Analysis of Energy Consumption and Sleeping Protocols in PHY-MAC for UWB Networks

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ABSTRACT

Energy conservation is an important issue in wireless networks, especially for self-organized, low power, low data-rate impulse-radio ultra-wideband (IR-UWB) networks, where every node is a battery-driven device. To conserve energy, it is necessary to turn node into sleep state when no data exist. This paper addresses the energy consumption analysis of Direct-Sequence (DS) versus Time-Hopping (TH) multiple accesses and two kinds of sleeping protocols (slotted and unslotted) in PHY-MAC for UWB networks. We introduce an analytical model for energy consumption of a node in both TH and DS multiple accesses and evaluate the energy consumption comparison between them and also the performance of the proposed sleeping protocols. Simulation results show that the energy consumption per packet of DS case is less than TH case and for slotted sleeping is less than that of unslotted one for bursty load case, but with respect to the load access delay unslotted one consumes less energy, that maximize node lifetime.

Key Words : Energy Consumption, Time Hopping (TH), Direct Sequence (DS), Ultra-wideband (UWB), PHY-MAC, Sleeping Protocols

I. Introduction

The basic idea of Ultra-wideband (UWB) for wireless communication starts in the late 1960s. At present impulse-radio Ultra-wideband (IR-UWB) is a prospective radio technology for wireless networks. It is a kind of spread spectrum technique and occupies very large bandwidth [1]. After the FCC's approval to the deployment of UWB on the unlicensed 3.1 - 10.6 GHz band with rules limiting the power (up to -41.3dBm/MHz) spectral density of UWB signal, this low level emission power system is mainly used in short-range wireless communications or ad-hoc networks[2][3]. Today, UWB technology has been considered as one of the most attractive candidates of wireless personal area networks (WPAN) with unique potential advantages such as, high data-rate, low-transmission power, immunity to multipath propagation, low capability of detection, capability in precise ranging and positioning. In this type of network, which consists of many tiny devices, powered by small-sized batteries, and operates unattended for prolonged duration, the focus is more on minimizing energy consumption than maximizing rate. That means energy conservation is crucial, since the lifetime of a node is determined by its energy consumption rate[4].

Several UWB MAC protocols have been proposed for regarding the high data-rate and low data-rate with rate adaptation, no power control, without mutual exclusion using interference mitigation so on in [5][6], but they do not discuss about en-

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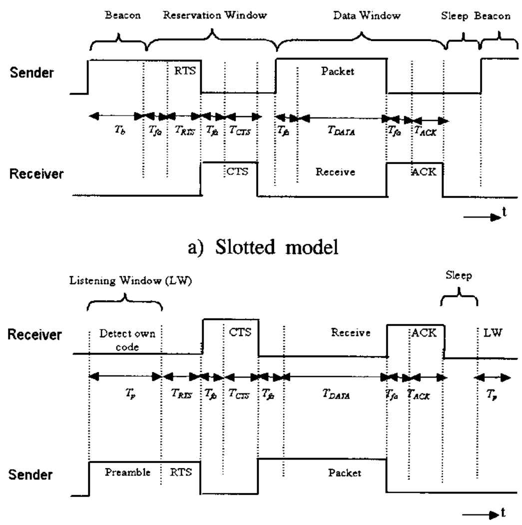
ergy conservation. In [7] the authors proposed an optimal PHY-MAC for UWB networks, which considers the energy conservation of nodes by introducing the sleeping protocol in their medium access control protocol design. In [7] they proposed two types of sleeping protocols, which are described in details in the section II. In [8] the authors introduced an energy consumption model with Time-Hopping multiple access, and with this model they have shown the performance of two kinds of sleeping protocols (slotted and unslotted) in view of node lifetime, but in their model the cost of energy consumption is not clear because, they do not give the accurate analytical value of the cost of the transmitting or the receiving energy consumption. In [8] they just assume the cost of energy consumption. In this paper, we introduced an analytical model of the cost of the energy consumption both for DS and TH multiple accesses and propose a new model. And finally with our proposed model, we investigate the energy consumption comparisons of two multiple accesses and two sleeping protocols in PHY-MAC for UWB networks.

In this regard, the paper is organized as follows. Section II outlines the PHY-MAC protocol. Section III describes the proposed energy consumption model. Section IV gives the simulation results of energy consumption comparisons. Finally, our conclusions are presented in section V.

