sensor nodes connected on the body to relay the information to the local or remote monitoring station. It uses the status register bank to adapt its wake up interval according to the traffic of all the transmit nodes with the purpose to reduce the energy consumption of all the nodes in the network. The status register bank includes individual status registers corresponding to each transmit node and accordingly the coordinating node evaluates different wake-up intervals for each transmit node. Moreover, the selection of a specific transmit node (for the beacon transmission) is calculated at the coordinator based on the immediate next wake-up-time of a node among all the transmit nodes.

The algorithm is designed such that as it converges to a steady state value of wake-up interval the TSR contains to a sequence of $[10101010\cdots]$ pattern. This typical sequence seems the best trade-off between the optimal wake-up interval $[11111111\cdots]$ (i.e., when each wake-up of the node is followed with a successful data reception), and too frequent wake-up $[1000100001\cdots]$. The optimal sequence contains the probability that it may miss a data as soon as there will be a change in the traffic rate and will result in degrading the performance whereas the sequence $[10101010\cdots]$ can incorporate variable traffic and afterwards adapt to another wake-up interval in order to converge to a steady state value. In this context, it is important to note that too frequent wake-ups waste the energy consumption by transmitting unnecessary wake-up beacons.

Fig. 7 shows the adaptation of the receive node wake-up interval towards a steady state value for four transmit nodes. It can be seen in Fig. 7 that there exists an oscillation pattern before reaching a steady state. This is due to the fact that during the evolution phase the receive node receives multiple data from the same transmit node (which means multiple consecutive ones in the TSR), at that instant the wake-up interval value reduces significantly. Similarly, during the evolution phase, the receive node also receives multiple back-to-back zeros in TSR, which results in an increase of wake-up interval. After a certain number of wake-ups, the receive node converges to a steady state. Fig. 7 shows that the wake-up interval for all the transmit nodes converges to 500 ms within 35 s for a fixed traffic rate of 1 s.

Fig. 9 which is the zoomed version of Fig. 8 shows the convergence of wake-up interval for the different traffic rates (one example is highlighted in these two figures here but various variations of the traffic rates are simulated which are presented later in Table I). The traffic rate for node 1 and node 2 changes from 1

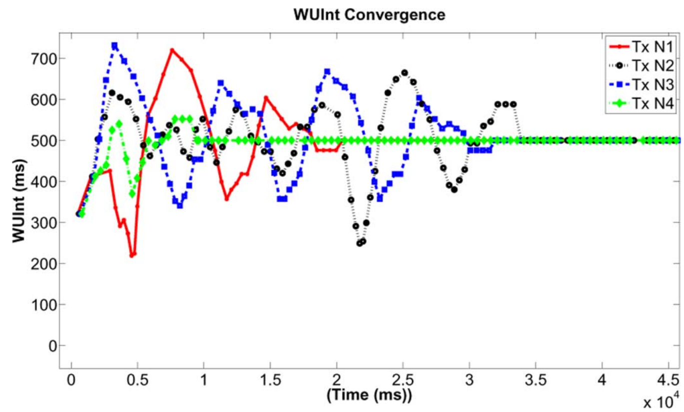

Fig. 7. Receive node adaptation with respect to transmit nodes based on the wake-up interval for a fixed data rate i.e., 1 s. It is to mention here that the reference clock's increment is 1 (ms), therefore all the time values are in ms.

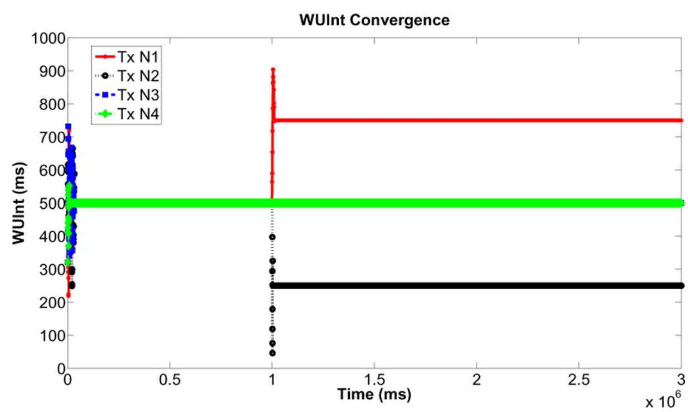

Fig. 8. Convergence of wake-up interval towards a steady state value for variable sensing rates. The traffic rate for node 1 and node 2 changes from 1 to 1.5 s and 500 ms, respectively.

