Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks

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Abstract—This paper presents a novel energy-efficient MAC Protocol designed specifically for wireless body area sensor networks (WBASN) focused towards pervasive healthcare applications. Wireless body area networks consist of wireless sensor nodes attached to the human body to monitor vital signs such as body temperature, activity or heart-rate. The network adopts a master-slave architecture, where the body-worn slave node periodically sends sensor readings to a central master node. Unlike traditional peer-to-peer wireless sensor networks, the nodes in this biomedical WBASN are not deployed in an ad hoc fashion. Joining a network is centrally managed and all communications are single-hop. To reduce energy consumption, all the sensor nodes are in sleep mode until the centrally assigned time slot. Once a node has joined a network, there is no possibility of collision within a cluster as all communication is initiated by the central node and is addressed uniquely to a slave node. To avoid collisions with nearby transmitters, a clear channel assessment algorithm based on standard listen-before-transmit (LBT) is used. To handle time slot overlaps, the novel concept of a wakeup fallback time is introduced. Using single-hop communication and centrally controlled sleep/wakeup times leads to significant energy reductions for this application compared to more “flexible” network MAC protocols such as 802.11 or Zigbee. As duty cycle is reduced, the overall power consumption approaches the standby power. The protocol is implemented in hardware as part of the Sensium™ system-on-chip WBASN ASIC, in a 0.13-μm CMOS process.

Index Terms—Hardware MAC, MAC Protocol, wireless body area sensor network, wireless sensor networks.

I. INTRODUCTION

The wireless communications revolution which is leading the convergence of all media and data services appears to be gaining 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 chronic conditions that require ongoing clinical management [1], [2]. Sensium™ is a trademark of Toumaz Technology Ltd, UK.

Vital signs monitoring using wireless sensor network technologies has previously been described, but these systems are typically bulky and power hungry and rely on MAC protocols such as Bluetooth and 802.11 which are inefficient for such WBASN applications [3]–[6]. More general Wireless Sensor Network (WSN) MAC protocols, which have been the focus of fairly intensive research [6], [7], [9], [10], are also not well suited to these specific biomedical WBASN applications either. Zigbee/IEEE 802.15.4 [6] 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 body 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 (a primary source of energy wastage [6], [7], [9], [10]), and the use of centrally controlled time slotting for sensor nodes. The complete hardware MAC also incorporates cross-layer optimization, performing some ISO/OSI upper layer functions (from session layer down to PHY) at the hardware MAC layer to reduce the power overhead of software implementations.

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 networks (WSN) and emerging wireless body area sensor networks (WBASN). In the following sections, the proposed MAC Protocol is presented in more detail, from conception to design, implementation together with measured results.

II. RELATED WORK

A. Review Stage

MAC Protocol design is a very broad research area, and a lot of recent work has focused on the area of wireless sensor networks [6], [7], [9], [10]. As widely reported [6], [7], [9], [10] major causes of energy wastage in wireless sensor networks are collisions, idle listening, overhearing, traffic fluctuations and protocol overhead.

In the more specific area of wireless body area networks, the first three sources of wastage can be eliminated by using...
a master-slave architecture with time division multiple access with clear channel assessment (TDMA/CCA) [6] network access scheme. In a recent paper, Lamprinos et al. [11] proposed a MAC protocol for Patient Personal Area Networks (essentially a wireless body 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.

### III. MAC 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 [6], 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 body area networks are outlined.

#### A. Attributes of Wireless Body Area Sensor Networks

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

1) All wireless sensor nodes are attached to the body.
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 (< 1 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 WBSAN 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 [3], [6] and collision avoidance with time division multiplexing (CCA/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.

The penalty is increased complexity of the central node. However, this is not a major problem because the central node is expected to have significantly more power and processing resources. The key idea used in this network architecture is to move much of the network and protocol complexity away from the power constrained wireless sensor nodes and into the much more capable central node.

This network topology is shown in Fig. 1. To accommodate for intercommunication between clusters, access to an IP network may be used. This way complex network structures can still be built which extend wide areas.

#### 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
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 [6] even if another slave flags an alarm condition, the novel concept of wakeup fallback 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. Also it allows a slave with a long sleep time more opportunities to communicate its data to the master without having to wait for the whole sleep-time again.

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 [12].