Ⅱ. PHY Aware MAC Protocol Descriptions

A detailed description of PHY-MAC protocol can be found in [7], here we summarize briefly. The main concern of PHY-MAC is to minimize the energy consumption than maximizing the rate. So far, a number of different solutions have been proposed in the context of data rate efficiency for IR-UWB. However, the choice made for rate-efficient designs are not necessarily optimal when considering energy efficiency. Hence, there is a need to understand the design tradeoffs in very low-power networks. A PHY-MAC design has to achieve interference management, access to a destination and sleep cycle management. For implementing the above three functions in [7], it describes six building blocks, as follows: 1) Power control is not needed, it transmits with maximum power or zero power[5][8]; 2) Rate control is needed because, if transmission rates are low, packet transmissions last longer, and more energy is consumed to keep circuit running; 3) A sub-optimal and simple form of multi-user detection is beneficial, because this is an efficient way to manage multiple accesses; 4) The mutual exclusion is not needed when interference mitigation is applied. It is shown by simulation in [7], for mutual exclusion the rate becomes very low but the energy increases a little in large exclusion size. However, the exclusion region implementation is more complex and costly, so they avoid exclusion region scheme; 5) The transmission medium is separated into several orthogonal or quasi-orthogonal transmission channels, that is a kind of multi-channel protocol should be used. Finally, 6) it is necessary to use sleeping protocols in order to conserve energy of nodes in a wireless network. However this requires a mechanism that allows nodes to be contacted even though they might sleep time to time.



a) Slotted model

b) Unslotted model

Fig. 1. Slotted and unslotted model: (a) Slotted sleeping protocol with T_b= length of the superframe beacon and T_{fa}= short preamble length, (b) unslotted sleeping protocol depicted.

Generally speaking, sleeping protocols can be categorized into two schemes: one is the time-slotted scheme, and other is the unslotted scheme. In the slotted scheme, time is divided into slots and the data transmission occurs during these slots. On the other hand in the unslotted scheme, the data transmission occurs during whole period. The detail characteristics and the working principles of these two schemes are described below.

2.1 Slotted Sleeping Protocol

Fig.1(a) shows the slotted protocol. The slotted sleeping protocol is time slotted and uses a periodic beacon. This beacon provides a coarse-level synchronization and denotes the start of a superframe. A superframe has two parts: a reservation window and a data transmission window. Transmission requests are carried out by sending an RTS in a reservation slot of the receiver. The receiver replies with CTS if it accepts the reservation. If a reservation is successful, the actual data transmission occurs in the corresponding data slots and is followed by an ACK.

2.2 Unslotted Sleeping Protocol

Fig.1(b) shows the unslotted protocol. For the unslotted sleeping protocol, each receiver wakes up according to its own listening schedule. A transmitter which wants to communicate with a given receiver first needs to learn its listening schedule. Reservations are done during the listening window at the beginning of the interval, and if successful, are followed by the packet transmission. The preamble sent by a transmitter should be long enough as long as the maximum sleeping time in order to make sure that the destination will wake up, receive the preamble and answer to the transmitter.

Ⅲ. Energy Consumption Model

In this section, the energy consumption of IR-UWB system is discussed in detail, and analytical models of energy consumption are proposed for DS and TH respectively, as follows.

3.1 Energy Consumption of Time-Hopping Multiple Access

The Fig.2 shows the frame structure of TH-code for IR-UWB signal. In this case, the frame time T_f is divided into N_h hops or chips and the duration of every chip is T_c, so $T_f = N_h \times T_c$. The frame time is also called the pulse repetition period, since only one pulse can be transmitted in a frame. In fact, one pulse is transmitted in one chip and the position of the pulse or the chip number is determined by TH code.

In a chip time, the physical layer can transmit a pulse, receive a pulse, perform signal acquisition, being in an active-off state, or going to sleep. The active-off state occurs due to time hopping, when a node is between two pulse transmissions or receptions, that is, energy is consumed only to keep the circuit powered up, but no energy is used for transmitting or receiving pulses.

We model the energy consumption by considering the energy per chip for each state. Define: E_{tx} is the cost for transmitting a pulse, E_{rx} for receiving a pulse, E_{ao} for being in the active-off state, and E_{acq} is the cost for signal acquisition.

The energy consumed by a transmitter is due to two sources: one part is due to RF signal generation, which mostly depends on chosen modulation and target distance and on the transmission power P_{txTH}. A second part is due to electronic components necessary for frequency synthesis, frequency conservation, filters and so on.

