Performance Evaluation of Optimized Medium Access Control Schemes based on Ultra Wideband Technology

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***Abstract*— In this paper we evaluate the energy, event delivery, and delay performance of a number of medium access control protocols suitable for ultra-wideband (UWB) physical layer. While ultra-wideband is a promising technology, it creates unique challenges in MAC protocol design. Firstly, we analytically inspect the energy consumption of three UWB suitable MAC protocols and secondly concentrate on simulation of the IEEE 802.15.4 MAC and its UWB version. Comparison between UWB and direct sequence radios with the 802.15.4 MAC protocol clearly show the superior performance of UWB technology.**

I. Introduction

Wireless sensor networking is a novel communication paradigm involving devices with low complexity that have limitations on processing power and memory, and severe restrictions on power consumption. Due to the features of the application, traffic in wireless sensor networks (WSNs) is often bursty with long inactivity periods. As a consequence, a device may remain idle for long periods, thus effecting the design of effective medium access protocols, radio communications technology, by always trying to optimize multiple access efficiency, reliability, and battery life.

The increasing interest ultra wideband (UWB)based applications has influenced also WSN field Impulse-radio-based UWB technology has a number of inherent properties that are well suited to sensor network applications. In particular, impulse radio-based UWB systems have potentially low complexity and low cost; have noise-like signals; are resistant to severe multipath and jamming; and have very good time domain resolution, allowing for location and tracking applications [1].

To realize the benefits of UWB in sensor networks, careful consideration must be given to the design of the medium access control (MAC), conservation of power, and efficient radio technology. Recently, IEEE New Standards Committee has going to develop a novel standard, called 802.15.4, to provide a system having ultra-low complexity, cost, and power for low-data-rate wireless connectivity among inexpensive fixed, portable, and moving devices. MAC layer of the IEEE 802.15.4 standard allows different methods for the access to the medium: beacon enabled or non beacon enabled mode, depending on the absence or the presence of an explicit synchronization mechanism. Within the content access period, the data delivering relies on employing the CSMA-CA mechanism for channel access that usually implies a great deal of collision, thus reducing the link throughput.

To enhance the overall MAC performance, several scheme are proposed in the following. The first scheme under consideration simply joins the basic 802.15.4 MAC with a PHY layer based on UWB. Moreover, some advanced approaches, like the PULSER Aloha-based MAC, and the UWEN TDMA-based MAC are presented.

The paper is organized as follows. Section II describes the IEEE Std 802.15.4 evolution to the 802.15.4a impulse radio (IR)-UWB proposal. In Section III the other considered MAC protocols are briefly discussed and their analytical energy consumption models are derived in Section IV. Section V describes the simulation environment and presents the analytical and simulated results. Lastly, Section VI concludes the paper.

II. Standards Evolution

A. IEEE802.15.4

Recently, IEEE New Standards Committee begun the development of a low-rate WPAN (LR-WPAN) standard, called 802.15.4. The goal of Task Group 4 (TG4) is to provide a standard having ultra-low complexity, cost, and power for low-data-rate wireless connectivity among inexpensive fixed, portable, and moving devices. To this aim, Task Group 4 defines the physical (PHY) and media access control (MAC) layer specifications [2].

The main features of the IEEE 802.15.4 standard are:

- data rates of 250 kb/s (2.4 GHz) and 20/40 kb/s (868/915 MHz)
- 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz ISM band and one channel in the European 868 MHz band

- CSMA channel access with double clear channel assessment for collision avoidance
- Beacon enabled and non-beacon enabled operation options
- support for low latency devices (guaranteed time slots in star networks)
- star or peer-to-peer network topologies as well as cluster topology supported

The specification for the PHY layer defines a low-power spread spectrum (SS) radio operating at 2.4 GHz with a basic bit rate of 250 kbps. There are alternative PHY specifications for 915 MHz and 868 MHz that operate at lower data rates, which are not however as widely used. The IEEE802.15.4 PHY layer accommodates high levels of integration by using direct sequence (DS) to permit simplicity in the analog circuitry and enable cheaper implementations.

