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An Energy Consumption Model for Time Hopping IR-UWB Wireless Sensor Networks

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ABSTRACT

In this paper we proposed an energy consumption model for IR-UWB wireless sensor networks. The model takes the advantages of PHY-MAC cross layer design, and we used slotted and un-slotted sleeping protocols to compare the energy consumption. We addressed different system design issues that are responsible to energy consumption and proposed an optimum model for the system design. We expect the slotted sleeping will consume less energy for bursty load than that of the un-slotted one. But if we consider latency, the un-slotted sleeping model performs better than the slotted sleeping case.

Key Words : PHY-MAC cross layer, sleeping protocol, ultra wide band, sensor networks, energy consumption

Ⅰ. INTRODUCTION

In 2002, the United States Federal Communication Commission (FCC) allocated frequency spectrum 3.1 GHz to 10.6 GHz as unlicensed frequency band for Ultra Wide Band (UWB) devices. According to FCC, UWB is defined as the fractional bandwidth $W/f_c \geq 20\%$, where W is the transmission bandwidth and f_c is the band center frequency or more than 500 MHz of absolute bandwidth. The energy of UWB is spread over a large spectrum and thus we can achieve power level up to 41.3 dBm [1], [2]. Ultra wide band pulses are typically of nano-second or pico-second order; these include the family of Gaussian shaped pulses and their derivatives [4], and therefore pulses spread their energy over a frequency band of several GHz. UWB signals can coexist with narrow band systems.

Recently, Impulse Radio (IR) based Time-Hopping (TH) ultra wide band technologies for short range high-rate and low rate multi-user wireless communications become an interesting area and there have been significant increase in research activities both in academic and industry in short range UWB communications [4]. UWB transmitter and receiver does not require expensive and large component, such as modulators, demodulators, and IF stages. It can reduce cost, device size, weight, and power consumption of UWB systems compared with conventional narrow band communication systems.

Presently UWB is a strong candidate for wireless sensor networks [4]. A typical wireless sensor network consists of sensors powered by small batteries that are hard to replace. The sensor nodes can only transmit a finite number of bits during the lifetime of the node because of power

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limitation. Thus reducing the energy consumption per bit for end-to-end data transmission is an important design consideration for such networks.

We assume that each information bit collected by a sensor is useful for a finite amount of time; after this time the information may become irrelevant. Hence all the bits collected by the sensors need to be communicated to a sink node within a certain deadline. Therefore, the maximum end-to-end transmission delay for each bit must be controlled to meet a given deadline under the hard energy constraint. So it is a challenging issue to design an optimal energy model, which can reduce energy consumption and also can take care of delay.

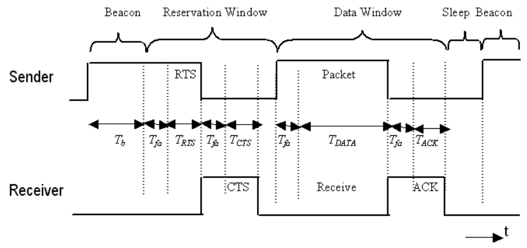
In [6] they introduced an energy consumption model where they showed transmitter electronics part and amplifier part required for transmission. They used ISM transceiver parameters to measure the energy consumption and compared their model for different MAC protocol namely Nano MAC, S-MAC and CSMA protocol. But carrier sensing is not defined well in IR-UWB physical layer [7]. Therefore we need a specific energy model, which can take the advantages of IR-UWB. In [7] they introduced a PHY aware MAC protocol for self-organized, low power, low data rate IR-UWB networks and described in detail. Finally they applied slotted and unslotted sleeping protocol to minimize energy consumption. But they did not propose any specific energy model, which can be used for single hop or multi-hop sensor networks. In [8] they proposed an energy consumption model for a node when it works as a transmitter and in another case works as a receiver, and used sleeping protocol to reduce energy consumption. Also this work does not consider amplifier part of a transmitting end in detail. Since distance between transmitter and receiver, path loss exponent, receiver SNR, transmitter efficiency etc. are also responsible for energy consumption. In our work we addressed transceiver electronics part as well as amplifier part and proposed an energy consumption model for IR-UWB sensor networks, and verified our model using PHY aware MAC slotted and unslotted sleeping protocol [7] for one hop communication. By extensive simulation we see our model figured out the actual energy consumption for two different sleeping protocols. Finally we discussed, the tradeoff depending on application of the sensor networks on the viewpoint of energy consumption, delay, and throughput.

