An Adaptive Energy Proficient Routing in Multi Slot MAC for Wireless Human Area Network

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Abstract: We present healthiness for energy-efficient MAC Protocol specifically designed for Wireless Human Area Networks. Wireless Human Area Networks consist of HAN protocol prefetched Transceiver and receiver attached to the human body to monitor vital signs such as Human body temperature, activity, pulse rate or heart-rate. The network embraces a master-slave architecture, where the Human body- slave node periodically sends (routing) sensor readings to a central master node(master router). Unlike out dated peer-to-peer wireless human area networks, the nodes in the bio medical Wireless Human Area Networks are not deployed in an ad hoc model. Construction of a network is centrally managed with single-hop communications. To reduce energy consumption, all the HAN nodes and sensor nodes are in standby or sleep mode until the centrally assigned time slot reaches its sneak point(cluster). When the node has joined in a network, there is no likelihood of collision within a cluster, as all of the communication node is initiated via central node and is addressed uniquely to a slave node. To avoid collisions with nearby transmitters, a clear channel (SoC) based assessment algorithm based on standard listen-before-transmit is used. To grip the time slot overlapping, the unique concept of a wakeup fall back time is presented. By means of single-hop communication and centrally controlled sleep/wakeup times leads to significant energy reductions for this application which was compared to more “Reliable” network MAC protocols such as 802.11(wifi) or Zigbee or Wireless Human Area Network. As the duty cycle of this application is reduced, in order to wake the overall (energy) power consumption approaches the standby power.
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Key Words: Routing, Medium Access Protocol, Wireless Communication, Wireless Sensor Network, Wireless Human Area Network, Listen-Before-Transmit.

1. INTRODUCTION

The wireless communications revolution which is leading the convergence of all media and data services appears to be acquisition of wide acceptance. The healthcare sector is becoming increasingly interested in using this new technology to more effectively administer healthcare delivery. In particular, wireless vital signs monitoring is an area of modern healthcare that is growing very fast. This is due to its potential for slowing down the unsustainable growth of healthcare spending due to an increasing number of people living for years or even decades with Vital signs monitoring using WSN technologies have previously been described, but these systems are typically bulky and power hungry and rely on MAC protocols such as Bluetooth and 802.11 (wifi) which are inefficient for such applications [N. Chevrollier and N. Golmie,2005] [D. Brunelli, E. Farella, L. Rocchi, M. Dozza, L. Chiari, and L. Benini, 2006] [www.bluetooth.org, 2001] [2003, IEEE Std. 802.15.4-2003]. More general Wireless Sensor Network (WSN) MAC protocols, which have been the focus of fairly intensive research [2003, IEEE Std. 802.15.4-2003], [W. Ye, J. Heidemann, and D. Estrin,2002], [I. E. Lamprinos, A. Prentza, E. Sakka, and D. Koutsouris,2005], [W. Y. J. Heidemann, 2003], are also not well suited to these biomedical applications. Zigbee/IEEE 802.15.4 [2003, IEEE Std. 802.15.4-2003] which is designed for similar networks does not have sufficient ‘network device’ flexibility in non-beacon mode. It also lacks the cross-layer optimization features which the proposed protocol brings to this particular area. This paper describes a novel MAC Protocol designed specifically for wireless Human area sensor networks focused on pervasive healthcare applications. Like other wireless sensor network MAC protocols, a primary design goal was low power consumption. This is achieved through a focus on collision avoidance.

From the statement of cited reference [http://academic.research.microsoft.com/Paper/2402865.aspx]. As a result of the network topology adopted in the MAC protocol, many of the traditional problems that plague wireless sensor networks have been either eliminated or significantly reduced. Specifically, idle listening and over-hearing are not an issue in this protocol as traffic is managed centrally. Table I highlights some of the key features of traditional ad hoc wireless sensor network and emerging wireless Human area sensor networks . In the following sections, the proposed MAC Protocol is presented in more detail, from conception to design, implementation together with measured results.