B. IEEE802.15.4a

The IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for Wireless Personal Area Networks (WPANs) has been established to define an alternative PHY layer [3]. In particular, TG4a focused on providing:

- communications and high precision ranging/location capability (1 meter accuracy and better)
- high aggregate throughput, and ultra low power
- scalability with respect to data rates
- longer range
- lower power consumption and cost
- new applications and market opportunities

In December 2005 the baseline specification had been selected, comprising two optional PHYs consisting of:

- Ultra Wide band Impulse Radio (UWB-IR), operating in the unlicensed UWB spectrum and able to deliver communications and high precision ranging
- Chirp Spread Spectrum (operating in the unlicensed 2.4GHz spectrum), which offers added robustness compared to the standard DS PHY.

The points of agreement for UWB signaling are still extremely generic. The modulation scheme should admit multiple classes of receivers and the transmitter might be based on deterministic pulse structures. Moreover, it should allow reception by coherent, differentially-coherent and non-coherent receivers with a possible ternary modulation and Code Division Multiple Access (CDMA) within frequency bands. The modulation for UWB scheme is PPM-BPSK combination.

III. Medium Access Control for UWB

The purpose of this section is to describe the medium access control schemes that are analyzed in the paper. The first scheme under consideration simply joins the basic 802.15.4 MAC with a PHY layer based on UWB. Moreover, some advanced approaches, like the PULSER Aloha-based MAC, and the UWEN TDMA-based MAC are presented.

A. Aloha UWB MAC

The Pervasive Ultra-wideband Low Spectral Energy Radio System (PULSERS) is a project aiming at investigating and developing novel communication systems based on UWB [4]. A PANs working with PULSERS technology can work at Very High Data Rate VHDR), High Data Rate (HDR), LDR and LDR with Location/Tracking LDR-LT), thus systems based on PULSERS technology can cover a wide range of applications from high-quality video streaming devices to very low cost and low power consumption devices for sensor networks. The PULSERS architecture follows the ISO-OSI reference model and its approach is to reuse as much as possible from the IEEE Std 802.15.4 in order to reduce the unproductive design of a completely new protocol, and to focus on the key issues described above [5]. The main features are the following:

- Support for peer-to-peer communication, whereas 802.15.4 requires mediation from the coordinator to allow this.
- Dedicated time slots for ranging and allocation request.
- Simplification of association, transaction to allow very low complexity implementations.

PULSERS project follows strictly the IEEE Std 802.15.4, to achieve low-complexity and low-cost devices: thus the features of the PULSERS MAC sublayer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association, and disassociation. In addition, the PULSERS MAC sublayer provides an improved mechanism for location and positioning system. Support for FFD and RFD devices is also provided. In a LDR scenarios [6], the huge bandwidth adopted for transmission translates in very short, rare pulses, and thus in a low probability of collisions between pulses emitted by different terminal. Under this hypothesis, all the devices can use a slotted ALOHA protocol to access the channel. This is translated in terms of lower complexity, and thus cost, and permits adaption between different PHY layers without particular issue, due the absence of specific PHY functions as the Carrier Sensing.

B. TDMA

The UWB Wireless Embedded Systems (UWEN) project [7] aims to develop a system capable of offering low rate communications with location and tracking for outdoor applications. The system concept is target for outdoor recreational activities such as cross country skiing, athletics and running. The concept includes the development of small, low power devices which are worn by the user. In a low infrastructure environment, the user is able to relay positioning and performance information via peer-to-peer connections to fixes nodes in the network. Devices which are not within range of the fixed node, called Access Point (AP), send their information using multi-hop techniques via intermediate nodes which act as relays.

The MAC protocol for the UWEN project is TDMA based to give to the mobile devices a guaranteed access to fixed points in the network. The fixed network is organized in clusters, each cluster contains a predefined number of AP.

The purpose of this division is to provide the moving sensor tags an area that is much larger than the span of a single access point. This provide a notable reduction of association requests and channel time allocations. Additionally, the APs have a variable transmission power in such a way that the area to be covered has a minimal amount of overlap and gaps. Even though the physical layer is the same, there are two fundamentally different MAC protocols to be defined; the sensor tag MAC and the AP cluster MAC. This is due to the necessity to have a very low cost and very simple MAC protocol in the sensor tags.

IV. Analytical Model

The aim of this section is to explain how the energy analysis model for multi-hop MAC [8] can be used to study the MAC of the IEEE 802.15.4, IEEE 802.15.4a and PULSERS devices.