to 1.5 s and 500 ms, respectively, whereas, for node 3 and node 4 sensing rate remains fixed i.e., 1 s during the entire simulation. These traffic rates are an indication of various application scenarios that range from medium to heavy traffic variations. The proposed adaptive technique converges to steady state values for all the traffic loads. Further in Table I, extended results are presented for very low and very high traffic rates. *TSR Length* is an optimization parameter, whereas *initial wake-up interval value* and the weighting parameter α are the two tunning parameters. After several simulations with variations from (0.1 to 1.0) the best value of α is found to be 0.7 (which remains constant during different traffic variations), whereas, the optimization parameters vary according to the traffic rates.

Table I shows the results of three different patterns of traffic variations that can be from very heavy traffic to normal and then very light traffic, and vice-versa. It is found during the simulations that initial wake-up interval value and length of TSR are important parameters for converging fast towards a steady state. The data packet contains a field called *data-type* which gives the information about the traffic rate whether it is burst, normal or very low and accordingly as the traffic switches, the receive node adjusts the length of TSR. In this regard, a low initial wake-up interval value or a value close to half of the sensing rate seems to converge most of the times with fast convergence speed as

TABLE I
LENGTH OF THE TRAFFIC STATUS REGISTER IS OPTIMIZED ACCORDING TO THE FASTEST CONVERGENCE SPEED TOWARDS A STEADY STATE VALUE OF THE WAKE-UP INTERVAL FOR VARIABLE TRAFFIC

Variable Traffic Packet Every(s)	Convergence Speed (No. of Wake-Ups)	TSR Length
0.5 - 1.0 - 1.5	7 - 14 - 16	4 - 6 - 8
0.5 - 1.0 - 2.0	7 - 14 - 18	4 - 6 - 8
0.5 - 1.0 - 10.0	7 - 14 - 15	4 - 6 - 12
1.5 - 1.0 - 0.5	17 - 4 - 16	6 - 6 - 4
2.0 - 1.0 - 0.5	15 - 10 - 16	6 - 6 - 4
10.0 - 1.0 - 0.5	38 - 10 - 16	10 - 6 - 4

TABLE II
PARAMETER SPECIFICATIONS OF THREE WIDELY USED RADIO CHIPS FOR WSN/WBASN

Parameters	**cc2420**	**aims52100**	**cc1000**
Modulation Schemes	OQPSK	ASK/OOK	FSK/OOK
Sensitivity (dBm)	−95	−117	−109
Size(mm)	7.0 × 7.0	7.5 × 7.8	9.7 × 6.4
Data Rate (Kbps)	250	19	76.8
Clock Drift (ppm)	40	80	50
Maximum Transmit Current (mA)	17.0	25	26.7
Maximum Receive Current (mA)	19.6	7.5	7.4

well. The *TSR length* is another important parameter of the proposed technique. Fig. 10 shows the comparison between TSR length and the corresponding convergence speed. Generally, if the length is too short, the convergence speed is faster, but in the case of variable traffic rates, the chance of convergence reduces. On the other hand, too long TSR takes much longer time to converge as can be seen in Fig. 11, which is more energy consuming. Table I presents the best possible values in terms of fastest and accurate convergence for variable traffic rates.

It is worth mentioning that the above results after convergence to a steady state value consider zero energy consumption due to idle listening but for the real-time physical implementation there will be very little energy waste due to clock drift and hardware latencies. Also, the energy consumed by wake-up beacon transmission is reduced significantly as the number of unnecessary wake-up beacons are avoided through the proposed technique. The proposed technique can be applied to both transmitter initiated and receiver initiated MAC protocols of preamble sampling category for various applications.

