An analytical model for Energy Consumption in Y-MAC Protocol

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Abstract

This paper presents an analytical model for estimating energy consumption in Y-MAC protocol for Wireless Sensor Networks (WSN). This protocol has been proposed to reduce the energy consumption of a node when involved in unicast or broadcast transmission of frames. In WSN a node consumes energy in transmitting and receiving of data, listening transmissions of other nodes, and in sleep mode. Therefore, energy consumption of a node has been estimated by adding up the energy consumed in each of the above activities. This has been achieved by estimating the time spent in each activity by a node. The protocol has been simulated using MATLAB. The simulation results show comparable energy savings as compared to Y-MAC protocol, therefore, the model validates the existing protocol.

Keywords: *Wireless sensor networks, Time Division Multiple Access, Poisson distribution, Binomial distribution, Energy efficiency.*

1. Introduction

Wireless Sensor Networks is a special kind of ad hoc networks. WSN is a technology that has grown very rapidly over the years with an increase in development of new protocols or methods to fulfill the needs. Though many protocols and methods were designed still WSN needs more contributions from researchers to meet the current requirements. Sensor Networks covers wider region, nodes have limited sensing region and processing power. Sensors consume energy in sensing the object, processing and transmitting. Energy consumed in processing is insignificant. However, energy consumed in other two tasks is significant that may result in partitioning of networks. WSN have been broadly applied in ecological, biological, event monitoring in remote areas, defense, health monitoring etc. WSN does not follow any infrastructure and sensor nodes in the network are equipped with battery, significant processing and wireless communication. Nodes are inexpensive with low data rate and are deployed in large numbers. Time synchronization in Wireless Sensor Networks has been studied in the literatures, by researchers yet there is no specific scheme to achieve accuracy. Applications of Sensor Networks require time for node to be synchronized within the network. Power control of a node is a vital issue in Wireless Sensor Networks. In this paper we propose Synchronization and power control model for Y-MAC protocol. Here we calculate the delay of a node involved in unicast and broadcast transmission and power consumption of nodes involved in these transmissions.

The rest of this paper is organized as follows. We discuss the related work in section 2. In section 3 design of proposed model is explained. Section 4 presents the simulation results. Finally, we conclude the paper in section 5.

2. Related Work

Numerous multichannel media access control protocols have been designed for ad hoc networks. However these protocols are not suitable for wireless sensor networks due to limited resources, power and cost. Y-MAC protocol was designed by **Y**oungminkin and implemented in **Y**onsei University and hence named as Y-MAC [6]. It is a multichannel media access control protocol designed with the help of Time Division Multiple Access method to support both unicast and broadcast transmission of data. It uses different time slot as transmit time slot and receive time slot to guarantee collision free access to the channels and reduces energy wastage to some extent. In this protocol every node in the network synchronizes their timing for upcoming events by exchanging the remaining time when transmitting in the current super-frame period among neighbors. It has been designed to work with heavy traffic conditions where several sink nodes are deployed in the network. Whenever a network partition is detected re-association is done by nodes where every node periodically turns on its radio to perform bootstrap. Timing Synchronization protocol for sensor networks is a multi-hop protocol attempts to reduce the uncertainty of sender node with low level time stamping packets in media access control layer. Greunen and Rabaey propose the Light weight Tree-based Synchronization protocol that decreases the complexity of synchronization, and the accuracy is achieved with minimal complexity [3].

Jeremy Elson and Deborah Estrin's propose Time Synchronization for wireless sensor networks where Post-facto synchronization method is designed for extremely low power consumption [4]. Gradient Time Synchronization Protocol (GTSP) is a distributed time synchronization protocol. In gradient time synchronization protocol the logical clock of nodes converges to a common logical clock and this protocol relies on local information making it robust to node failures and changes in the network topology. The remaining synchronization error between neighbors is reduced while still maintaining acceptable global skew. Nodes in gradient time synchronization protocol can convert the current hardware clock reading into a logical clock value and vice versa [5].