The MAC algorithm employed in the IEEE 802.15.4 and in the IEEE 802.15.4a proposal is CSMA based, whereas the PULSERS employs a slotted ALOHA algorithm. Thus, the energy analysis has been performed using the respective finite state machine for those algorithms, as shown in Fig.s 1-2.

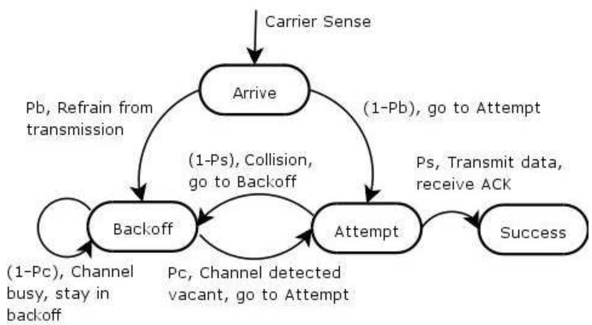

Fig. 1. Transmit energy model for CSMA-CA.

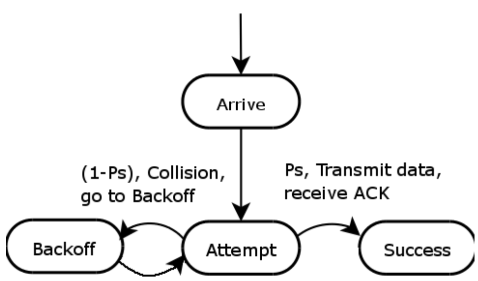

Fig. 2. Transmit energy model for slotted ALOHA.

The model assumes that the process of data arrival is Poisson-like and the number of nodes in the network approaches infinite, therefore the inter-arrival probability is exponentially distributed. The model predicts the energy consumed in a network in the transmission of data, taking into account average contention times, average backoff times and possible frame collisions. The evaluation of the energy consumption is done by investigating the transition probabilities between two MAC protocol states and the related times consumed in transmit, receive, idle and sleep. According to this model, the energy consumption is only due to operations connected with a state transition. The average energy consumption upon transmission from the point of packet arrival from the upper layer to the point of receiving an ACK frame is in general of the form:

$$E_{TX} = E_{Arrive} + P_{prob_1} E(A) + (1 - P_{prob_1}) E(B) \quad (1)$$

$$E(A) = P_{prob_2} E_{Success} + (1 - P_{prob_2}) E(B) \quad (2)$$

$$E(B) = P_{prob_3} E(A) + (1 - P_{prob_3}) E(B) \quad (3)$$

where $P_{prob_{\{1,2,3\}}}$ are the probabilities of entering a a certain state, E_{Arrive} is the carrier sensing energy consumption when coming to the *Arrive* state and $E_{Success}$ is the expected energy consumption upon reaching the Success state from the *Attempt* state. As far the CSMA-CA scheme, once the transition probabilities, the times and the transceiver modes explicitly, Eq. (1) becomes:

$$E_{TX} = T_{CS} M_{RX} + (1 - P_b) E(A) + (1 - P_b) T_{RT} M_{TX} + \\ + P_b E(B) + P_b N_1 M_{RX} \quad (4)$$

where:

- M_{TX} is the transceiver transmit power consumption related to the time consumed entering to a state. Similarly, M_{TX} is transceiver reception power consumption.
- T_{CS} is the time required for carrier sensing
- T_{RT} is the time required to change the transceiver state from receive to transmit.
- P_b is the probability of finding the channel busy during the carrier sensing.
- N_1 considers the backoff time window and the number of the slot spent before attempt another carrier sensing.

In the case of the slotted ALOHA used by PULSERS devices, the energy consumption model is obtained starting from Fig. 2, obtaining:

$$E_{TX} = E(A) \quad (5)$$

$$E(A) = P_S M_{TX} T_{PKT} + P_S \psi M_{RX} + (1 - P_S) E(B) + \\ + (1 - P_S) T_{PKT} M_{TX} + (1 - P_S) T_o M_{RX} \quad (6)$$

$$E(B) = E(A) \quad (7)$$

and after some manipulations it follows that:

$$E_{TX} = [P_S M_{TX} T_{PKT} + P_S \psi M_{RX} + \\ + (1 - P_S) T_{PKT} M_{TX} + (1 - P_S) T_o M_{RX}] P_S^{-1} \quad (8)$$

that gives the transmit energy consumption E_{TX}.