The rest of the paper is organized as follows. Section II describes features of PHY-MAC cross layer and sleeping protocols; slotted and unslotted, section III describes the proposed energy model. Section IV describes the simulation and conclusion of our work.

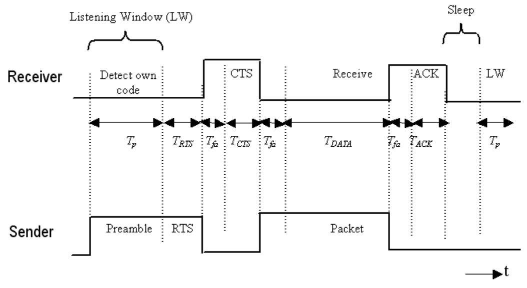
Ⅱ. CROSS LAYER MAC FOR UWB SENSOR NETWORKS: SLEEPING PROTOCOLS

To utilize UWB in sensor networks, specialized MAC algorithms are needed to work with the properties of the technology and which can minimize energy consumption [4]. There are many proposals for cross layer design. It is expected that future wireless networks would be enhanced by PHY-MAC cross layer and higher layer protocols [9]. PHY-MAC cross layer, where the wireless medium is shared with higher layer in order to provide efficient methods of allocating network resources and application over internet. The authors in [7] proposed a PHY-aware-MAC protocol for self-organized, low power, low data rate IR-UWB networks. They discussed nine building blocks; 1) rate adaptation, 2) power control, 3) mutual exclusion, 4) multi-channel, 5) multi-user reception, 6) random-schedule access, 7) time slots, 8) centralized architecture and 9) sleeping protocol, those are the proposals to minimize energy consumption. They showed sleeping can be more effective to save energy. Also [10] proposed for MAC and Routing cross layer protocol for energy efficient wireless sensor networks, where they aimed to increase the node sleeping time. So we choose to use sleeping protocol in our energy model to reduce energy consumption. Also we assume within one hop distance we have power control to reduce energy consumption.

We choose to use slotted and unslotted sleeping protocol as in [7], [8] to verify our energy model and finally our goal is to increase the network lifetime by increasing the sleeping time of a node. Figure-1 shows two sleeping protocols. In the *slotted sleeping* protocol we have four steps: beacon, reservation window, data window and sleep. Before starting communication the beacon ensures a coarse-level synchronization and denotes the start of super frame, where the length of super frame is equal to the length of reservation window plus data transmission slots. Before transmitting a data packet, a reservation is required according to this protocol. Assume we have a perfect slot reservation protocol for data transmission. By sending an RTS, a transmitter requests for a number of data slot on the TH code of the receiver. If the receiver grants the slots that were requested by a source, then data transmission begins, and should be finished within the allocated slots. Since, transmission occurs only within the allocated time slots, for the rest of the time the node can go into sleep mode. In case of *unslotted sleeping*, we assume each receiver has its own listening schedule. When the node wakes up according to its listening schedule, it can listen other node's schedule. After knowing their schedules, a node can decide whether it can transmit data to a certain node or not. If all nodes have the same sleeping schedule but little bit delayed in time, a transmitter should send a long preamble, as long as the maximum sleeping time. When the targeted node wakes up, that will receive the preamble and will reply to the preamble. If the node permits to transmit data, the sender will immediately start transmitting. Unlike slotted sleeping, there are no reservation slots in unslotted sleeping protocol.



(a) Slotted sleeping



(b) Unslotted sleeping

Fig. 1. Sleeping protocols: (a) slotted and (b) unslotted

Ⅲ. MODEL DESCRIPTION

3.1 Time Hopping UWB Code

In our model we use Time-Hopping (TH) IR-UWB. We divide a fixed amount of time into frame which consists of N_c number of very short durations called chips as in [7], [8]; duration of a chip is T_c. Therefore pulse repetition period is $T_f = N_c \cdot T_c$. In this case one pulse carries one information bit. During a chip time, the physical layer can perform any of the following tasks: (a) transmit a pulse, (b) receive a pulse, (c) perform signal acquisition, (d) be in active-off state, or (e) sleep. The active off state occurs due to time hopping. When a node is in between two pulse transmissions or receptions, energy consumption occurs to keep the circuit powered up, but no energy is used for transmitting or receiving pulses. Every single chip consist of a finite amount of energy, thus it defines a chip-level model of energy consumption. The time hopping code is shown in figure-2.