MAC layer has a vast impact on the energy consumption of sensor nodes, because of radio communication. Communication is a major source of power consumption and the MAC layer design manages the transmission and reception of data over the wireless medium using the radio The MAC layer is responsible for access to the shared medium. MAC protocols assist nodes in deciding when to access the channel. Pattern-MAC (P-MAC) for sensor networks adaptively determines the sleep-wake up schedules for a node based on its own traffic, and the traffic patterns of its neighbors. This protocol achieves a better throughput at high loads, and conserves more energy at light loads. In P-MAC, the sleep-wake up times of the sensor nodes is adaptively determined. The schedules are decided based on a node's own traffic and that of its neighbors. The improved performance of P-MAC suggests that 'pattern exchange' is a promising framework for improving the energy efficiency of the MAC protocols used in sensor networks [6].

3. Proposed Work

The total power consumption of a node is the combination of overheads introduced due to hardware design and software complexity. Solution to hardware overhead is up to the engineers who design sensor devices. Software overheads occur because of delay in context switching and execution time. The time synchronization between the sender clock and the receiver clock may have a symmetrical nominal delay. Following is algorithm for calculating nominal delay.

3.1 Symmetrical Nominal Delay Algorithm

Step 1: Receiver calculates nominal delay
Step 2: Sender calculates nominal delay
Step 3: Nominal delays are calculated by all nodes, and delays are stored and forwarded to one hop neighbors. Nominal delay packet has information such as Sender ID, Receiver ID, time delay and Next sleep time of a node.
Step 4: Nominal delays are calculated after fixed time interval and disseminated to neighbors to alert them for future transmission.

Nominal delay calculation by receiver.

1. Node A transmits a request packet to node B at r_1 µsec
2. Node B receives request packet at r_2 µsec
3. Node B calculates and stores the nominal delay (ND) on its delay table

Nominal delay calculation by sender.

1. Node B transmits a response packet to node A at t_1 µsec
2. Node A receives response packet at t_2 µsec
3. Nodes A calculate and store the nominal delay (ND) on its table

This protocol is designed to supports unicast & broadcast communications with multichannel transmission. The communication may happen between sender and the nearest devices in the range of receivers in the network. Events occurring are independent of time. Traffic may be control packets or data packet. Traffic may be exponentially increasing or decreasing. Every node in a network senses the events in a given area and forwards its data to the group of neighbors. The sensed data which is to be transmitted may exceed the maximum frame size. In this case a node sends frames by dividing it into different frames of equal size.

3.2 Power level and exchange of control packets and frames

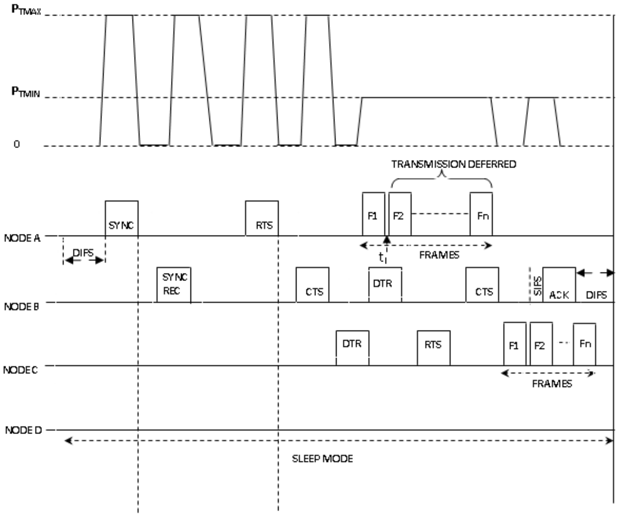

Fig. 1 Power level of nodes

In the above figure node A sense the status of the wireless medium for DIFS duration. If it found that the medium is continuously idle for DIFS duration then it transmit SYNC packet to node B. Node B records the SYNC information. Once the synchronization is done Node A sends RTS packet to Node B with maximum transmission power level P_{TMAX}. Node B calculates the minimum required power, and replies the CTS packet with minimum power level. But the minimum power level should lie within the nominal limits of transceivers. The ratio of the received power and the transmission power is given by [1]

$$\frac{P_r}{P_t} = \left[\sqrt{Gl\lambda} \big/ 4\pi d \right]^2 \qquad (1)$$

Where $\sqrt{Gl\lambda}$ is product of transmit and receive antenna field radiation patterns in the Line of Site direction, λ is the wavelength, and d is the distance. Minimum transmission power of a node is given by

$$P_{TMIN} \geq \left[\Pr_{threshold} * 16\pi^2 d^2 \big/ Gl\lambda \right] \tag{2}$$

There are 'm' sensors are distributed uniformly over a circular area A.