II.LITERATURE SURVEY:

Minimum Cost Forwarding Algorithm (MCFA): Jamal N. Al-karaki, Ahmad E.Kamal says that the MCFA algorithm deeds in detail that the routing direction is always known, that is, towards the fixed external base-station. Hence, a sensor node need not have a distinctive (Unique)ID nor sustain a routing table. Each node preserves the least cost estimate from itself to the base-station. Each message to be sent from the sensor node is broadcasted to its neighbour nodes. When a node receives the message, it checks if it is on the least cost path between the source node and the base-station. If so, it again broadcasts the message to its neighbour nodes. This process iterated until the base-station is reached. In MCFA, each node should know the least cost path estimate from source to the base-station. This is obtained as follows. The base-station broadcasts a message with the cost which is set to zero while every node initially set its least cost to the base-station (1). Jamal N. Al-karaki, Ahmad E.Kamal says that Each node, upon receiving the broadcast message initiated at the base-station, checks to realize if the estimate in the message and the link on which it is received is less than the current estimate. If yes, the current estimate and the estimate in the broadcast message are updated. If the received broadcast message is updated, then it is re-sent; otherwise, it is removed and node elimination is done. However, the previous procedure may result in some nodes having multiple updates and those nodes far away from the base-station will get more updates from those closer to the base-station. To avoid this, the MCFA was modified to run a back off algorithm at the setup phase. The back off algorithm dictates that a node will not send the updated message until a time units have elapsed from the time at which the message is updated, where a is a constant and the link cost from which the message was received based on [http://academic.research.microsoft.com/Paper/2402865.aspx].

Gradient-Based Routing: According to Schurgers et al. proposed another variant of directed diffusion, called Gradient-Based Routing (GBR). Jamal N. Al-karaki, Ahmad E.Kamal says that the key idea in Gradient Based Routing is to learn the number of hops when the interest is diffused through the whole network.Each node calculates a parameter called the height of the node, which is the minimum number of hops to reach the BaseStation. The difference between a node's height and that of its to their neighbour is considered the gradient on that link. A packet is forwarded on a link with the largest gradient. Gradient based routing uses some supporting techniques such as data aggregation and traffic spreading in order to uniformly divide the traffic over the network. When multiple paths pass through a node, which acts as a transmittion node, that transmittion node may combine data.

According to a certain energy function in Gradient Based Routing, three different data broadcasting techniques have been discussed

(1) Stochastic Outline, node picks one gradient at once in random when there are two or more next hops that have the same gradient,

(2) Energy-based outline, node increases its height when its energy drops below a certain threshold, so that other sensors are discouraged from sending data to that node, and

(3) Stream-based outline, where new streams are not routed through nodes which are currently part of the path of other streams. The main objective of these outlines is to obtain a balanced distribution of the traffic in the network, which increases the network lifetime according to the author cited [Jamal N. Al-karaki, Ahmad E. Kamal].

Energy Aware Routing: Jamal N. Al-karaki, Ahmad E.Kamal proposed the main objective of energy-aware routing protocol [J. Yao, R. Schmitz, and S. Warren, 2005], which is a destination initiated reactive protocol, used to increase the network lifetime. It is similar to directed diffusion, which differs in the sense, it maintains a set of paths rather than maintaining or applying one optimal path at higher rates. These paths are maintained and chosen by means of a certain likelihood values. The value of this probability depends on how low the energy consumption for the network path relies upon. By having multi paths chosen at different times, the energy of any single path will not diminish quickly. This can achieve longer network lifetime as energy is degenerated more equally among all nodes. Network survivability is the main stat of this protocol. The protocol assumes that each node is addressable through a class-based addressing which includes the location and types of the nodes.

According to the citated reference [http://academic.research.microsoft.com/Paper/2402865.aspx] the protocol initiates a connection through localized flooding, which is used to discover all routes between source/destination pair and their costs; thus building up the routing tables. The high-cost paths are discarded and a forwarding table is built by choosing neighbouring nodes in a manner that is proportional to their cost. Then, forwarding tables are used to send data to the destination with a probability that is inversely proportional to the node cost.

