Power Efficient Networking Using a Novel Wake-up Radio

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***Abstract*—Many protocols have been developed for the Wireless Body Area Networks, reducing the transceivers duty cycle, and the energy consumed for the communication. But, since regular transceivers use significant amount of power for idle channel listening, all of these protocols have high overhead in power consumption when sensors need to work with asynchronous events triggered from outside the network, or have long sleep modes without any operation. Therefore, we introduce a protocol that works with our ultra low power receiver to deal with these events, while the rest of the sensors can be placed into off mode. We discuss possible application of the wake up receiver (and compare it with applications that do not use it) regarding the average power consumed for communication. Results show that using our low power wake up radio has significant advantages when the sensor has long sleep times.**

***Index Terms*—WBAN, protocol, wake up radio, low power**

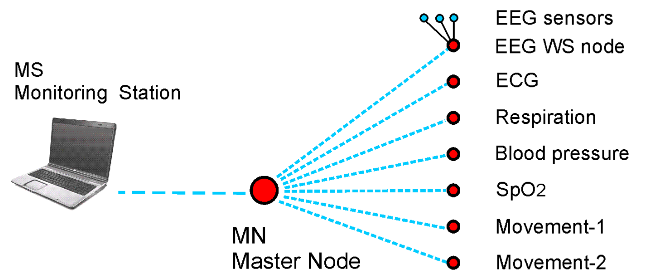

Fig. 1. Typical WBAN topology.
Sensors are gathered around a Master node (MN), communication is one-hop and MN is used as a gateway

I. Introduction

Recent years have seen the expansion and development of Wireless Sensor Networks for various applications for remote monitoring. If the monitoring subject is a human, we have a specific type of Wireless Sensor Network, so called Wireless Body Area Network (WBAN). WBAN consist of a number of sensors that are either placed on a persons body or are small enough to be implanted. The main characteristic of a WBAN is that the sensors are heavily power constrained and power budget for communication is limited. Numerous communication protocols were developed with the same idea in mind: ”Reducing the power consumption, while still keeping the network functionality and flexibility”. These sensors also need to transmit data at wide range of data rates (Body temperature, Heart rate, Glucose level, ECG, EEG, etc.). Also, for the majority of medical applications in normal operating conditions sensors are not operational constantly, but the patient is regularly monitored at certain time intervals or monitored on demand.

If the sensors are independent and wireless transmission is used, these long sleep times or on-demand functionality are very difficult to achieve using the regular transceivers, because idle listening on a radio channel consumes significant amount of energy, and it is needed in order to ”call” the sensor on demand. Also, for regular monitoring at fixed time intervals, sensor’s microcontroller must have some timers turned on constantly, in order to trigger time interrupts for sampling. For modern low power microcontrollers, where we have different low power modes, this energy can be significant.

With the introduction of the Master Node (MN) also called as gateway node, network coordinator or personal server, power consumption can be reduced, as explained in [1]–[4], as well as the well-known beacon-enabled IEEE 802.15.4 MAC [5]. MN is a less energy constrained device worn around the persons belt, acting as a gateway between WBAN and the surrounding.

But, as all this protocols are low duty cycle and low power for constant patient monitoring, they fail to achieve optimal power consumption when on-demand functionality is needed and sensors are supposed to send data at long time intervals, while spending most of the time in off mode. This is because with regular transceiver, in this type of applications we balance between power consumption and latency. Having on-demand, emergency application with very low power consumption and low latency is only possible by using the external ultra-low-power wireless wake up receiver which takes over the task of listening for asynchronous signals, allowing the primary transceiver and/or sensor to be shut down.

This is a nice way of greatly increasing network flexibility without adding much communication power overhead. Solutions that discuss this are [1], [6], [7]. We will discuss the TDMA protocol described in [2] and adapt it to the medical environment with on-demand and low frequency data acquisition applications, using the real wake up receiver (WUR) developed in our laboratory [8]. The wake up receiver that we use in this protocol compares well with other works where WURs were developed.