V. PERFORMANCE EVALUATION

In this section, the energy estimation of different energy efficient MAC protocols is presented. The results are split into fixed and variable traffic rates, further the energy consumption of three different widely used radio chips are explained. Based on the energy consumption of different MAC protocols and radio chips the lifetime of the sensor nodes is presented.

Table II illustrates the important parameters of three different widely used radio chips of WSN/WBASN, these being $cc2420$ [24], $amis52100$ [25], and $cc1000$ [26]. With regards to the energy consumption, clearly $amis52100$ and $cc1000$ are designed specifically for protocols that consume more energy in receive states (such as receiving the data or waiting to receive the preambles, waiting for the beacon or acknowledgment, etc.). Whereas, $cc2420$ consumes slightly more power in the receive state but the transmit power is much less than the other two chips. Another important contrasting design feature is the operating frequency band. $cc2420$ chip is designed for higher spectrum ISM band i.e., 2.4 GHz and it also has much higher data rate capabilities in comparison with the other chips. Whereas, $cc1000$ and $amis52100$ operate at lower frequency bands such as 433-MHz ISM band, MICS (medical implant communications service), and WMTS (wireless medical telemetry service) bands.

A. Energy Consumption Evaluation for Fixed Traffic

In order to evaluate the energy consumption by various radio chips it is necessary to analyze various MAC protocols that actually control the functionality of the radio chip. In this regard, for a static network and fixed traffic, low power and energy efficient preamble sampling MAC protocols are selected for comparison with the presented protocol. These protocols are used in majority of the WSN motes for applications ranging from health care, environment monitoring to surveillance and many more.

The network simulator *WSNet* [27], [28] is used to evaluate the time spent by different MAC protocols in various states. The simulation setup consists of 10 nodes including a coordinating node based on star topology. During the simulation, it is assumed that the network traffic follows Poisson distribution and uses a relay fading channel model. Based on the application model, each node senses the channel with a fixed rate of 100 ms and the data rate is considered as 1 packet/s. The simulation runs for 50 min. For the selected protocols, i.e., BMAC, XMAC, RICER, WiseMAC, and TAD-MAC, the average time spent by transmit and receive nodes are evaluated as shown in Table III, further the energy consumption of different MAC protocols for three different radio chips is also illustrated.

In BMAC protocol (with detailed description of the protocol can be found in [11]), intended transmit node appends a long preamble ahead of the data such that the destination node must receive the preamble as it wakes up. There is significant energy waste due to long preamble in the form of idle transmission (at Tx Node) and overhearing (at Rx Nodes). The time spent by the transmit node in *Tx* state is 0.7 and 110 ms in *Idle* state, whereas the receive node spends 11 ms in *Rx* state. It can be observed that actual transmission and reception time is very less in comparison to the *Idle* state. Total energy consumption by various radio chips for BMAC protocols are shown in Table III, which is evaluated by taking the maximum current levels of the chips (provided in Table II) multiplied with the time evaluated for different states and a constant 3 V battery.

XMAC [12] improves the energy waste by replacing the long preamble with multiple short preambles that being transmitted at short intervals and as soon as the transmit node receives the acknowledgment from the destination, it transmits the data. With these optimizations, XMAC reduces the idle transmission cost as well as the overhearing cost. The transmission and reception time values are 0.0120 and 0.0128 ms, respectively, whereas the idle transmission time is 100.052 ms.

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RICER [10] is a receiver initiated protocol in which the transmit node waits for the wake-up beacon from the destination before it transmits the data. The transmit node spends maximum energy in idle listening (for waiting the wake-up beacon). It is important to note that the radio chips $amis52100$ and $cc1000$ consume less energy in comparison with $cc2420$, this is due to the fact that the current level of $amis52100$ and $cc1000$ is much lower than $cc2420$.