Stated in the reference [http://academic.research.microsoft.com/Paper/2402865.aspx] Localized flooding is performed by the destination node to keep the paths alive. When compared to directed diffusion, this protocol provides an overall improvement of 21.5% energy saving and a 44% increase in network lifetime. However, the approach requires gathering the location information and setting up the addressing mechanism for the nodes, which complicate route setup compared to the directed diffusion [http://academic.research.microsoft.com/Paper/2402865.aspx].

Hierarchical or cluster-based routing, Jamal N. Al-karaki, Ahmad E.Kamal proposedan optimal routing methods in wire line networks, well-known techniques with superior advantages related to scalability and efficient communication in networks. The concept of hierarchical routing is also utilized to perform energy-efficient routing in Wireless sensor networks. In a hierarchical architecture, higher energy nodes can be used to process and send the information while low energy nodes can be used to perform the sensing in the proximity of the target. This means that creation of clusters and assigning special tasks to cluster heads can greatly contribute to overall system scalability, lifetime, and energy efficiency. [http://academic.research.microsoft.com/Paper/2402865.aspx] Hierarchical routing is an efficient way to lower energy consumption within a cluster and by performing data aggregation and fusion in order to decrease the number of transmitted messages to the Base Station. Hierarchical routing is mainly two-layer routing where one layer is used to select cluster heads and the other layer is used for routing. However, most techniques in this category are not about routing, rather on “who the sender and when to sent the message packets or process” the information, channel allocation etc., which can be orthogonal to the multi hop routing function.

Sensor Aggregates Routing: Jamal N. Al-karaki, Ahmad E.Kamal says that the set of algorithms for constructing and sustaining sensor aggregates were proposed in this routing model. The objective is to collectively monitor target activity in a certain environment (target tracking applications). [http://academic.research.microsoft.com/Paper/2402865.aspx] A combination of sensors comprises those nodes in a network that satisfy a grouping predicate for a collaborative processing task. The parameters of the predicate depend on the task and its resource requirements. The formation of appropriate sensor aggregates were discussed in [http://www.st.com/stonline/products, 2007]. In terms of allocating resources to sensing and communication tasks. Sensors in a sensor field are divided into clusters according to their sensed signal strength, so that there is only one peak per cluster. Then, local cluster leaders are elected. One peak may represent one target, multiple targets, or no target in case the peak is generated by noise sources. To elect a leader, information exchanges between neighbouring sensors are necessary. If a sensor, after exchanging packet switch all its one-hop neighbours, finds that it is higher than all its one-hop neighbours on the signal field landscape, it declares itself a leader. This leader-based tracking algorithm assumes the unique leader knows the geographical region of the collaboration [http://academic.research.microsoft.com/Paper/2402865.aspx].

Virtual Grid Architecture routing (VGA)-flat based: Jamal N. Al-karaki, Ahmad E.Kamal saya that An energy-efficient routing paradigm is proposed in [K. Langendoen and G. Halkes,2005] that utilizes data aggregation and in-network processing to maximize the network lifetime. Due to the node stationary and extremely low mobility in many applications in WSNs, a reasonable approach is to arrange nodes in a fixed topology as was briefly mentioned in [http://focus.ti.com/lit/ds/symlink/cc2430.pdf, 2007]. A GPS-free approach[K. Langendoen and G. Halkes, 2005] is used to build clusters that are fixed, equal, adjacent, and non-overlapping with symmetric shapes. In [K. Langendoen and G. Halkes, 2005], square clusters were used to obtain a fixed rectilinear virtual topology. Inside each zone, a node is optimally selected to act as cluster head. Data aggregation is performed at two levels: local and then global. The set of cluster heads, also called Local Aggregators, perform the local aggregation, while a subset of these Local Aggregators is used to perform global aggregation. However, the determination of an optimal selection of global aggregation points, called Master aggregators is NP-hard problem. From the citation [http://academic.research.microsoft.com/Paper/2402865.aspx] IT illustrates an example of fixed zoning and the resulting virtual grid architecture used to perform two level data aggregation. Note that the location of the base station is not necessarily at the extreme corner of the grid, rather it can be located at any arbitrary place [http://academic.research.microsoft.com/Paper/24028 65.aspx].