The rest of the paper is organised as follows. Section 2 presents an overview of the work. Section 3 details the WUR

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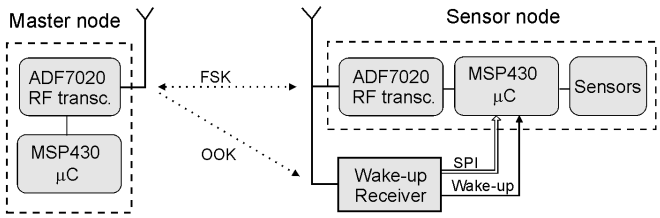

Fig. 2. Master node and Sensor with attached WUR
Data communication is done using transceivers FSK mode, and wake up signals are sent using the OOK mode.

developed in our group, while Section 4 presents how this WUR can be used in an application. Section 5 presents the power consumption model for low frequency data acquisition applications, while Section 6 makes some concluding remarks.

II. Overview

We consider a WBAN as a one-hop star network, built around a Master Node (MN). We use this network topology rather than multi hop, since idle listening is reduced, and even with higher transmission power, the communication power consumption is reduced. The typical network topology can be seen in Fig.1. MN is usually a less power constrained device, equipped with larger battery. Those nodes can be dedicated gateways for the transmission over longer distances, or in general can be some PDA devices which can provide some basic monitoring as well as acting as a relay. Sensors are medical devices with added microprocessor and wireless connectivity and by function we will split them in three groups:

1) *Sensors that stream data*
They have high sample rates and are used for data transfer on demand (ECG, EEG, EMG, SPO2, etc.)
2) *Sensors that are used for constant patient monitoring*
They are usually with very low sample rates, and in general would be sleeping for extended periods of time, but regularly waking up, measuring some value and sending it. Examples of those would be temperature, glucose level, etc.
3) *DSP enabled sensors*
Sensors that can transfer data on demand, but can also do local DSP and send values, like the sensors 2. For example, ECG or SPO2 sensor can stream data, but can also give status for heart rate, or respiration.

Sensors from groups 2 and 3 are interesting for the wake up receiver based applications, since they measure values that do not change much in normal conditions, and can have low monitoring frequency.

Overview of the MN and the sensor is presented in Fig.2. For communication, MN uses the BAN transceiver and sensor uses the same transceiver with an added circuitry used for idle channel listening and wake-up generation. We will consider that data transfer is done using the transceiver in frequency shift keying (FSK) mode, and wake up signals are sent to the sensors using the transceiver in On Off Keying (OOK) mode.

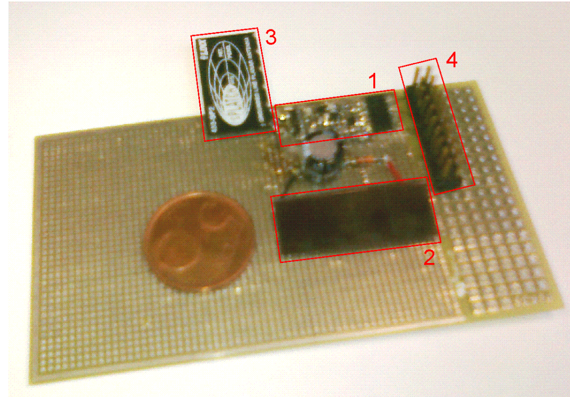

Fig. 3. Wake Up Receiver.
1 - Wake Up Receiver circuit with SPI decoding interface.
2 - Solar cell.
3 - Planar 433Mhz antenna
4 - Connectors (used for measurements)

III. Wake up receiver

If the sensor is most of the time in sleep mode, and should be woken up at long intervals to send data, then a good low power strategy must be developed to accommodate for events on-demand. In general, using only the transceiver, the lower latency one needs, the more energy will be spent on idle listening. Therefore, the need arises for a component that can listen continuously on a channel, and still consume less power than any regular wireless protocol that accommodates on-demand events. Communication requirements for this type of Wake-up Radio (WUR) receiver are modest. There are two levels of functionality. A basic WUR simply wakes up every sensor in the proximity of the wake-up signal sender, while more sophisticated WUR can receive a simple command which identifies and wakes up only the sensor being addressed. But, energy consumption requirement for this receivers quiescent power (P_{ws}) and dynamic power (P_{wd}) are critical. The WUR will be active for extended periods of time while the other components are either in sleep mode or shut down entirely. Therefore, in order for this wake up radio to be practical, it must fulfil following requirements, regarding power consumption:

- *Very low WUR power consumption* - The WUR will remain active for extended periods of time (depending on the MAC protocol) while the rest of the node is in sleep mode, therefore its power consumption for P_{ws} and P_{wd} must be very low.
- *Small effect to overall power consumption* - The WURs effect to the overall power consumption of the rest of the sensor (primarily microcontroller) should be minimal.