First, the amplifier of a transmitter generates the transmitted power. Its own power consumption P_{amp} depends on its architecture, but for most of them, their consumed power depends on the power they are to generate. For a more realistic model we assumes that a certain constant power level is always

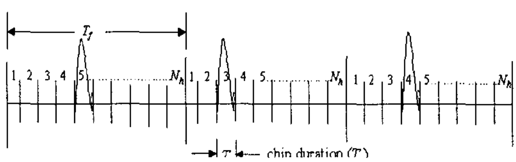


Fig. 2. Frame structure of TH code for IR-UWB signal

required irrespective of radiated power, plus a proportional offset, as is expressed by [9]

$$P_{amp} = \alpha_{amp} + \beta_{amp} P_{txTH} \quad , \qquad (1)$$

where, P_{txTH} is the actual power radiated by the antenna and α_{amp}, β_{amp} are the parameters representing the linearized efficiency of the power amplifier.

Second, in addition to the amplifier, other circuitry has to be powered up during transmission as well, for example, baseband processors. So, the energy consumption of the transmitter electronics for each frame is defined as

$$E_{txElecTH\_frame} = P_{pulse} T_c + (N_h - 1) E_{ao} \quad , \qquad (2)$$

where, P_{pulse} is power of per pulse signal, $P_{pulse}T_c$ is the energy when pulse is present, and $(N_h\text{-}1)E_{ao}$ is the energy in active-off state.

Finally, the energy needs to transmit a packet of total size N-bits with S-bits synchronization preamble and then depends on how long it takes to send the packet and on the total consumed power during transmission. Also, if the transceiver has to be turned on before transmission, startup costs are incurred and can be expressed by combining (1) and (2) as

$$E_{pkt-tx-TH} = T_{start} P_{start} + \left\{ S + \frac{(N-S)}{R_{code}} \right\} \left\{ (P_{pulse} + P_{amp}) T_c + (N_h - 1) E_{ao} \right\} \quad , \qquad (3)$$

where, R_{code} is the coding rate, T_{start} is the time to leave sleep mode to transmitting mode and P_{start} is the consuming power to leave sleep mode to active mode. In this model, the antenna efficiency is missing as well, that is, it is assumed to have a perfect antenna. Otherwise, there would be further power loss between the output of the power amplifier and the radiated power.

In the receiver, the energy required to receive a packet is the sum of the energy dissipated by a similar startup time (T_{start}) and power (P_{start}) of transmitter, the synchronization, the active receiver electronics, and the digital circuits used for decoding.

First, the receiver needs to synchronize with transmitter for communicating with each other, and some energy is consumed for this purpose. If a packet contains total N-bits with S-bits synchronization preamble, the energy consumption for synchronization is defined as

$$E_{syn\,TH} = S \times N_h \times E_{acq} \quad . \qquad (4)$$

Second, during the time of actual reception, receiver circuitry has to be powered up, requiring the energy of $E_{rxElectTH}$ - for example, to drive the LNA in the RF front end. So, the energy consumption of receiver electronics for each frame is defined as

$$E_{rxElecTH\_frame} = E_{rx} + (N_h - 1) E_{ao} \quad . \qquad (5)$$

Third, in receiver the last component of energy consumption is the decoding overhead, which is incurred for every bit-E_{decBit}, this decoding energy depends on a number of hardware and system parameters-for example, the decoding done in dedicated hardware (as in a dedicated Viterbi decoder for convolutional codes) or in software on a microcontroller; It also depends on supply voltage, decoding time per bit (which in turn depends on processing speed influenced by techniques like Dynamic Voltage Scaling), constraint length of the used code, and other parameters. So the decoding energy consumption can be expressed as in [9]

$$E_{decBit} = C_0 \alpha_c^{k_c} V^2_{DD} + \left(T_0 \alpha_t^{k_c} \right) \frac{f_{\max}}{f} V_{DD} I_0 e^{\frac{V_{DD}}{nV_T}} \quad , \qquad (6)$$

where, f_{max} represents the maximum clock frequency, and f represents the actual frequency. The constants C_0, α_c, T_0, and α_t can be regressed for hardware being modeled; V_{DD} supply voltage, I_0 leakage current, V_T thermal voltage, and n path loss exponent.