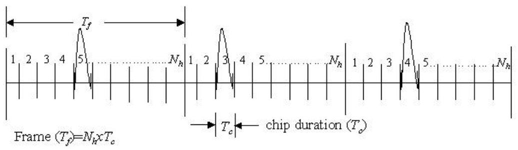


Fig. 2. TH code for IR-UWB signal

3.2 The radio energy model

We assume that all devices in the network are simple and inexpensive, the nodes have a common optimal transition range and within that range packet transmission is error free. Now we divide our model into two parts, transmitter and receiver.

Transmitter Energy consumption model: For every transmission the minimum required energy as in [11]:

$$P_{Tx} = P_{elec} + P_{amp} \tag{1}$$

where, P*elec* is non-transmitted device electronics power, which includes the power decapitated in the oscillator, frequency synthesizer, mixer, filters, base band processing etc. P_{amp} is the power above P_{elec} needed by the transmitter for an acceptable E_b/N_o at the receiver's demodulator. Using equation (1) we can find energy required at the transmitter for a single bit:

$$E_{Tx} = P_{Tx}/R_{bit} \tag{2}$$

where, R_{bit} is raw bit rate at the physical layer.

$$\begin{aligned} &\Rightarrow E_{Tx} = (P_{elec} + P_{amp})/R_{bit} \\ &\Rightarrow E_{Tx} = E_{elec} + E_{amp} \end{aligned} \tag{3}$$

where, E_{elec} is energy of electronics part and E_{amp} is energy of amplifier part for a single bit. E_{amp} [11] is expressed as follows:

$$E_{amp} = \frac{(S/N)(NF_{rx})(N_o)(BW)(4\frac{\pi}{\lambda})^{\gamma}(10)^{\gamma}(d)^{\gamma}}{(G_{ant})(\eta_{amp})(R_{bit})} \tag{4}$$

where, *(S/N)* is the minimum required signal to noise ratio at the receiver's demodulator for an acceptable E_b/N_o, NF_{rx} is the receiver noise figure, N_o is thermal noise floor, *BW* is bandwidth in Hertz, λ is wavelength in meter, γ path loss exponent, *d* is distance between transmitter and receiver, G_{ant} antenna gain, η_{amp} is the transmitter efficiency. If the distance between transmitter and receiver is longer E_{amp} will require more energy per bit. For non-line of sight transmission depending on communication environment path loss exponent can be different. At this we can have rapid changes in E_{amp} value.

In the TH-IR UWB case, energy consumption of transmitter electronics [8] for each time hopping frame can be expressed as

$$P_{Tx\_elec} T_f = P_{pulse} T_c + (N_c - 1) E_{ao} \tag{5}$$

where, $T_f \geq N_c \times T_c$; T_f is frame duration. But [4] suggest that to avoid overlap between two transmitted symbols from the same user we should use $T_f > N_c \times T_c + \zeta$, where ζ is the maximum delay spread of the dense multipath channel, P_{pulse} is energy of a single pulse, E_{ao} is active off energy. Taking the help of equation (3) we can derive energy equation for a complete packet, where a packet defines the actual size of a data packet expressed in bytes. The energy needed to transmit a complete packet can be obtained by combining (4) and (5) as follows:

$$\begin{aligned} E_{Tx\_pkt} = {} & T_{st\_t} P_{st\_t} + [l_p + l_s + \frac{l_T - l_s}{R_{code}}] \times [(P_{pulse} \\ & + P_o d^{\gamma}) \times T_c + (N_c - 1) E_{ao}] \end{aligned} \tag{6}$$

Let,

$$P_o = \frac{(S/N)(NF_{rx})(N_o)(BW)(4\frac{\pi}{\lambda})^{\gamma}(10)^{\gamma}}{(G_{ant})(\eta_{amp})} \tag{7}$$

Here, T_{st_t}, P_{st_t} is device start up time and power respectively, needed to reach transmitting state from sleep state, R_{code} is coding rate, l_p, l_s, l_T are length of preamble, synchronization bit and total length of packet in bits respectively. Encoding energy per bit is very low, which is negligible.