Fig. 1. Proposed MAC Protocol Network topology ($S =$ Slave Node, $M =$ Master node).
IV. MAC PROTOCOL IMPLEMENTATION

A. Implementation Platform—Sensium™

Following detailed system modeling, the MAC Protocol was implemented as a key part of a custom system-on-chip (SoC) ASIC for biomedical WBASN 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. Which blocks are active in a given mode is controlled by the power management unit. The Sensium™ system block diagram is shown below in Fig. 3.
From the above analysis, it has been shown that the duty cycle in continuous monitoring applications like ECG is affected mainly by the communication symbol rate.

Table II illustrates this using typical numbers for 3 important applications. For spot measurement applications, we can reduce duty cycle by increasing the sleep time because more payload data means that the overhead time becomes less significant and (3) approaches (4). This is however not the case for continuous monitoring applications like ECG as the amount of sensor data must increase with sleep time. For applications like this, the sleep time is usually limited by the system memory resources available for storing the sensor data. Fig. 4 shows the graphs of obtained by plotting (1) and (2) for a temperature sensing application. The payload size was kept fixed; while the sleep time was changed (which means that sampling interval was spread evenly over the chosen sleep time which is acceptable since the data is significantly more than required as shown in Table II). It can be concluded from the plot that the power is dependent on the sleep time (4a) as well as the number of retransmissions (4b). Fig. 4(b) also shows that the power consumption approaches the standby power as sleep time increases.

\[ P_{AVE} = \text{average power} \]
\[ P_A = \text{active power} \]
\[ P_{SB} = \text{standby power (sensors acquiring data)} \]
\[ T_S = \text{allocated sleep time (time between wakeups)} \]
\[ T_A = \text{active time (RF on + Sensor Active)} \]
\[ N_R = \text{number of retransmissions} \]
\[ T_{FO} = \text{Frame overhead time (RF Setup, preamble, sync, control, address and CRC)} \]
\[ F_{ADC} = \text{ADC sampling frequency} \]
\[ N_S = \text{Number of samples taken in a sleep period} \]
\[ E_S = \text{Effective sampling rate} = \frac{N_S}{T_S} \]
\[ N_{bps} = \text{Number of bits per sample} \]
\[ F_{SYM} = \frac{\text{TX time}}{\text{sec}} \]
\[ R_{EO} = \text{Error overhead ratio} \approx 1.5 \]
\[ DC = \text{Duty Cycle} = \frac{T_A}{T_S} (1 + N_R). \] (1)

The general equation for average power is

\[ P_{AVE} = P_A \cdot DC - P_{SB} \cdot (1 - DC). \] (2)

Expanding the DC equation further, we have

\[ DC = \frac{T_FO + \frac{3}{2} \cdot N_S \cdot N_{bps} \cdot T_r}{T_S \cdot F_{SYM}} (1 + N_R) \]
\[ = \frac{2 \cdot T_{FO} \cdot F_{SYM} + 3 \cdot N_S \cdot N_{bps} \cdot T_r}{2 \cdot T_S \cdot F_{SYM} (1 + N_R)} \] (3)

For spot measurement applications, \( T_{FO} \) is significant because of the small data payload and hence cannot be ignored.
However for continuous monitoring applications like ECG, where the payload bits are \( \gg \) frame overhead bits, \( N_a = F_{\text{ADC}} \cdot T_s \) and so \( T_{FG} \) becomes insignificant. Equation (3) then becomes

\[
DC = \frac{3}{2} \frac{F_{\text{ADC}} \cdot N_{\text{MAX}}}{F_{\text{SYM}}} (1 + N_R) \tag{4}
\]

The transmit time for the data payload is \( \sim 40 \text{ ms} \) (~100 samples), giving a typical duty cycle (for 1 sec sleep time) of 4%. The majority of target applications however have much longer sleep times, so the duty cycle would be much smaller and hence lead to greater power savings.

A more realistic plot is shown below for (3) in Fig. 5. Here the typical numbers from Table II are used. The plot shows that as sleep time increases, the duty cycle decreases, quickly converging even for 9 retries.

In the case of an ECG streaming application, the duty cycle is fixed by the Transmit/Receive symbol rate. Fig. 6 is a plot of duty cycle versus symbol rate for this implementation (4). In all applications, the duty cycle would determine the time slot allocations to the slave devices in a cluster network and ultimately limits how many can be supported. Hence, network scalability is mainly application dependent. For example, the ECG example above in Table II can support a maximum of 8 slave node because of the 8% duty cycle. However in practice this would be kept to 6 to allow for possible retransmissions. Also an application like blood glucose monitoring (0.0014% duty cycle) could have up 255 slave nodes which is the maximum number that can be supported by the master node.