Finally, the energy needs to receive a packet of total N-bits long with S-bits synchronization preamble is expressed by combining (4), (5), and (6) as

$$E_{pkt-rx-TH} = T_{start} P_{start} + E_{synTH} + \frac{(N-S)}{R_{code}} \left\{ E_{rx} + (N_h - 1) E_{ao} \right\} + (N-S) E_{decBit} \quad . \qquad (7)$$

3.2 Energy Consumption of Direct-Sequence Multiple Access

The Fig.3 shows the frame structure of DS-code for IR-UWB signal. In this case, the frame time T_f is divided into N_c chips according to the length of spreading code and the duration of every chip is T_c, so $T_f = Nc \times T_c$. In fact, one bit is spread according to spreading code and one chip carries one pulse but active-off sate is absent here.

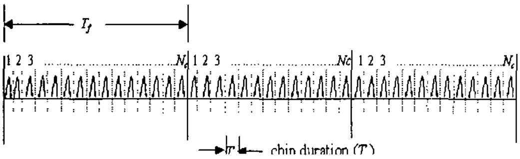


Fig. 3. Frame structure of DS code for IR-UWB signal

The energy consumed by a DS transmitter can be expressed as similar as TH transmitter with the transmission power P_{txDS}.

First, the energy consumption of transmitter Power amplifier is expressed like (1) as

$$P_{amp} = \alpha_{amp} + \beta_{amp} P_{txDS} \quad . \tag{8}$$

Second, in addition to the amplifier, other circuitry has to be powered up during transmission as well and the energy consumption of transmitter electronics for each frame is defined as

$$E_{txElecDS-frame} = E_{txDS} \times N_c \quad , \tag{9}$$

where, E_{txDS} is the energy when the pulse present.

Finally, the energy need to transmit a packet contains N-bits with S-bits synchronization preamble can be expressed as like (3) by combining (8) and (9) as

$$E_{pkt-tx-DS} = T_{start} P_{start} + \left[\left\{ \left(S + \frac{(N-S)}{R \times R_{code}} \right) \times P_{amp} \right\} + NE_{txDS} \right] \times N_c \quad , \tag{10}$$

where, R is the bit rate, and R_{code} is the coding rate.

In the receiver, the energy consumed by a DS receiver is similar with TH receiver calculation as follows.

First, the energy consumption for synchronization preamble can be expressed like (4) as

$$E_{synDS} = S \times N_c \times E_{acq} \quad . \tag{11}$$

Second, we assume the same transceiver is used for transmitting and receiving case, so the energy consumption of receiver electronics for each frame is same as (9) above.

Third, the energy consumption for decoding a bit is same as (6) above.

Finally, the energy needs to receive a packet of total N-bits long with S-bits synchronization preamble is expressed by combining (6), (9), and (11) as

$$E_{pkt-rx-DS} = T_{start} P_{start} + E_{synDS} + \left\{ \left(\frac{(N-S)}{R \times R_{code}} \times P_{amp} \right) + (N-S) E_{rxDS} \right\} \times N_c + (N-S) E_{decBit} \quad , \tag{12}$$

where, $E_{rxDS} = E_{txDS}$.

3.3 Extra Energy Consumption of Sleeping protocols

The above subsection 3.1 and 3.2 discussed the energy consumption about physical layer. In this section we will discuss about the energy consumption in MAC layer for different sleeping protocols scheme.

In the slotted sleeping protocol, the sender sends a periodic beacon that provides coarse-level synchronization and denotes the start of a superframe. In this scheme, sometimes the beacon is sent but there is no data to send, so this is a kind of energy wastage. If P_b is the power of beacon pulse and T_b the beacon period, then the energy consumption of beacon in one superframe is expressed as

$$E_{beacon} = P_b \times T_b \quad . \tag{13}$$

In the unslotted sleeping protocol, the sender sends a long preamble at the beginning of sending packet in the listening window. The preamble should be a long enough that the receiver will wake up and receive. In this scheme, if there is no data to send then the sender will not send the preamble. So, this is an energy efficient scheme. If the period of preamble is T_p and Power level of preamble is P_p, then the energy consumption of preamble is expressed as

$$E_{preamble} = P_p \times T_p \ . \quad (14)$$

Ⅳ. Simulation Results

In this section, numerical solutions of the proposed scheme are simulated; to evaluate our result we assume that T_f is the time duration of a frame. T_c is the chip or hop width in TH-UWB system satisfying $T_f = N_h \times T_c$, while it is the chip duration in DS-UWB system satisfying $T_f = N_c \times T_c$, in order to compare the energy consumption comparison of DS-UWB versus TH-UWB systems we assume the frame time is same. T_b is the length of the superframe beacon necessary to achieve coarse acquisition and T_{fa} is the length of a short preamble before every packet. Since the same transceiver elements are used for signal acquisition and reception, the acquisition energy consumption E_{acq} is assume equal to E_{rx}. The cost of sleeping is negligible. The remaining assumptions and simulation parameters are listed in Table 1, which are consistent with those from [7][9].