Receiver Energy consumption model: Receiver energy consumption for each frame can be expressed as follows:

$$P_{rx\_elec} T_f = E_{rx} + (N_c - 1) E_{ao} \tag{8}$$

where, E_{rx} is energy spends to receive a pulse.

For a single transceiver E_{rx} energy is equal to the acquisition energy for a pulse. Energy consumed to receive a single packet can be written as follows:

$$E_{Rx\_pkt} = T_{st\_r}P_{st\_r} + l_s N_c E_{acq} + [l_p + \frac{l_T - l_s}{R_{code}}] \times [E_{rx} + (N_c - 1)E_{ao}] + (l_T - l_s)E_{decode\_bit} \quad (9)$$

Here, T_{st_r}, P_{st_r} are startup time and power respectively, needed to reach at receiving state from sleep state. Decoding energy is explained in detail as in [12]

$$E_{decode\_bit} = C_o \alpha_c^{k_c} V_{DD}^2 + (T_o \alpha_t^{k_c}) \frac{f_{\max}}{f} V_{DD} I_o e^{\frac{V_{DD}}{\gamma V_T}} \quad (10)$$

where, $f_{\max}$ is the maximum clock frequency, f is the actual frequency which can be changed due to dynamic voltage scaling, C_o, α_c, T_o, α_t are hardware constants, V_{DD} supply voltage, I_o leakage current, V_T thermal voltage, γ path loss exponent. Thus combining equations (6) and (9) we can get total energy consumed for a single packet in one hop communication:

$$\text{ETotal=ETx\_pkt + ERx\_pkt} \quad (11)$$

The Table-1 shows the physical layer, sleeping protocol and energy consumption parameters used in our model. First we simulated to find useful number of slots, for slotted sleeping and later we select one hop distance for error free communications. We selected path loss exponent for indoor communications.

Table 1. Energy consumption model parameters

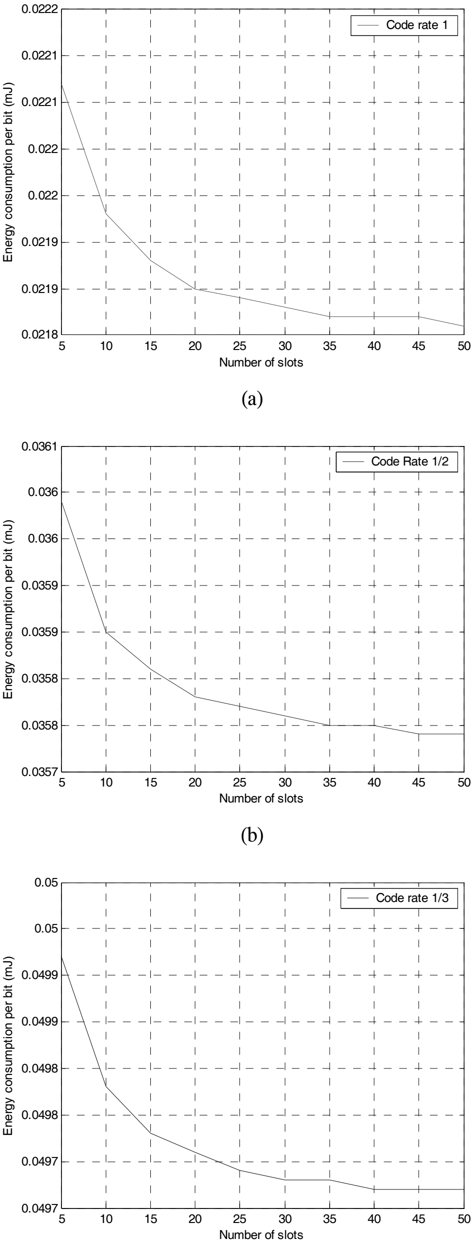
Physical layer parameters	Number of chips per frame N_c=1000 Chip duration T_c=1 ns R_{code} =1, 1/2, 1/3
Sleeping Protocol parameters	T_b = 20 μs, T_{fa}=10 μs T_{RTS}=T_{CTS}=T_{ACK}=800 μs T_{DATA}= 9600 μs
Energy consumption parameters	P_{pulse}=0.2818 mW, T_{st_t} = T_{st_r} = 0.9 ns E_{rx}=$P_{pulse}T_c$, P_{st_t}= P_{st_r} = 0.12 mW $E_{deccode-bit}$ =4.18 mJ P_o = 10 mW [14], γ=4