WiseMAC is another energy efficient MAC protocol in which transmit node adapts itself according to the wake-up schedule of the receive node. At the very first communication the receive node informs the transmit node about the next wake-up time in the *acknowledgment*. WiseMAC contains a very short preamble which is calculated based on the formula $4\theta L$, where θ is the clock drift and L is the time elapsed since the last communication. Further, it also includes *medium reservation preamble* to avoid collision by introducing a short random offset (the detailed description of the protocol can be found in [13]). It is important to note that since the transmit node waits until the receive node wakes up, it sleeps the radio component until the time close to the receive node wakes up, which eventually avoids the unnecessary idle energy waste. On the other hand, the *MCU (Microprocessor Computing Unit)* continues to remain in the transmit mode, though it consumes much less energy in comparison with the radio being in receive state (idle listening). *MSP430* is a low power micro-controller that is being used throughout the experiments. It is to mention here that in all the other protocols (which means in different states of the protocol) the energy consumption of MCU is approximately the same [22].

TAD-MAC is a dynamic version of a receiver initiated protocol which is adaptively adjustable to various traffic variations. For fixed traffic, TAD-MAC also improves the energy waste due to idle listening and, as the receive node converges towards the steady state according to the transmit node, the idle listening is present only to mitigate the effect of clock drift and hardware latency. The energy consumption is less than 1 mJ for $cc2420$ and is less than 0.5 mJ for $aims52100$ and $cc1000$. The time spent by the transmit node in idle listening is only 0.7258 ms which helps to reduce the important energy consumption due to idle listening.

Lifetime estimation of the battery and its improvement is the ultimate design objective in WBASN. Fig. 12 shows the lifetime estimation for the different MAC protocols. The total available energy is estimated from the capacity of two AA alkaline batteries provided by energizer company with 1.5 V nominal voltage. [29] shows the current and voltage discharge profiles for various operations and we have considered the battery capacity equals 3124.2 mAh. Lifetime is defined as the time when first node reaches out of energy. The bar graph presented in Fig. 12, clearly shows that the TAD-MAC with $amis52100$ or $cc1000$ radio chips has huge difference in comparison with other MAC protocols and $cc2420$. Lifetime using TAD-MAC protocols is estimated to be equal to *2100* days, *3400* days and *3500* days for $cc2420$, $cc1000$, and $amis52100$ chips, respectively. TAD-MAC have 3 to 18 times more battery lifetime in comparison with other protocols. It is noteworthy to mention here that for low traffic rate $amis52100$ and $cc1000$ are preferable but for higher traffic rate $cc2420$ is more suitable.

B. Energy Consumption Evaluation for Variable Traffic

Typical WBASN exhibits huge variations in traffic rates emanating from various sensors connected on the body. For example, there are 30 times more packets per second from *ECG* monitoring in comparison to *pulse rate* or *body temperature* monitoring [9]. For example, the data rate of *EEG*, *ECG* and *EMG* according to [30]–[32] ranges from 32 to 256 to 600 kb/s, respectively. Due to these high data rates, these signals are normally compressed and even then there exists a big difference in data rate among compressed signals due to different compression algorithms. For that matter, [33] provides the *ECG-compressed* rate equal to 1.2 kb/s, whereas [34] provides *ECG-compressed* rate equal to 3.96 kb/s. Similarly, for the low data rate (such as temperature and heart rate) monitoring, there exist variations based on the condition of the patient being monitored [30]–[32], [35].

In this context of WBASN's variable traffic, it is very important to consider a realistic comparison for different MAC protocols. The protocols that are used for the fixed traffic can not be used for comparison with our TAD-MAC protocol for the case of variable traffic because all the protocols are designed with fixed wake-up interval. BMAC, XMAC, and RICER suffers from packet losses, latency and huge energy consumption, whereas, WiseMAC, which can be considered as a traffic-aware protocol, yet needs significant modifications to be able to be applied in WBASN.