We designed and tested an ultra low power, multi-frequency capable Wake Up Receiver [8]. The whole prototype that was used for measurements including a planar antenna and a solar cell is shown in Fig.3. The radio was fully tested for power consumption and robustness to communication interference from wireless devices commonly found in vicinity of a person carrying a WBAN. Measurements show that the power consumption of our receiver is 470nW (idle listening). This was further reduced to P_{ws} of 270nW (idle listening) and P_{wd} of $3\mu W$ (receiving a packet), using the NPS1101 CMOS comparator by NanoPower Solutions, Inc. [9] as the comparator with lowest power consumption on the market at the time. The wake up receiver also has the Serial Peripheral compatible Interface (SPI) that standardises the connection and reduces power overhead on signal decoding. Its power consumption is included in 270nW figure. Our radio has lower power consumption than the other state-of-the-art radios, and can be used in WBAN environment. Data has to be On Off Keying (OOK) modulated and coded as Pulse Width Modulated (PWM) signal. Transceiver that can change between OOK and FSK modulation can be used for both, communication, and wake up signal sending.

Using this wake up receiver has the advantage when we need low power network management (activating sensor, switching the sensor state, generally when asynchronous event is needed). Therefore, it adds the needed flexibility for very low power sensors that would send data on demand.

IV. Using the WUR in existing protocols

The basic idea for a WUR is to be used with the existing WBAN protocols and standards in order to increase flexibility. But, in order to do so, some modifications must be introduced in existing protocols to accommodate for the new wireless component. In general, standard communication protocols would not be altered much for the constant data monitoring and data streaming, but would have added components for flexibility in low frequency data acquisition and in on-demand situations. We will consider our protocol [2] as the lowers power consuming protocol for WBAN data streaming, and add our WUR [8], to increase flexibility.

A. TDMA frame and Wake-Up packet

Proposed protocol's TDMA frame can be seen in Fig.4. It consists of a beacon (B), sent by MN, and number of timeslots. Every measured value is assigned to one or more timeslots, depending its size. Values, such as heart-rate, or blood pressure can be sent using only one timeslot, and hence it is given only one. On the other hand, streaming of ECG needs multiple timeslots in order to achieve required data-rate. Some slots can be also united and packet can be sent across all of them to reduce overhead. Of course, some reserve timeslots should be left for real-time data stream, in case of errors. Deciding what values are going to be measured is done by MN, using the predefined scenarios for types of treatment, or can be selected using MN or MS. For example, if patient is a flu case, slot "S1" would be used for temperature, "S2" for blood pressure and so on. Or, if patient needs to be monitored for ECG, for example "S1" would be heart rate, and "S2-12" would be used for ECG data stream. Every measured value should also have preferred sensor to obtain it, or if possible, backup sensor (or

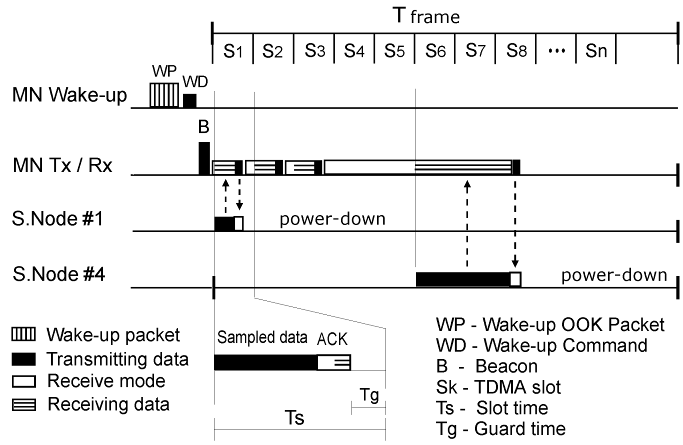

Fig. 4. TDMA frame
Beacon (B) is sent every timeslot. Wake up signal (WP, WD) are sent on demand. Sensors can occupy one or more timeslots, depending on type of signal and type of data they measure

Preamble	Start bit	RF Channel	WBAN ID	Sensor node Address	Check

Fig. 5. Wake up packet - OOK modulated packet (WP from Fig.4)

sensors). Data can be sent in longer time intervals, where WUP will be used, or streamed as explained in [2].