D. Measured Results

The fabricated chip was mounted on a demo board with other interfaces for SPI, UART and USB as well as a bread boarding area for connecting the application sensors. The constructed demo board is shown below in Fig. 7. Table III below gives the component and system standby and active power with a 1 V supply. These are actual measured current consumptions from the fabricated PCB including the sensor currents for body temperature sensing and ECG streaming applications. As shown in Table III, there are 3 power states; active, sleep/standby and deep sleep. In active mode, all the blocks are turned on. For sleep
Fig. 7. Application demonstration board photo [18].

<table>
<thead>
<tr>
<th>Block</th>
<th>Deep Sleep – Sensor Off (μA)</th>
<th>Sleep/Standby – Sensor ON (μA)</th>
<th>Active – RF+Sensor ON (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF – Tx</td>
<td>1</td>
<td>1</td>
<td>2400</td>
</tr>
<tr>
<td>RF – Rx</td>
<td>1</td>
<td>1</td>
<td>2100</td>
</tr>
<tr>
<td>Sensor Interface</td>
<td>1</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>MAC</td>
<td>1</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>AT subsystem @1MHz active @32 kHz standby</td>
<td>20</td>
<td>20</td>
<td>500</td>
</tr>
<tr>
<td>System Tx</td>
<td>25</td>
<td>70</td>
<td>3000</td>
</tr>
<tr>
<td>System Rx</td>
<td>25</td>
<td>70</td>
<td>2700</td>
</tr>
</tbody>
</table>

TABLE IV

<table>
<thead>
<tr>
<th>BLOCKS</th>
<th>ACTIVE</th>
<th>SLEEP/STANDBY</th>
<th>DEEP SLEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>Sensor Interface</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>Processor</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>Processor clock source</td>
<td>16 MHz</td>
<td>32 kHz</td>
<td>32 kHz</td>
</tr>
<tr>
<td>MAC</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>MAC Timers</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>16 MHz clock</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>32 kHz Clock</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
</tbody>
</table>

Fig. 8. Transmit power (−10 dBm) pie chart. The MAC Protocol power is about 1% of the total power.

One of the observations from measurements is that on average, the number of retries is very low (< 1%), but ultimately depends on the agility of the radio when there is relative movement between the communicating nodes. In addition, the overall measured packet error rate is 0.04%. This is however detectable using CRC and so the data can be retransmitted at a later communication. All performance measurements used a dipole antenna with both master and slave nodes stationary.

Also the separation distance was 5 meters and RF transmit power was −10 dBm.

E. Comparing With Existing Systems

The power consumption of this work compared with other systems is bar charted in Fig. 9. 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.

V. CONCLUSION

This paper presents a new energy-efficient MAC Protocol targeted at wireless body 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 fallback' 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 (Sensium™), and measured results have validated the effective operation of the new MAC protocol.

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REFERENCES


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Prof. Toumazou is recipient of the 1992 IEEE Circuits and Systems (CAS) Society outstanding Young Author Award, the 1995 IEE Electronics Letters Prize award, and the IEE Raleigh book award for his work on current-mode signal processing. He has served on the Board of Governors of the IEEE CAS Society and also as VP for Technical activities from 1996 to 1999. He is an Advisor to many healthcare panels, including the Singapore Government in the field of medical devices. He is a Senior Advisor to the Board of Grace Semiconductor, Taiwan, R.O.C., one of the largest Semiconductor Foundries in the World and Senior Advisor to Advanced Nanotech Inc. He was a member of the U.K. foresight committee on a report for infectious diseases as well as a member of the UK MOD Defence Strategic Advisory Committee on critical technologies. He is also Editor-in-Chief of the IETs Electronics Letters. He was invited to deliver the 2003 Royal Society Clifford Patterson prize Lecture, entitled “The Bionic Man”, for which he received The Royal Society Clifford Patterson bronze medal. He was awarded the 2005 IEEE CAS Society Education Award for pioneering contributions to telecommunications and biomedical circuits and systems, Fellowship of the IEEE and in 2006 the Membership of Europea Academia. Chris was also awarded the 2007 UK Royal Academy of Engineering Silver Medal for his contributions to Industry.