Table 1: Cluster based routing Vs Virtual Grid routing

Cluster based routing	Virtual Grid routing
Reservation-based scheduling	Content-based scheduling
Collisions avoided	Collision overhead present
Reduced duty cycle due to periodic sleeping	Variable duty cycle by controlling sleep time of nodes
Data aggregation by cluster head	node on multi hop path aggregates incoming data from neighbours
Simple but non-optimal routing	Routing can be made optimal but with an added complexity.
Requires global and local synchronization	Links formed on the fly without synchronization
Overhead of cluster formation throughout the network	Routes formed only in regions that have data for trans-mission
Lower latency as multiple hops network formed by Cluster heads always available	Latency in waking up intermediate nodes and setting up the multipath
Energy dissipation is uniform	Energy dissipation depends on traffic patterns
Fair channel allocation	Fairness not guaranteed

III. RELATED WORK

MAC Protocol design is a very wide-ranging research domain, and a lot of focuses are towards the area of wireless sensor networks[2003, IEEE Std. 802.15.4-2003], [W. Ye, J. Heidemann, and D. Estrin,2002], [I. E. Lamprinos, A. Prentza, E. Sakka, and D. Koutsouris,2005], [W. Y. J. Heidemann,2003].As widely reported [2003, IEEE Std. 802.15.4-2003], [W. Ye, J. Heidemann, and D. Estrin,2002], [I. E. Lamprinos, A. Prentza, E. Sakka, and D. Koutsouris,2005], [W. Y. J. Heidemann,2003] major origins of energy wastage in wireless sensor networks are collisions, listening, eavesdropping, traffic fluxes and protocol overhead. In the more specific area of wireless Human area networks, the basic three sources of wastage can be removed by using a master-slave architecture with time division multiple access with clear channel assessment TDMA/CCA) [2003, IEEE Std. 802.15.4-2003] network access scheme. In a recent paper, Lamprinos*et al.* [K. Langendoen and G. Halkes,2005] proposed a MAC protocol for Patient Personal Area Networks (essentially a wireless human area network application) in which a master-slave architecture is employed, whereby, to avoid idle listening, all the slaves have to lock onto the Rx slot of the master and go into standby at the same time. This approach imposes a limitation on the duty cycles of the slaves on the network. Some would have low duty cycle because they are serviced first while others would have a higher duty cycle since they are serviced later in the Rx slot.

IV. PROTOCOL DESIGN

The main goal of the proposed MAC Protocol is to reduce power consumption from sources like idle listening, overhearing and collision.

The closest existing MAC Protocol to the one presented is IEEE 802.15.4 [2003, IEEE Std. 802.15.4-2003], however it had 3 differences which were not well suited to this specific application.

1) Data reliability isn't handled in the MAC layer.

2) Multiple communication modes increase the complexity of implementation. Hence, this new scheme is easily implemented in hardware.

3) Time-slotting is limited *(16 slots in a super frame)* and must all be equally spaced Before describing the MAC Protocol, assumptions about wireless human area networks are outlined.

A. Attributes of Wireless Human Area Sensor Networks

In specifying this MAC Protocol, the following attributes can be inferred about the wireless Human area sensor network.

1) All wireless sensor nodes are attached to the Human.

2) The data being monitored is of low frequency.

3) The network does not need to respond immediately to changes (can be inferred from 2).

4) Sensors monitor a range of vital signs which are typically at a low data rate kB e.g., Temperature, pressure or heart-rate reading. However some higher data rate applications must also be catered for, such as streaming of electrocardiogram (ECG) signals.

5) The nodes are miniature; battery powered and need to run ideally for days from very low capacity batteries such as flexible printed battery technologies or miniature coin cells.

6) Sensor nodes are resource constrained, i.e., they have low processing power and limited memory.
7) Data from the wireless sensor nodes is forwarded to a central master node for processing; this central node is significantly less resource and power constrained relative to the wireless sensor nodes.