Finally, as for a UWEN device resorting to a TDMA access protocol, an approach based on the superframe structure to evaluate the transmit energy consumption is to be considered. The energy consumption is due, besides transmission, also to listening the superframe waiting for the trasmission grant slots and to switching to transceiver status from transmit, receive and sleep states. Thus, considering the superframe structure it follows that:

$$E_{TX} = (T_{SR} + T_B)M_{RX} + (T_{RS} + T_R)M_{SL} + \\ + (T_{ST} + 2T_S)M_{TX} + (T_{TR} + 2T_S)M_{RX} + \\ + (T_{RS} + ((((CUS - 1) + (CDS - 1))SS)/BR) + \\ + NGT_G)M_{SL} \tag{9}$$

where:

- M_{RX}, M_{TX} and M_{SL} are the transceiver transmit power consumption during receive, transmit and sleep states, respectively
- T_{SR}, T_{ST}, T_{RS} and T_{TR} are the time employed to change the transceiver state from one to another
- T_R, T_T, T_S and T_G are the time spent during the reception, transmission, sleep and guard slots, respectively
- *CUS*, *CDS* and *NG* are communication uplink and downlink slots and the number of guard period for superframe, respectively
- BR is the bitrate [bps]
- SS is the slot [bit].

Eq. (9) gives the transmit energy consumption E_{TX} for a UWEN device.

V. Simulation Results

A. Simulation Model

To evaluate the performance of the proposed MAC schemes, several simulations have been carried out, configuring each node respectively as an IEEE 802.15.4 and IEEE 802.15.4a device. Moreover, the network size has been varied to o verify how it can affect the performance of the network. Then, the network has been set up with a fixed number of nodes and increasing the number of the sources to verify how the network performances are affected from an increasing number of active sensors. The node are randomly deployed within an area whose dimension is chosen to have a fixed node density independently from the number of the nodes. The sink node and the sources nodes are randomly selected inside the network. Each node uses the directed diffusion algorithm [9], the interests were periodically generated every 5 seconds and each source generates two events for second. The energy model used for the IEEE 802.15.4 devices has been set up to work has a Chipcon CC2420 [], whereas the IEEE 802.15.4a has been modeled as a generic UWB chip.

The behavior of two kind of devices at different data rates are compared, evaluating the typical parameters that have a relevance inside a sensor network, such the average delay to deliver successfully an event packet from a source to the sink, the average delivery ratio (that is the ratio between the number of the event packet that are successfully delivered and the total number of event packet generated in the network), and the average dissipated energy to successfully transmit an event packet. This last parameter might be useful to analyze the *effort* done by the network to deliver successfully an event packet.

B. Performance Analysis

Fig.s 3–4 show the average dissipated transmission energy per useful received bit obtained as a function of the normalized traffic G. The average, normalized offered traffic (in Erlang) is normalized to the capacity of the channel ($G = 1\% \rightarrow 100\%$ channel capacity). This peculiarity can be seen in Fig. 3 where the random access protocols are almost constant for value of G included in the interval $[0 - 100]$ and then they diverge for value of G greater than 100. This means that, for a traffic offered to the network greater than 100 times the channel capacity, the collision and the contention algorithm employed bring the whole network to the congestion. The UWEN system, being based on TDMA, is totally unrelated from G since each node transmits only in its own slot without any contention. In the other hand we have the worst energy efficiency and this is visible in Figure 3.

Fig. 4 shows a detail of Fig. 3 to show better and to comment the performance of the three random access MACs. It is evident that the energy saving obtained using UWB instead of the IEEE 802.15.4 devices. This gain can be imputed to the lowest reception and idle power. It is to be noted the point where the devices begin to diverge. In the IEEE 802.15.4a devices this point is greater than PULSERS devices that use slotted ALOHA: for this devices, as expected, the congestion point is lower. Despite it utilize the same access algorithm of the IEEE 802.15.4a, the IEEE 802.15.4 has a *congestion point* lower than the former.