There are two important issues related with WiseMAC with regards to variable traffic of WBASN. If the wake-up interval is kept fixed but its value is selected based on the fastest rate of physiological data, in this case, the nodes which are used to send body temperature and heart rate will wake-up unnecessarily tens and hundreds of times more than they need which will result in energy waste. On the other hand, if each node has a different wake-up interval (which is known among the neighbor nodes), according to the amount of packets a node transmits and receives, as soon as there will be variations within one physiological data, the transmission rate demands the change in wake-up interval which will not be possible as the wake-up intervals are different but fixed. Lastly, if each node allows to change its wake-up interval at run time, WiseMAC can update the new wake-up interval of the receive node but only a specific transmit node will be able to have that update, whereas the other nodes will still have the old wake-up interval value. [36] presents an extended WiseMAC to improve the throughput but it does not address the above issues.

TAD-MAC results for variable traffic are presented in Table V. Four different physiological data (as shown in Table IV) are transmitted to the coordinator node, these include *ECG-compressed* (10 packets/s), *oxygen saturation* (1 packet/s), *Temperature* (1 packet/s), and *Heart Rate* (2 packets/s). The transmission and reception time values are 0.73 and 0.71 ms, respectively, whereas the idle transmission time is 3.2 ms. These time values are the average values evaluated based on the simulation run of 50 min in $WSNet$.

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TABLE III
ENERGY CONSUMPTION (FOR ONE COMPLETE COMMUNICATION) IS EVALUATED FOR DIFFERENT RADIO CHIPS AND FOR DIFFERENT MAC PROTOCOLS. TIME SPENT BY PROTOCOLS IN *TX*, *RX*, AND *IDLE* STATES ARE EVALUATED THROUGH SIMULATOR *WSNET*. FURTHER BY USING THE CHARACTERISTICS OF DIFFERENT RADIO CHIPS (SHOWN IN TABLE II) ENERGY CONSUMPTION IS ESTIMATED

	Radio Chips	States	BMAC [11]	XMAC [12]	RICER [10]	WiseMAC [13]	TAD-MAC
Time (ms)		Tx	0.70	0.0128	0.73	0.71	0.73
		Rx	11.0	0.0128	0.73	0.04	0.70
		Idle	**110.0**	**100**	**51.3**	**50.21**	**2.56**
		Total	121.7	100.07	52.7	50.9	3.99
Energy (mJ)	cc2420	Tx	0.035	0.000652	0.0376	0.038	0.037
		Rx	0.646	0.000752	0.0433	0.045	0.043
		Idle	**5.610**	**5.102**	**3.01**	**0.56**	**0.15**
		Total	6.291	5.104	3.096	0.648	0.230
Energy (mJ)	cc1000	Tx	0.056	0.00102	0.059	0.059	0.059
		Rx	0.244	0.000284	0.016	0.016	0.016
		Idle	**8.811**	**8.014**	**1.138**	**0.57**	**0.056**
		Total	9.111	8.015	1.214	0.66	0.131
Energy (mJ)	amis52100	Tx	0.052	0.000960	0.055	0.055	0.055
		Rx	0.247	0.000288	0.016	0.016	0.016
		Idle	**8.250**	**7.503**	**1.154**	**0.57**	**0.057**
		Total	8.549	7.505	1.225	0.653	0.128