These listed attributes are the main influences leading to the specific MAC Protocol implementation described in this paper. These attributes also differentiate the particular application from more generic wireless sensor network protocols, and other protocols which have been deployed in biomedical applications such as Bluetooth, IEEE 802.11 and 802.15.4.

B. Network Architecture

As a result of the attributes in the previous section, a point to multi-point (star) network architecture is proposed. In this architecture, the central node acts as the master while the other nodes are slaves. The slave nodes are the actual WBASN nodes which acquire sensor data and transmit to the central node for processing. Each individual master-slaves network is referred to as a cluster. For ease of management, the maximum number of slaves connected to a master in one cluster is 8 *(many more can be connected, but the time-slotting would have to be managed outside the protocol).* Although it is possible to form complex networks of a "central master" with other masters, this paper concentrates on the protocol as it relates to one cluster. Also in this architecture, the network access is clear channel assessment [N. Chevrollier and N. Golmie,2005], [2003, IEEE Std. 802.15.4-2003] *and collision* avoidance with time division multiplexing (CA/TDMA). This network access scheme significantly reduces the likelihood of collision and idle listening, leading to significant power savings. In addition time-slot allocation is dynamically controlled by the master, so a slave time slot could be changed every time it communicates with the master. This enables the system to better cope with fluctuating traffic.

C. Basic Operation

The proposed MAC protocol operations are based on three main communication processes. The first is when a wireless sensor node wants to join a cluster. This is called the Link establishment process. The second is when a slave and master wake-up after an assigned sleep period. This is called the wakeup service process. The last process is an exception process which occurs when a slave urgently wants to send information to the cluster master. This is called an Alarm process. In all three processes, communication can only be initiated by the master. In addition only one slave can join the network at a time as the network is non- ad hoc.

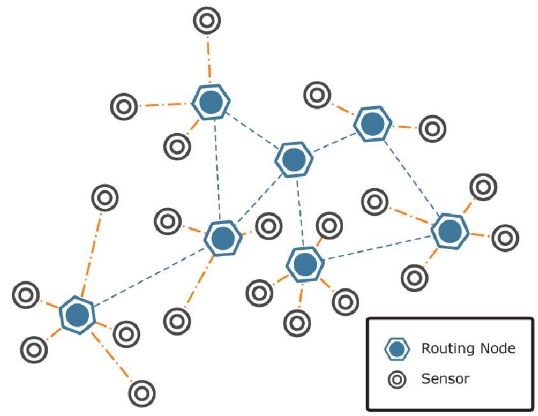

Fig. 1. Proposed MAC Protocol Network topology

Basic Routing Policies:-

1)Link Establishment:

When a master node is first enabled, it continuously tries to establish a link with unattached slave nodes. It does this by first scanning for a vacant RF channel. When it finds one, it remains on that channel and starts sending out a beacon containing a unique address and configuration for a slave and then listening for a fixed time for a response. The sum of the master's beacon transmit and listen time is termed.

2) Wakeup Service:

After link establishment, both master and slave sleep timers start to count up to the sleep time. Hence, they both wake-up at about the same time, the difference in wake-up times determined by the offsets between both timers and the length of the sleep time. On wake-up, the master interrogates the slave which alternatively listens. It (master) may simply request for its (slave's) sensor data, or request status information.Whatever the communication, a new sleep time is assigned to the slave, setting the next wakeup time-slot [Fig. 2] To mitigate long-term time-slot drift between the master and slaves in a cluster, there is an optional synchronization phase during every communication when the slave can synchronize its timer to that of the master. The master's timers never change. This dynamic time-slotting does not in any way preclude the use of the protocol in a fixed time-slotting application. It just offers this added functionality which may be used if required.