For the simulation, we the tools on the Matlab®. We consider that all nodes are static and have an identical physical layer with the same initial battery power. Nodes are randomly distributed on a 20m x 20m square, and the links chosen randomly. In our simulation results, it shows, the per packet energy consumption (on the y-axis) for transmitting and receiving a packet in AWGN channel, Varies with different network traffic load (on the x-axis). These energy consumptions are the calculated values, described in (3), (7), (10) and (12) above.

Fig.4 shows the energy consumption comparisons of DS-UWB and TH-UWB in the slotted sleeping and the unslotted sleeping protocols with respect to varying network traffic load. For comparison of these two multiple accesses, we assume the same frame time, and the fixed bit error rate. However, we can see from our simulation result that per packet energy consumption for the DS multiple access is less than the TH case, because of the gain of spreading code. And the slotted sleeping protocol consume less energy than the unslotted sleeping one. The network with low traffic load the energy consumption is less than the high traffic one. This is because, at the high traffic case a node becomes active maximum time to do work and consume more energy. And at low traffic case a node can go to sleep during unused slots that conserve the energy. Therefore, we can take decision from our result that the DS multiple access is preferred for energy efficient applications.

Now, we will analyze more, about the slotted and the unslotted sleeping protocols with respect to per packet energy consumption using DS multiple accesses.

Fig.5 shows the energy consumption comparisons of slotted sleeping and unslotted sleeping protocols with respect to varying network traffic load. We assume the network is designed to occasionally sustain a maximum traffic load per receiver during burst intervals, and compute its energy consumption assuming that most of the time it is subject to a normal network traffic load. We can see from our result that at low load rates the energy consumption of the two protocols nearly the same. But at high load rates, the energy consumption difference is more, and the slotted sleeping protocol outperforms the unslotted sleeping one by consuming less energy. This is because, in the slotted sleeping protocol, at the beginning of a superframe, the sender sends a short periodic beacon for synchronization. In this scheme, sometimes the beacon is sent but there is no data to send. So this is a kind of energy wastage, and it occurs at low load rates case. In the unslotted scheme, it needs to send long preamble at the start of transmission for synchronization, and the preamble should be long enough that the receiver will wake up an receive. Therefore, when the load rates become high, the unslotted protocol consumes more energy for long preamble. In the slotted protocol, the short periodic beacon energy consumption is less than the long preamble one.

Fig.6 shows the effect of reservation slots on energy consumption. In our result comparison, we used 5 and 20 reservation slots (S_a), and it shows that at high traffic load the energy consumption is high because, node needs to wake up more time to work. Other observation, in the slotted sleeping scheme, if the number of reservation slots increases, then per packet energy consumptions decrease, that is, the node lifetime increases. This is because, if the slot increases, a node can sleep during unused slots to conserve energy.

Here, we will analyze a different scenario of previous discussion. We still assume that most of the time, the network is subject to an average traffic load. However, it has to occasionally support a small number of unpredicted, but very urgent data instead of a bursty high load. In Fig.7, the access delay is defined as, when a node generates a packet, it cannot send it immediately, first it needs to wait a reservation period to access the destination. In the slotted sleeping protocol a node has to wait at most a superframe time to send a packet. In the unslotted sleeping protocol a node has to wait according to receiver listening schedule. We then compare the energy consumption for the two approaches as a function of access delay. Our result shows that per packet energy consumption of the unslotted sleeping protocol is less than the slotted sleeping one. This is because, the unslotted sleeping protocol has only one listening window per time, whereas the slotted sleeping one has S_a reservation slots and every node has to listen for an RTS during these S_a slots.

In summary, our simulation results and discussion shows that the DS multiple access is energy efficient than the TH multiple access. The two sleeping protocols perform well in energy consumption point of view under various traffic constraints. As, the slotted sleeping is preferred with less energy consumption if occasionally, a network needs to support a bursts (traffic due to an emergency situation, resulting for example in network flooding). The unslotted sleeping is preferred if occasionally, a network needs to support a delay sensitive, unpredicted or very urgent loads like, fire alarm or shutting down life threatening device, urgent rescue situation, and in military operations.