The node density of network is m/A.

Therefore, average distance between one-hop neighbor nodes is $\sqrt{A/m}$ [11].

Let 'e' is the latent error in the node position from the center. The distance between one-hop neighbor nodes is calculated as $d = \sqrt{A/m} \pm e$.

Therefore, the minimum power level of a node is

$$P_{TMIN} \geq \left[\Pr_{threshold} * 16\pi^2 \left(\sqrt{A/m} \pm e \right)^2 \Big/ \mathrm{Gl}\lambda \right] \tag{3}$$

The network is designed for high priority jobs and any node in the network is prone to receive High Priority Request (HPR). In this case the ongoing transmission is blocked and the remaining data is saved in buffer and priority is set in priority scheduler table (PST). Priority scheduler table has information such as Sender ID, Receiver ID, Priority of transmission and sleeping time. Here t_l is the time lapse between the reception of ACK of $n\text{-}1^{th}$ frame and beginning of transmission of n^{th} frame where t_l is less than SIFS time. Node C has High Priority Request sent to node B. so node C is sending a deferred transmission request (DTR) to node B. Node B forwards the data to node A during t_l time and interrupts the transmission. Now B and node C involves in transmission of frames, once the transmission is over. Node B initiates a clear to send (CTS) frame to node A to receive the remaining frames. Node A checks the priority scheduler table (PST) to send the pending frames based on priority.

When a sender node broadcast a frame to group of neighbors, the frame traversing through shorter path reaches the receiver earlier than those on longer paths. The direct effect of these non uniform arrivals of frames causes delay in the whole network. The delay puts a limitation on the maximum transmission capacity on the wireless channel. Specifically, if the transmission time is larger than that of delay, inter-symbol interference will occur at the receiver. It is a type of distortion due to multipath resulting in spreading out of the received frame. It occurs when identical frame arrive via different paths and have different time delays. The sender chooses the path through which a frame reaches to the destination with minimum delay.

3.3 Delay Calculation

When a node has a packet to transmit, it competes with its neighbor nodes that are ready with packets. Therefore, it also has to consider certain delays like carrier sense and back-off delay s. These delays are the same as IEEE 802.11 protocol. A node can also suffer from packet transfer delay.

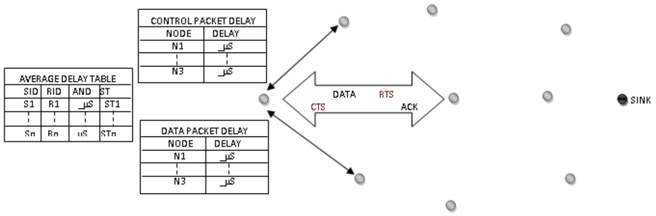

Fig. 2 Network Scenario

In wireless sensor networks events can happen at any point of time. Any node in the network can forward the sensed data to its neighbor or destination node. When a node has a frame to transmit it initiates the transmission with control packet exchange.

To transmit an RTS packet a node takes μ_R time, therefore the average arrival rate of receiving an RTS packet $\lambda = \dfrac{1}{\mu_R}$.

We assume that the packet arrival follows Poisson distribution. Therefore, probability of transmitting an RTS packet is calculated as

$$P(X=1) = \frac{e^{-(1/\mu_R)} * (1/\mu_R)^1}{1!} \tag{4}$$

Similarly, the probability of transmitting a CTS packet can be represented

$$P(X=1) = \frac{e^{-(1/\mu_C)} * (1/\mu_C)^1}{1!} \tag{5}$$

3.4 Round-trip delay of control packet and frame exchange

c_0 is the time of RTS transmission by a sender,
c_1 is the time of RTS reception by a receiver,
c_2 is the time of CTS transmission by a receiver and
c_3 is the time of CTS reception by a sender.
$c_e = c_3 - c_0$ is the time elapsed between the release of the RTS and the reception of the CTS packet,
$c_w = c_2 - c_1$ is the time the receiver waited before sending the CTS.
The round-trip delay of RTS and CTS exchange is