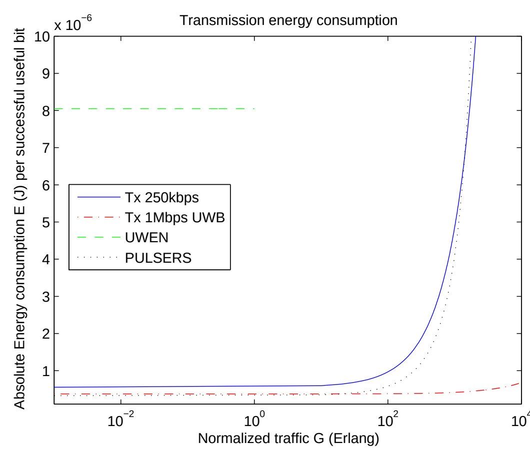

Fig. 3. Average energetic consumption for different MAC protocols.

C. Numerical Results

The simulations have been done on the following devices: IEEE 802.15.4 with 40 kbps and 250 kbps data rates, IEEE 802.15.4a 1Mbps IR-UWB and PULSERS 1Mbps IR-UWB. In all the simulations the occupied area has been dimensioned to have the same nodes density. In this way is possible to evaluate how much the performances are affected by the network dimension.

In the first scenario, with a fixed number of nodes and an increasing number of sources, it can be noticed the behavior

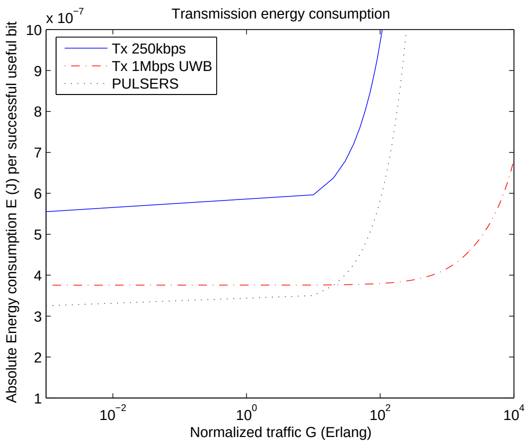

Fig. 4. Comparison of average energetic consumption at the transmitter side.

of the devices working at 40 kbps, 250 kbps and 1 Mbps in the Fig.s 5–7. This simulation can help us to evaluate the performance of the network when is subjected to an high generated traffic from the sources. The generated events have a dimension of 111 bytes, thus we are in condition of a network that generates events of big dimensions. More accurately, in Fig. 5, the Event Delivery Ratio (EDR) for the three devices are shown. The EDR is the ratio between the total number of generated events and the total number of the events received correctly. This parameter gives an indication of the reliability of the network from the point of view of the event delivery and is more reliable when the EDR value is close to 1. As expected, the devices working at 40 kbps are not able to sustain the increasing level of traffic and lead the network to the congestion with a lot of packet-loss. Differently the devices working at 250 kbps and 1 Mbps UWB that maintain the same performance that deteriorate increasing the traffic in the network. In Fig. 6, the average dissipated energy for received event are pointed out. This parameter gives an idea on how much the network is stressed to deliver an event. The UWB system consume considerably less than classic transmission systems, this is due to the lower energy consumption during the transmission and idle phases. It is interesting to notice the divergent trend of the graphic related to the 40 kbps devices. More the network is congested more the average dissipated energy diverge. This gives also the indication of the behavior for the 250 kbps and 1 Mbps network when the traffic increase further. In Fig. 7 are showed the average delivery time for an event. The devices working at 250 kbps and at 1 Mbps UWB show a regular trend, that indicate a good capability to handle the network also with an high traffic. Differently the devices at 40 kbps have a divergent trend that highlight the incapability to handle the generated traffic, as showed in Fig. 5.

Finally, Fig. 8 shows the average dissipated energy for received event. The network is a network with constant sources and sinks nodes number but with a global nodes number variable. Also in this case the UWB system consume considerably less than classic transmission systems, this is always due to the lower energy consumption during the transmission and idle phases.