The TDMA frame and slot timings are determined by communication data-rates and packet size, which in term is determined by sample rates. For example, if communication data rate is f_c, bit/s and status packet takes maximum n bits in total, time of the timeslot does not need to be longer than $T_s = n/f_c + T_{guard}$ for optimal channel utilisation. T_{guard} is the guard time and it is determined by clock accuracy and resynchronisation time. On the other hand, number of timeslots needed for streaming is determined by the sample rate, data rate and TDMA frame. The guard time is necessary to avoid overlapping of the transmissions from different sensors due to clock drift. Usually there would be more than one packet per TDMA frame for streaming, depending on BER (bit error rate) and packet overhead, for optimal communication. Also, when slots are assigned, there should be some free timeslots left for reserve, in case of errors. This is especially important in case of real-time streaming.

A timeslot would be freed for wake up packets. Every wake up packet should be followed by a command packet. This is because if there is a need for longer commands, they should not be sent by WUR since communication data rate of a WUR will be lower than data rate for a regular transceiver (for example, [8] has 5-10kb/s, and ADF7020 has 200kb/s). Therefore, if long commands are needed, more time will be used for the WUP packet. It should be kept short, having only WBAN i.d., and address for a sensor that next command is intended for.

Also, a low power WUR does not have multi-frequency operation. To be low-power, WUR design must be kept simple, and this feature might be unnecessary power overhead. Wake-up communication would have its own carrier frequency and it cannot use multiple channels. Therefore, wake-up packet should also have information about the frequency channel where wake-up command will be sent. Example wake-up packet can be seen in Fig.5. It consists of:

1) *Preamble* - used to generate wake-up signal
2) *Frequency channel* - Frequency channel in which to expect a command.
3) *WBAN ID* - WBAN ID, given on network forming.
4) *Sensor address*
5) *Check* - CRC or FEC

B. Example protocol

As mentioned earlier, every timeslot has its value assigned to it, and preferred sensor to obtain it. For example, if pulse is needed, MN assigns a timeslot for all communication regarding this value. Then it sends a wake up signal and a command to the address that is used by SPO2 sensor, to measure the pulse. If sensor does not respond, MN addresses alternate sensor (DSP enabled ECG), asking for the same value, before eventually concluding that signal is unavailable. Also, if streaming of the data is necessary, MN addresses the sensor, and gives it a number of timeslots, depending on data rate and required latency (generally, it would give number of timeslots for streaming, and some reserve timeslots, in case of data loss). After this is performed, streaming works as described in [2], and further commands are provided using ACK/NACK packets.

There are 4 modes of operation for a sensor:

1) *Disconnected* - Sensor state straight after the reset. It is in a deep sleep mode, waiting for a wake-up signal to be assigned to a WBAN.
2) *Stand-by* - Sensor is in a deep sleep mode, but paired with a MN, waiting for a wake-up signal to change state, and get assigned a channel.
3) *Monitoring* - Sensor is in a stand-by mode, but is woken up once or periodically, with a period assigned by MN, to send a measured or DSP calculated value. Depending on the signal, it might be needed to switch on probes earlier.
4) *Stream* - Available for some sensors. Sensor is on, collecting data, packetising the raw samples and sending it to the MN.

For the wake up receiver to be useful, as far as sensor is concerned, it should be in states 1) 2) and 3). For the state 4), WUR would not have any function. Master Node can change the state of the sensor, using a wake up + command, or alternatively using ACK packet, if the sensor is active in the timeslot.

As far as MN is concerned, there are two states of operation. This is generalised and depending on the medical practices there can be various sub-modes. But all of them can be split in two basic modes:

1) *Normal monitoring* - All sensors are stand by mode, paired. MN is not sending beacons in order to free channel, and every hour or so, it searches for a free channel, starts sending beacons and wake up packets, collects data from the sensors, and frees the channel.
2) *Emergency - On demand monitoring* - MN occupies channel permanently. This would usually mean that there is an emergency, or somebody requested constant monitoring or a channel stream.

V. Power consumption model

When a power consumption model for communication needs to be built, duty cycle needs to be considered first. Duty cycle is calculated as the fraction of time that a system is in an ”active” state. For the sensor transceiver, this is the time the transceiver is on (RF activity time), regardless if it is transmitting data, receiving data or idly listening to a clear channel. Low power protocols try to reduce these times so that transceiver can be switched off for longer durations of time. Introducing the wake up receiver as a component that can listen to a channel reduces this duty cycle (Time spent on idle listening), but introduces new component with quiescent power consumption. Good power model must be derived to justify the introduction of this component and maximum power consumption it can have, to be practical to use in applications.