$$c_{rd} = (c_e - c_w)$$

f_0 is the transmission time of FRAME
f_1 is the reception time of FRAME by the receiver,
f_2 is the transmission time of an ACK and
f_3 is the reception time of an ACK.
$f_e = f_3 - f_0$ is the time elapsed between the release of the FRAME and the reception of the ACK frame,
$f_w = f_2 - f_1$ is the time a receiver wait before sending the ACK.
The round-trip delay of FRAME and ACK exchange is

$$f_{rd} = \left(f_e - f_w\right)$$

After exchange of control packets and FRAMEs, the round trip delay, total power consumption and number of frames to be transmitted is shared by both the sender and receiver. The receiver forward a REQUEST packet which has information about as round trip delay, total power consumed, and number of frames to be transmitted to one hop neighbors for unicast communication. On receiving the request packet the receiving node checks P_{AVAIL} (Power Available) and reply with ACCEPT packet. If P_{AVAIL} is less than the required one, a node goes to sleep mode. In case of broadcast communication the REQUEST packet is broadcast to the nodes in the circular region. On receiving the request, nodes which has sufficient power reply by sending the ACCEPT packet with P_{AVAIL}. Once the sender receives ACCEPT packet, it transmits the frame to those nodes which have maximum power and forms the route to the sink node. Nodes which are not involved in broadcast transmission back-off until transmission is over. In the active state a node may sense the events, then transmits the sensed events as frames or receives frame from neighbor nodes. If no events are sensed the node goes to sleep state.

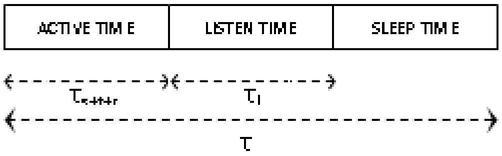

Fig. 3 Time Cycle of a node

Sleep time $= \tau - \left(\tau_{(s+t+r)} + \tau_l\right) => \left(1 - \left(\left(s+t+r\right)+l\right)\right)\tau$

Probability of **transmitting** '*n*' number of frames by a node to its neighbor is

$$P\left(T_{f=1,2\ldots n}\right) = \left(\frac{e^{-(1/\mu_f)} * \left(1/\mu_f\right)^n}{n!}\right) \tag{6}$$

where $1/\mu_f$ is the average arrival rate of transmitting a frame. During transmission of frames from a source node to a destination node or a sink node, the frames may experience store and forward delays. However a first frame may not experience delay. Therefore the probability of successful transmission of first frame is

$$P\left(T_{f=1}\right) = \left(\frac{e^{-(1/\mu_f)} * \left(1/\mu_f\right)^1}{1!}\right) \tag{7}$$

As the network is designed for high priority jobs, a neighbor of the transmitting node or receiving node may block the ongoing transmission by initiating high priority request. Therefore the probability of remaining frames being queued in the buffer is

$$P\left(B_{f=n,\ldots N}\right) = \left[1 - \sum_{i=1}^{N} \frac{e^{-(1/\mu_f)} * \left(1/\mu_f\right)^{N-n}}{N-n!}\right] \tag{8}$$

where '*n*' is a frame from 2nd frame till *n-1th* frame and '*N*' is the last frame. The probability of receiving '*k*' number of frames from total of *N* frames can be represented by using binomial distribution

$$p_p\left(k/N\right) = \frac{N!}{k!\left(N-k\right)!} p^k \left(1-p\right)^{N-k} \tag{9}$$

$\left(1/\mu_f\right) = N * p$ Where $\left(1/\mu_f\right)$ is the average arrival rate and 'p' is the probability of successful transmission,

$$p = \frac{1/\mu_f}{N}$$

$$P_{1/\mu_f/N}\left(k/N\right) = \frac{N!}{k!\left(N-k\right)!} * \left(\frac{1/\mu_f}{N}\right)^k * \left(1 - \frac{1/\mu_f}{N}\right)^{N-K} \tag{10}$$