Ⅳ. SIMULATION RESULTS

We used simulation tool Matlab. Assume all the nodes have the same battery power level, same physical layer, and no packet retransmission. In both slotted and unslotted sleeping we assume synchronization before every transmission, and the beacon is used to achieve coarse acquisition [7]. At first we simulated to select number of useful slots, a duty cycle and maximum one hop distance. Duty cycle is defined as: the ratio, expressed as a percentage of the maximum transmitter ON-time, relative to a one-hour period [6]. Our simulation result showed low duty cycle ensures minimum energy consumption, but low duty cycle increases access delay. After generating a packet a node can't send that packet immediately. Because the node needs to wait until a reservation period to obtain access to the destination, this waiting time is called the access delay. Through the work we used data rate 100 kbps and packet size 120 bytes.

Select number of slots: Before simulating our energy model, we selected number of useful slots that will possibly; consume minimum energy for slotted sleeping. We used code rate 1, 1/2 and 1/3 to fix slot number. Figure-3 (a), (b), (c) show the curves for energy consumption per bit vs number of slots. Among three figures, (a) shows lowest energy consumption when coding rate was 1. In all three figures after 25 slots, change of energy consumption was minor. So, we choose to use code rate 1 and number of slots Sa = 25.

Select duty cycle: Figure-4 shows a three-dimensional curve to select duty cycle. In the figure we can see energy consumption increased for increasing duty cycle in both sleeping protocol. However, when duty cycle increased, access delay decreased. This is because, when we have large ON time, waiting time for resource reservation decreases. During simulation, we found maximum time required getting access to the destination was 1.8 sec for a certain case, when the load was



(a)

(b)

(c)

Fig. 3. (a), (b), (c) Energy consumption vs number of slots

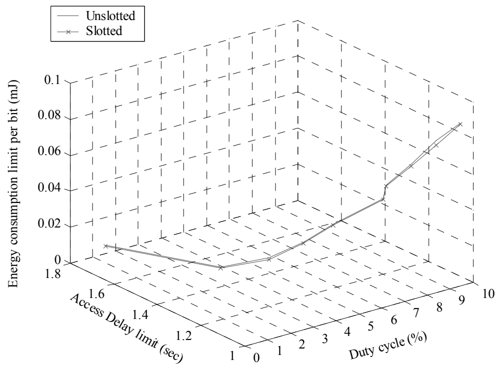


Fig. 4. Energy consumption for different duty cycle and access delay in unslotted and slotted case.

very high. But for a small amount of load the time required to get access was around 1 sec. Our aim is to reduce energy consumption, and we can see when duty cycle was 1% it consumed minimum amount of energy. Since the proposed energy model is for non-real time application, we assume some specific application can tolerate this amount of delay. So, we selected 1% duty cycle for our work.

Select maximum one hop distance: We used unslotted sleeping and slotted sleeping to find maximum error-free one-hop distance with as low as possible energy consumption. Figure-5 shows curves of energy per bit vs maximum one hop distance. In the figure we can see, unslotted sleeping consumed a little more energy for the same hop distance than that of slotted sleeping. Both sleeping protocol consumed the same amount of energy, when the distance was 20 meters for unslotted case, and 30 meters for slotted one. So, they can have different one hop distance for error free transmission. Beyond those distance energy consumption increased rapidly. Since energy difference was small within 20 and 30 meters, we selected on an average one-hop distance d_{one_hop} = 25 meters, which was useful to compare both protocols in our next works.