VI. Conclusion

UWB transmission scheme represents a significant promise for low-power, low-cost, WSN. The high burst data rates, robust signal structure, and potentially high positioning accuracy mean that sensor networks can offer additional location services as well as extended battery life since devices are able to sleep for much of the time. A critical part of designing a UWB sensor network that takes advantages of these features is to develop a suitable MAC that supports positioning, minimizes interference, and maximizes sleep periods. In this paper we evaluate the energy, event delivery, and delay performance of a number of medium access control protocols suitable for UWB physical layer. Firstly, we analytically inspect the energy consumption of three UWB suitable MAC protocols and secondly concentrate on simulation of the IEEE 802.15.4 MAC and its UWB version. Comparison between UWB and direct sequence radios with the 802.15.4 MAC protocol clearly show the superior performance of UWB technology.

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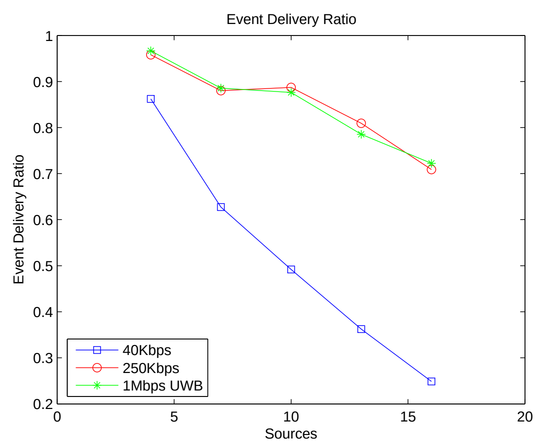

Fig. 5. Comparison of Event Delivery Ratio for schemes with and without beacon at different data rates (first case).

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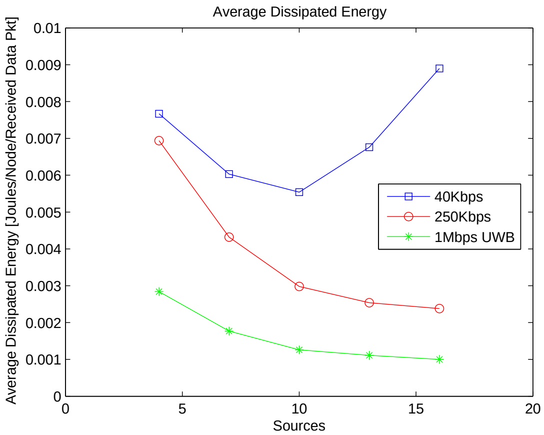

Fig. 6. Comparison of average energetic consumption for schemes with and without beacon at different data rates (first case).

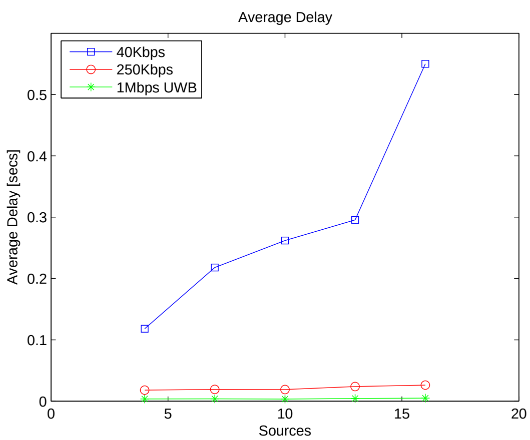

Fig. 7. Comparison of latency for schemes with and without beacon at different data rates (first case).

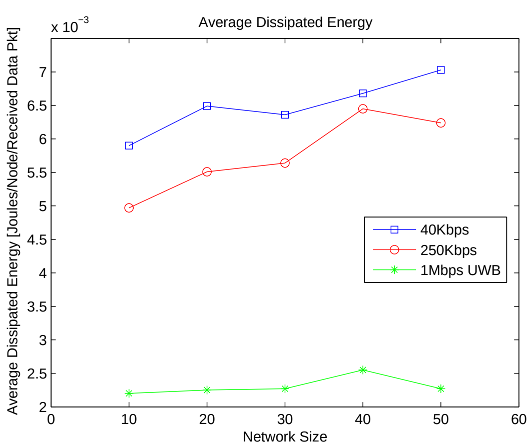

Fig. 8. Comparison of average energetic consumption for not beacon enabled schemes at different data rates (second case).

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