For large N binomial distribution becomes Poisson bistribution

$$\begin{aligned} P_{(1/\mu_f)}\left(k\right) &= \lim_{N\to\infty} p_p\left(k/N\right) \\ &= \lim_{N\to\infty} \frac{N\left(N-1\right)\ldots\left(N-k+1\right)}{k!} * \frac{\left(1/\mu_f\right)^k}{N^k} * \left(1 - \frac{1/\mu_f}{N}\right)^N * \left(1 - \frac{1/\mu_f}{N}\right)^{-k} \\ &= \lim_{N\to\infty} \frac{N\left(N-1\right)\ldots\left(N-k+1\right)}{N^k} * \frac{\left(1/\mu_f\right)^k}{k!} * \left(1 - \frac{1/\mu_f}{N}\right)^N * \left(1 - \frac{1/\mu_f}{N}\right)^{-k} \\ &= \left(\frac{\left(1/\mu_f\right)^k}{k!} . e^{\left(-1/\mu_f\right)}\right) \end{aligned} \tag{11}$$

Power consumption of a node varies when involved in unicast or broadcast transmission. Power consumption of a node when involved in **unicast** transmission is expressed as

$$\begin{aligned} p_{ut} = \tau_{sn} * p_{sn} &+ \left(\frac{e^{-(1/\mu_R)} * \left(1/\mu_R\right)^1}{1!}\right) * P_{TMAX} + \\ &\left(\frac{e^{-(1/\mu_C)} * \left(1/\mu_C\right)^1}{1!}\right) * P_{TMAX} + \\ &\left(\frac{e^{-(1/\mu_f)} * \left(1/\mu_f\right)^n}{n!}\right) * P_{TMIN} + \\ &t_{ACK} * P_{TMIN} + \tau_i * p_i + \\ &\left(1-\left(\left(s+t+r\right)+l\right)\right)\tau * p_{sp} \end{aligned} \qquad (12)$$

τ_{sn} and p_{sn} is the time spent and power consumed in sensing the events. τ_i and p_i is the time spent and power consumed in listen mode. $\left(1-\left(\left(s+t+r\right)+l\right)\right)\tau$ is the time spent in sleep mode. Power consumption of a node when involved in **broadcast** transmission is given as

$$\begin{aligned} p_{bt} = \tau_{sn} * p_{sn} &+ \left[1-\sum_{i=1}^{N} \frac{e^{-(1/\mu_f)} * \left(1/\mu_f\right)^{N-n}}{N-n!}\right] * p_b + \\ &\left(\frac{e^{-(1/\mu_{Rq})} * \left(1/\mu_{Rq}\right)^n}{n!}\right) * P_{TMAX} + \\ &\left[\sum_{i=1}^{n} \frac{e^{-(1/\mu_{At})} * \left(1/\mu_{At}\right)^1}{1!}\right] * P_{TMAX} + \\ &\left(\frac{e^{-(1/\mu_f)} * \left(1/\mu_f\right)^n}{n!}\right) * P_{TMIN} + \\ &t_{ACK} * P_{TMIN} + \tau_i * p_i + \\ &\left(1-\left(\left(s+t+r\right)+l\right)\right)\tau * p_{sp} \end{aligned} \qquad (13)$$

where $1/\mu_{Rq}$ is the time taken by a node for broadcasting the request message and $1/\mu_{At}$ is the time taken by the receiver nodes for replying accept message. Power consumption of frames being received by a receiver is

$$\begin{aligned} p_r = \tau_{sn} * p_{sn} &+ \left(\frac{e^{-(1/\mu_R)} * \left(1/\mu_R\right)^1}{1!}\right) * P_{TMAX} + \\ &\left(\frac{e^{-(1/\mu_C)} * \left(1/\mu_C\right)^1}{1!}\right) * P_{TMAX} + \\ &\left(\frac{\left(1/\mu_f\right)^k}{k!} . e^{\left(-1/\mu_f\right)}\right) * P_{TMIN} + \\ &t_{ACK} * P_{TMIN} + \tau_i * p_i + \\ &\left(1-\left(\left(s+t+r\right)+l\right)\right)\tau * p_{sp} \end{aligned} \qquad (14)$$

4. Simulation and Results

The proposed analytical model for estimating energy consumption in Y-MAC protocol is implemented in MATLAB. This protocol has been designed to support high priority transmission request. The proposed protocol has been tested for both single hop and multi-hop transmission of frames. The protocol also supports irregular time interval whereas Y-MAC protocol supports constant time interval between events. The Simulation parameters are listed in the table below.