D. Wakeup Fall back Time:

The central management of time slotting can be a complex task for the master especially when complicated by the occurrence of sporadic alarm conditions. To ensure that every sensor slave node maintains a guaranteed time slot [2003, IEEE Std. 802.15.4-2003] even if another slave flags an alarm condition, the novel concept of wakeup fall back time (WFT) is proposed. If a slave wakes up and fails to communicate with the master (either because it is busy servicing an alarm, or the channel is temporarily occupied by an interferer), it goes back to sleep with a sleep time set by the WFT. During this time it continues to buffer the sensor data. After the WFT, it wakes up and searches for the master again. Similarly, if the master is unable to communicate with the slave at the wakeup time, it also defaults to the WFT. Hence, both master and slave wakeup at the common WFT and communicate, restoring the schedule. The WFT is a programmable parameter and is a fraction of the shortest sleep time on the network to mitigate continuous time-slot collisions. Also it is global to the network and originally set by the master during the link establishment process. This scheme ensures that time slot overlaps are seamlessly managed and do not degrade the network in the long run.

E. Cross Layer Functionality

When a data packet transmission fails, the MAC automatically retries a programmable number of times before dropping the packet. In addition large packets can be automatically broken in to smaller frames and transmitted one at a time. The protocol also provides for the receiver to reassemble the fragmented data packets as they are received. One additional function provided is the control of the frequency and rate of sensor data acquisition depending on the application. These functions are usually handled by higher layers in the ISO/OSI protocol stack. In this protocol, hardware implementation directly at the MAC layer is preferred as significant power savings over software implementations is achieved. This is because the processor would normally need to run continuously (significantly increasing standby power) to perform these functions like determining when to take the next sensor reading, how many should be taken and when to switch to another sensor. Also the delay involved in communicating through the protocol stack layers is eliminated [I. F. Akyildiz, M. C. Vuran, and O. B. Akan,2006].

V. PROTOCOL IMPLEMENTATION

Following detailed system modelling, the MAC Protocol was implemented as a key part of a custom system-on-chip (SoC) ASIC for Wireless Human Area Network applications. This mixed-signal SoC, known as Sensium, integrates a half-duplex transceiver, programmable sensor interface circuitry and a digital block containing the hardware MAC plus a low power 8051 microcontroller integrated with 32 kB of code and 32 kB of data memory. The data memory is directly accessible via a DMA controller by both the Sensor Interface ADC (to write sensor readings) and by the hardware MAC (to read/write sensor readings for direct transmission/reception). Having direct access to system memory allows the slave devices to operate entirely without processor intervention. The processor can therefore be switched to a low clock frequency and used to service irregular events like link errors. On the master, processor intervention is also minimal and so it is freed up to handle higher layer functions or transferring acquired data to a PC for further processing.

Mac Complexity

The entire Hardware MAC protocol, including the error control and framing block, was under 12 K-gates for the slave and K-gates for the master. The gate count of the hardware implementations points to the simplicity of the protocol. Since no hardware implementations of 802.15.4 were found, we compared the software implementations of both protocols. The proposed protocol can be implemented in around 16 kB of code (including application code) while 15.4 would require at least 32 kB. The power consumption for this implementation is around 500 W while it is 15.4 [http://focus.ti.com/lit/ds/symlink/cc2430.pdf, 2007], [http://www.embedded.com/columns/technicalinsights/189500078, 2006]. This is because of the difference in clock frequency required to run both protocols.

System Power and Duty Cycle Analysis

The average power consumption is dependent on the duty cycle of operation. So even though a sensor node has a very long sleep time, but also has a long active time, the duty cycle would be high and hence average power can be computed for spot measurement applications like for temperature and glucose and also for continuous monitoring applications like ECG,Packet Transfering,Control log etc. A detailed analysis of the relationships between the parameters of duty cycle versus sleep time and average power computation for symbol rate sequences are compared as follows.

Comparison Scenario:

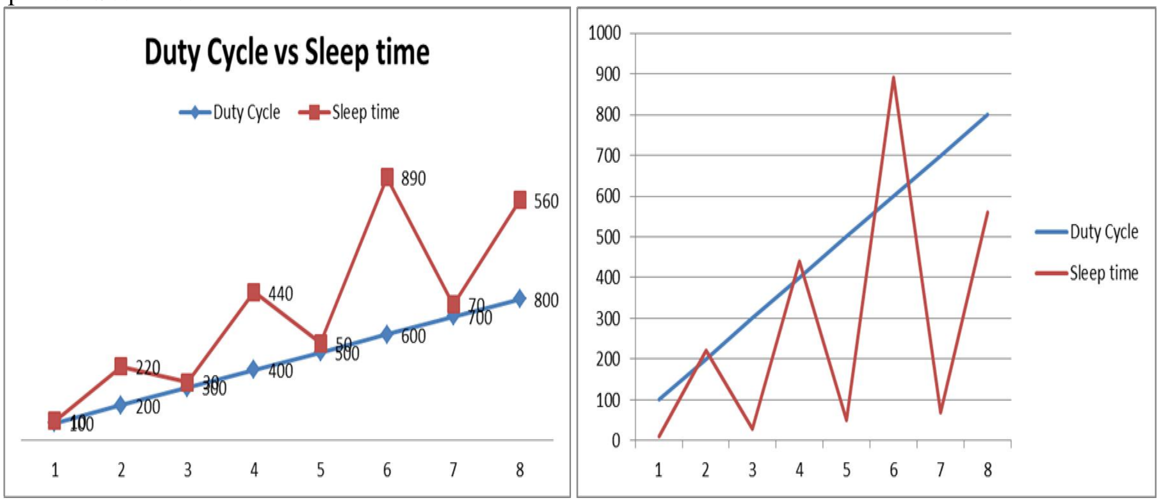

Fig 2: Duty Cycle and Symbol Rate

VI. IMPLEMENTATION OF THE WIRELESS HUMAN AREA NETWORK PROTOTYPE

A. Experimental Environment

Our *controlled* environment for measurements and evaluations is depicted in Fig. 2.denotes Exact error evaluations and require the accurate knowledge of the input signals. Since real sensors do not faithfully represent their input, we opted to employ ECG recorded signals instead. As seen, the definition of the input signal u(t), the implementation of the PDA and the TDM, and the performance evaluation were carried out in a computational environment. software package (ArbExpress, Tektronix) allows data transfer between the computational environment and the generator nand/or oscilloscope using the CSV (comma-separated value) file format. As shown, the samples of the demodulator output serve as input to the reconstruction (PDA and TDM) and the performance evaluation module. The calibration unit evaluates relevant error measures and establishes the accuracy limits of the arrangement. For completeness, we included a brief description of error measures and calibration.

B. Reconstruction Accuracy in the Computational Environment

In order to emulate a realistic class of sensor-generated signals, we selected and G signal from the MIT-BIH public arrhythmia database [http://focus.ti.com/lit/ds/symlink/cc2430.pdf, 2007]. This database contains a number of ambulatory ECG recordings digitized at 360 samples per second with 11-bit resolution over a 10 mV range. One of the (scaled) signal segments obtained after a 7-th order polynomial interpolation. Due to measurement constraints, we employed a periodic input in our experimental platform. A periodic Wireless Human Area Network limited waveform u(t) was generated by expanding a segment of length 2.5 s of the signal into Fourier-series. The fast FFT algorithm computed 750 Fourier coefficients. Measured results of u(t) so obtained and employed.

E. Comparing With Existing Systems

The power consumption of this work compared with other systems is bar charted in Fig.2 One of the key differences that comes out of this is that the RF power requirement is significantly lowest for this work. This makes it possible for much smaller batteries like flexible-thin or zinc-air which cannot be used for any of the other standards. It is concluded that power is the penalty these protocols pay for their generality. A proprietary protocol like the one presented can be tailored to a specific application area to achieve much reduced power requirements. It can also be argued that the required generality can be provided at the master, which can interface to the wider communication network as shown in Fig. 1.

VII. CONCLUSION

This paper presents a new energy-efficient MAC Protocol targeted at wireless Human area sensor networks focused on pervasive healthcare applications. The protocol exploits the attributes of this type network to implement a very low power architecture which is still capable of fast reaction to sporadic Alarm events. The novel concept of 'wakeup fall back' time is also presented as a means of reducing the complexity of time-slot management in the presence of link failures resulting from Alarm events or other interference. The MAC has been implemented as part of a larger SoC, and measured results have validated the effective operation of the new MAC protocol and its efficient routing algorithm.

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