Now we have fixed data rate, packet size, number of slots, duty cycle and error-free one hop distance. Next we compared energy consumption with different load and access delay. Figure-6 shows curves of energy consumption vs maximum load. We can see unslotted sleeping consumed more energy than slotted sleeping. For higher load unslotted sleeping consumed almost double energy than slotted sleeping. Thus, slotted

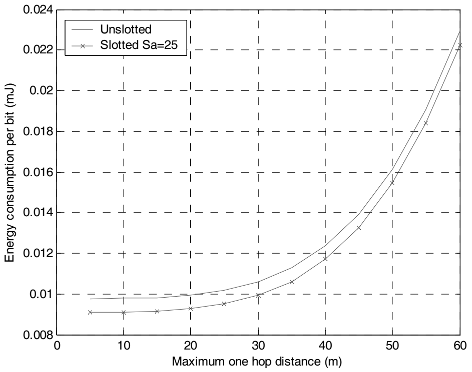


Fig. 5. Energy per bit vs maximum one hop distance

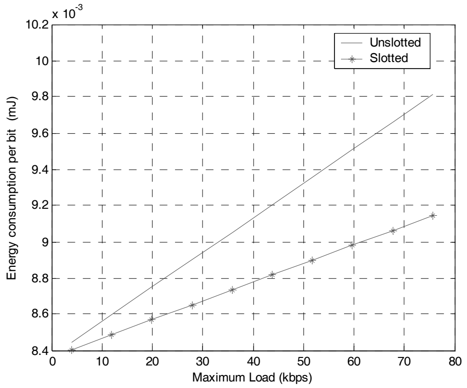


Fig. 6. Energy consumption per bit vs throughput

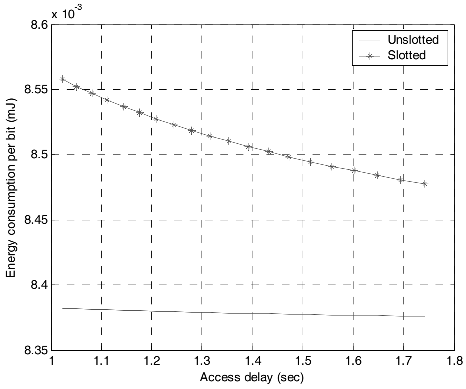


Fig. 7. Energy consumption per bit vs access delay

sleeping can perform as more energy saving in this case.

Finally we compared energy consumption per bit and access delay. In this case we found slotted sleeping consumed higher amount of energy than unslotted sleeping as in Figure-7. However, when the access delay increased to reserve the resource for the communicating node, energy consumption decreased a lot in slotted sleeping. But the effect of access delay on unslotted sleeping was very negligible. The reason is we don't have any reservation time in unslotted sleeping but only listening time. Whereas the slotted sleeping has Sa number of slots and every node has to listen for an RTS during these slots. Therefore, slotted sleeping consumed more energy than unslotted sleeping.

Based on the above simulation results, we should consider a tradeoff to select a proper sleeping protocol for some specific applications. Both sleeping protocol showed advantages and limitations as well. If an application uses higher rate of load, but don't care about the delay then slotted sleeping can be a good choice for that application. But if it is intolerable to delay, and don't care about the load rate then unslotted sleeping can be energy saving for that application. So, we must select a sleeping protocol for the energy model according to application types. In this paper we proposed a time-hopping energy model. In this time-hopping model only one chip is used to carry one bit among the total number of chips within a time hopping frame and a node can enter into sleep mode for the remaining chips within that time frame. That means it gives chance for the nodes to sleep in every time frame. Thus our proposed model saves more energy and increases lifetime of a sensor network.

V. CONCLUSION

In this paper, we proposed an optimal energy consumption model for IR-UWB sensor networks that takes the advantages of PHY-MAC protocol to increase the battery lifetime. We addressed different system design issues and implemented them in our energy model and verified our model using two sleeping protocols for one hop distance, within selected number of slots, fixed packet size and data rate. Performance comparison showed there should be some tradeoff to implement this energy model for different applications. We did not consider error and mobility for one hop communication within the selected range, but including these we may expect some more interesting results. Also we can use other sleeping protocols to verify the energy model. We hope to include these in our future work.

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