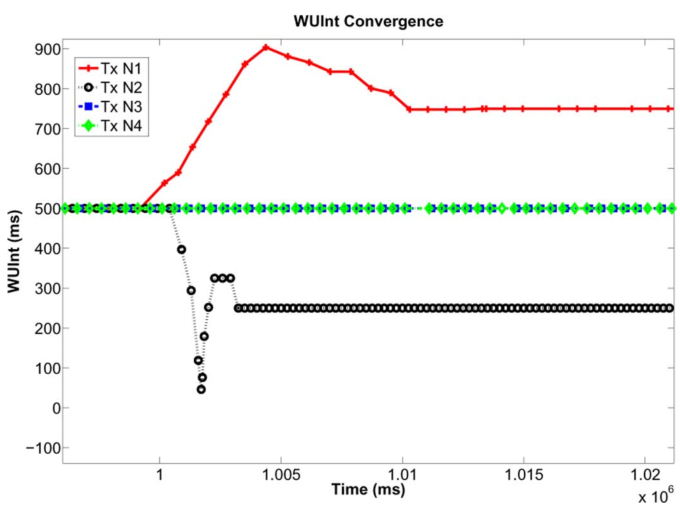

Fig. 9. Zoomed version of Fig. 8 to show convergence after changing the traffic rate. It can be seen that the receive node converges very fast as the appropriate TSR length is selected based on the indication from the packet type. The traffic rate for node 1 and node 2 changes from 1 to 1.5 s and 500 ms, respectively. Node 1 converges to a steady wake-up interval value of 750 ms, whereas node 2 converges to 250 ms for the traffic pattern of $[10101010\cdots]$.

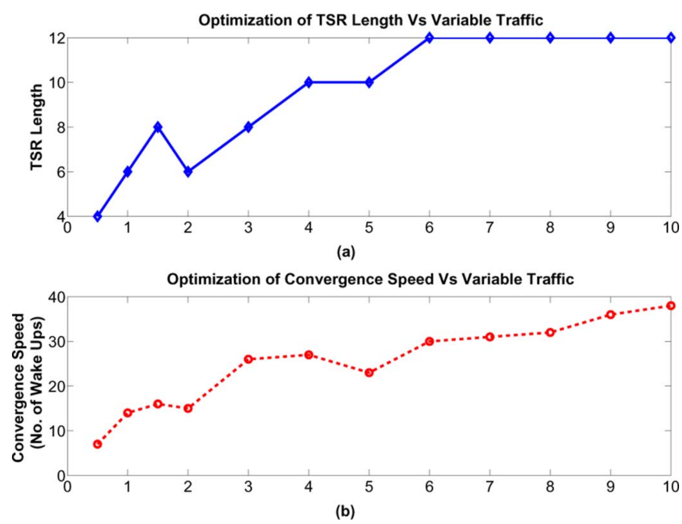

Fig. 10. Optimization of TSR length and corresponding convergence speed for different data transmission rates, starting from two packets per second to one packet in 10 s. It can be seen that the convergence speed increases as the rate reduces, this is due to the fact that with reduced rate TSR filled slowly and it results in slow convergence speed.

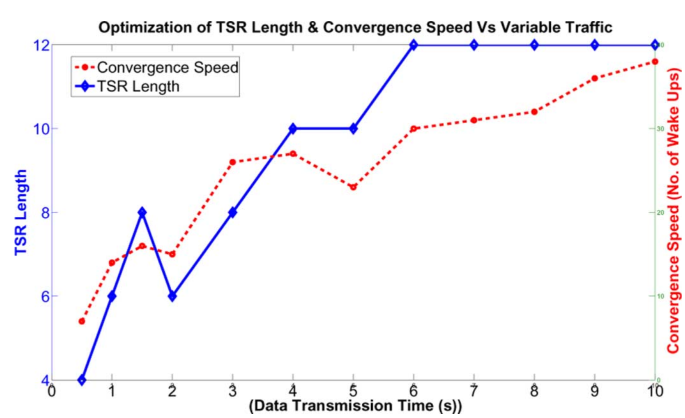

Fig. 11. Joint illustration of TSR length and convergence speed.

By using the results presented in Table V, the lifetime using the TAD-MAC protocol is estimated to be equal to *1765* days, *3100* days, and *2980* days for $cc2420$, $cc1000$, and $amis52100$ chips, respectively.