Table 1. Simulation Parameters.

Item	Value
Energy consumption models	P_{pulse} = 0.2818mW T_{start} = 0.9 ns P_{start} = 0.12 mW P_{start}<P_{rxElec}, α_{amp}, β_{amp}, E_{decBit} [9] DS: E_{rxDS} = $(P_{pulse}/N_c)\times T_c$ TH: E_{rxTH} = $P_{pulse}\times T_c$ [7]
Physical layer parameters	Number of slots of superframe = 1000 DS case: Chip duration T_c=0.5ns Number of chips per frame N_c=64[12] TH case: Chip duration T_c=1ns Number of chips per frame N_h=32 Transmitted power = -30 dBm[10]
Sleeping Protocols parameters	Slotted sleeping case: T_b=25μs Unslotted sleeping case: T_p=50μs T_{fa}=10μs T_{RTS}=T_{CTS}=T_{ACK}=800μs T_{DATA}=10200μs
Channel model	Multi-path free AWGN channel [11]

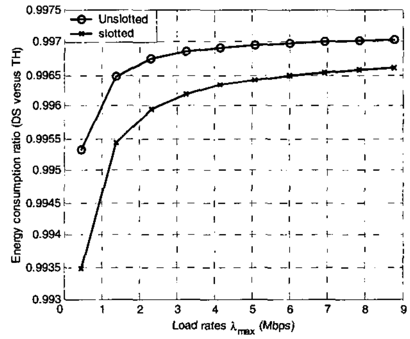


Fig. 4. Energy consumption ratio of DS-UWB and TH-UWB under slotted and unslotted Sleeping Protocols in different traffic load

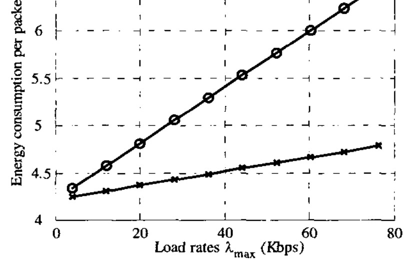


Fig. 5. Energy consumption comparisons of slotted and unslotted Sleeping Protocols in different traffic load for DS

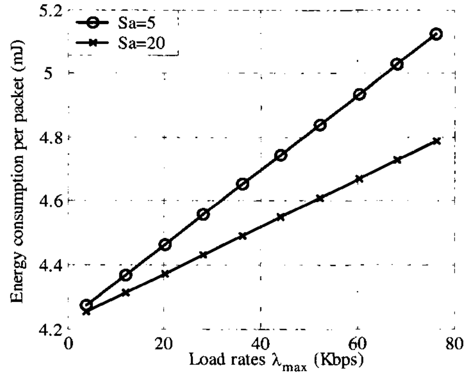


Fig. 6. Effect of slot on Energy consumption for DS

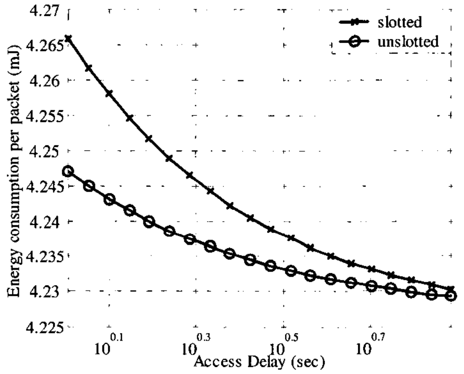


Fig. 7. Energy consumption comparisons of slotted and unslotted Sleeping Protocols in Access delay load case for DS

V. Conclusions

In this paper, we proposed an energy consumption model by which it is possible to design an optimal node for UWB network applications. Here, we have tried to give an accurate calculation of energy consumption at the transmitter and receiver both for DS-UWB and TH-UWB case. We analyze the energy consumption comparison of two multiple accesses and show the simulation results. In the result we can see that in DS case the energy consumption is less than TH case, so DS is preferred for energy efficient MAC protocol. Further, we analyze the impact of the slotted sleeping and the unslotted sleeping on PHY-MAC in UWB networks in view of energy consumption of nodes for transmitting and receiving packets by varying network traffic load. Throughout our simulations, we can find that each sleeping protocol performed better than each other for different network load case; for bursty load case the slotted sleeping one and for delay sensitive load case the unslotted sleeping one performs better with low energy consumption, which maximize the node lifetime and also network lifetime. We do not consider channel estimations and any error case. Further analysis is needed with considering these factors.

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