For wake up packets, energy spent by sensor, for receiving one wake up signal is calculated as:

$$E_{wup} = P_{wd}T_{wup}(1 + wer + per) + P_R T_{cmd}(1 + per) \quad (1)$$

P_{wd} and T_{wup} is dynamic power consumed by wake up receiver while receiving a wake up packet, and its duration. P_R is average power while receiving packet (command) and T_{cmd} is duration of a command. wer and per are error rates for wake up and data packets. Energy consumption for sensor, for sending one information (status) packet can be calculated as:

$$E_{stat} = (P_R T_{beac} + P_T T_{stat} + P_R T_{ack})(1 + per) \quad (2)$$

P_T is average power while sending data (status packet). P_R is average power while receiving packet (beacon or acknowledgement). T_{beac}, T_{stat} and T_{ack} are durations of beacon, status and acknowledge packets.

Therefore, total power overhead for communication when sensor is in a WBAN (normal monitoring) is calculated as:

$$P_{total} = P_{ws} + \frac{n_{wup}E_{wup} + n_{stat}E_{stat}}{T_{on}} \quad (3)$$

P_{ws} is quiescent power consumption of the wake up receiver. n_{wup} and n_{stat} is number of wake up commands and statuses in period where we measure power consumption (T_{on}).

For example, we will consider ADF7020 transceiver for data transfer, MSP430 microcontroller, and our added wake up circuit. For our wake up receiver, values are:

TABLE I
COMPARISONS FOR WITH AND WITHOUT WUR

	1h	30min	1min	10sec	1sec
WUR (μW)	1.142	1.194	4.23	19.76	188.32
No WUR (μW)	16.002	16.054	19.09	34.62	203.18
No WUR / WUR	14.01	13.45	4.51	1.75	1.08

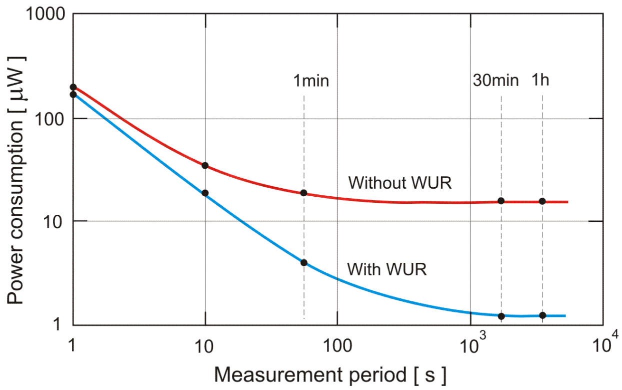

Fig. 6. Power consumption with and without WUR

ADF7020 transceiver

Communication band - ISM	433 Mhz
Communication data rate	200 kb/s
RF output power	-10 dBm
Low Power Sleep Mode	230 nW
Consumption in receive mode	$\mathrm{P_R} = 57$ mW
Consumption in transmit mode	$\mathrm{P_T} = 47.7$ mW
Wake up receiver (WUR) [8]	
Data rate	5.5 kb/s
Quiescent power	$\mathrm{P_{ws}} = 270$ nW
Receiving-Dynamic power	$\mathrm{P_{wd}} = 3\ \mu$W
MSP430F5x microcontroller	
Shut-down mode LPM 4.5	0.52μW
Stand-by mode LPM 3	7.8μW

Using these values, power consumption model for application with WUR (equations 1, 2 and 3) and power consumption model for application without WUR (from [2]) we compare the application with and without WUR for longer monitoring intervals. Quiescent power consumption for transceiver, wake up radio, and as well the microcontroller is considered. One must note that in order for TDMA frame to be active, MSP430 needs to be in low power mode LPM3, while if WUR is listening on a channel, it can be in shut-down mode LPM4.5. Full comparison can be seen in Fig.6. For considered timing intervals in which data is collected, power is given in Table I.

VI. CONCLUSION

It can be seen that in direct comparison with the very low power protocol, for longer measurement intervals, using wake up radio has significant benefits with approximately 14 times lower power consumption for communication. This is for regular protocols with quite high latency (20s in our model calculations). If lower latency is needed, this ratio would be even better for using the WUR. Since most of the devices in a WBAN have a very low energy consumption requirements, but still need to have high flexibility and low latency, Wake Up Radio can be seen as one of the devices that will find its use in this type of sensors. The methodology used here can be also adapted to other short range Wireless Sensor Networks topologies where power consumption is the most important.

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