VI. CONCLUSION AND FUTURE WORK

Idle energy consumption is the dominant energy waste in WBASN and is few multiples of the energy used in the actual transmission. In this paper we proposed a novel MAC protocol (TAD-MAC) that allows the sensor nodes to adapt themselves dynamically according to the traffic. The dynamic adaptation of TAD-MAC results in ultra low energy consumption from idle listening, overhearing, collisions and unnecessary wake-up beacon transmission. Each node has a traffic status register bank which contains the traffic status according to the data received from all the neighbor nodes. A body area network with hybrid topology is considered, which is suitable for both invasive and noninvasive BAN. Firstly, the simulation results of fixed and

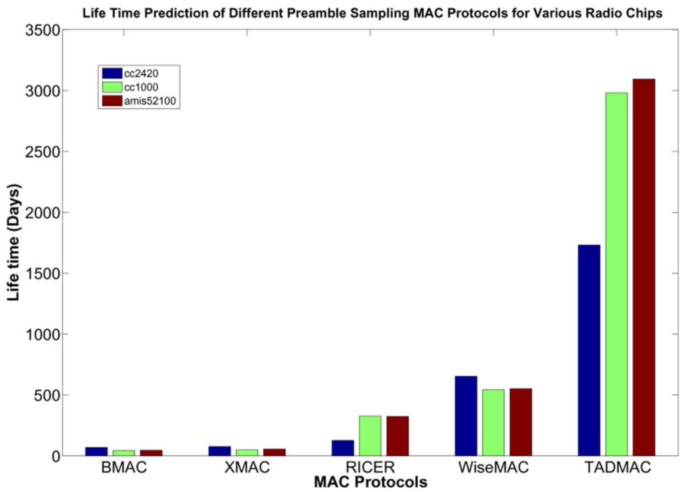

Fig. 12. Lifetime prediction of AA alkaline battery is evaluated for various MAC protocols and radio chips. TAD-MAC along with $amis52100$ or $cc1000$ radio chips have major difference in comparison with other MAC protocols and $cc2420$. It is noteworthy to mention here that for low traffic rate $amis52100$ and $cc1000$ are preferable but for higher traffic rate $cc2420$ is more suitable.

TABLE IV
PHYSIOLOGICAL DATA BEING MONITORED AND THEIR RESPECTIVE DATA RATES

Monitored parameters	**Transmit Packets/sec**
ECG.	10
Oxygen saturation	1
Temperature	1
Heart rate	2

TABLE V
ENERGY CONSUMPTION OF THE TAD-MAC PROTOCOL UNDER VARIABLE TRAFFIC OF WBASN FOR THREE DIFFERENT RADIO CHIPS. ENERGY CONSUMPTION FOR ONE COMPLETE COMMUNICATION IS LESS THAN 0.3 mJ FOR $cc2420$ AND IS LESS THAN 0.2 mJ FOR $aims52100$ AND $cc1000$. TIME SPEND BY THE TRANSMIT NODE IN IDLE LISTENING IS ONLY 3.2 ms

States	**cc2420 (Joules)**	**amis52100 (Joules)**	**cc1000 (Joules)**
Tx	3.76×10^{-5}	5.52×10^{-5}	5.90×10^{-5}
Rx	4.33×10^{-5}	1.65×10^{-5}	1.63×10^{-5}
Idle	0.18×10^{-3}	0.07×10^{-3}	0.07×10^{-3}
Total	0.26×10^{-3}	0.14×10^{-3}	0.14×10^{-3}

variable traffic are presented, it is shown that the wake-up interval converges efficiently to a steady state value for different traffic rates. The *TSR Length* is adjusted as an optimization parameter to obtain fast convergence and its values for various variations of traffic rates are presented. Secondly, performance evaluation of different energy efficient preamble sampling MAC protocols for fixed and variable traffic rates is presented.

Our proposed dynamic MAC protocol outperforms all the other protocols in fixed and variable traffic. Moreover, the energy consumption of three radio chips using TAD-MAC have clear difference in comparison with other protocols implementation. For the fixed traffic, the closest comparison is with WiseMAC, for $cc2420$ radio chip TAD-MAC has three times more lifetime than WiseMAC. Whereas, TAD-MAC has six times improvements by using $cc1000$ and $amis52100$. For variable traffic, there is a significant degradation in performance of nondynamic protocols with regards to energy consumption, quality of service and latency, to be able to show a fair comparison there is a need of modifications among other protocols. Thus, a discussion of several modifications that are necessary before we can perform a fair comparison is presented.

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