Table 1: Simulation parameters

Parameters	**Values**
Number of nodes	50
Simulation time	150 seconds
Transmission Range	22 meters
Bandwidth	11 Mb
Transmitting and Receiving antenna gain	Gt=1, Gr=1
Transmission power	0.031622777W
Carrier Sense Power	5.011872e- 12W
Received Power Threshold	5.82587e-09W
Traffic type	CBR
Initial Energy	1000 Joule
Time synchronization message interval	10 seconds
Contention window	12ms
Packet header length	16 bytes
Payload length	32 bytes
Control packet interval	10 seconds
Number of retransmissions	1
Number of channels	6

The performance of the proposed work is analyzed and compared with Y-MAC protocol. The performance is evaluated in terms of two metrics - energy efficiency and reception rate. Every node broadcast its remaining time in the current frame period after every 10 seconds. Each node records the time difference when it receives time synchronization messages from the neighbors. It reports average time difference to the sink node at fixed time intervals. The number of transmitting nodes is varied to analyze the relationship between performance and node density. The sink node in Y-MAC protocol continuously hops to the next channel so that it does not interfere with data reception by other nodes. Energy saving by sink node in Y-MAC protocol is not considered since the sink node is normally powered by rechargeable battery or by other supply source. The transmission rate is restricted by varying the traffic load in the network.

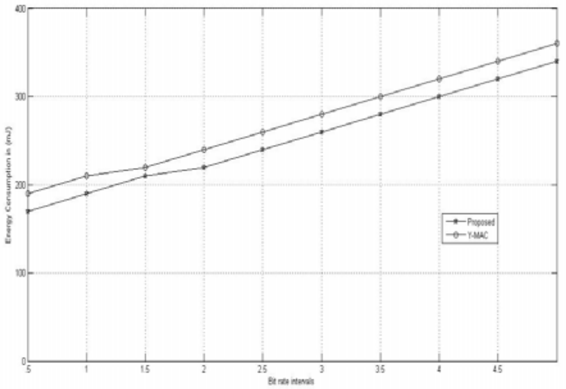

Fig. 4 Comparison of Energy Consumption

The above figure shows the comparison of energy consumption between Y-MAC and proposed protocol. This figure shows-the impact of the bit rate interval between the nodes on the energy consumption of nodes in milli-joules. It is quite clear from the figure that the proposed protocol out performs the Y-MAC in energy consumption. It consumes approximate of 60 milli-joules lesser than energy consumed by Y-MAC protocol.

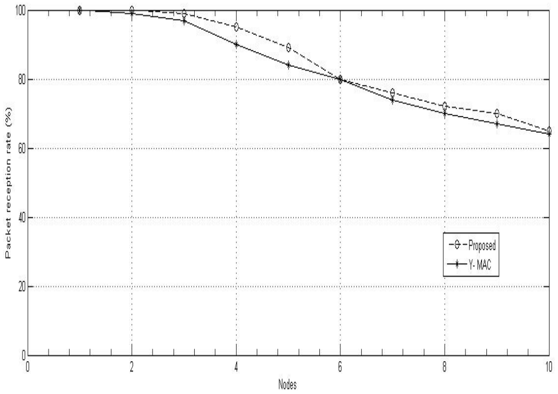

Fig. 5 Single hop average Data reception

Fig 2 shows the average data reception percentage for single hop transmission. In Y-MAC protocol every node transmits message once in every second. But, the proposed protocol transmits 'n' number of messages at different time interval. The data reception rate of proposed protocol is better than Y-MAC protocol. In both cases it decreases gradually with the increase in number of nodes.

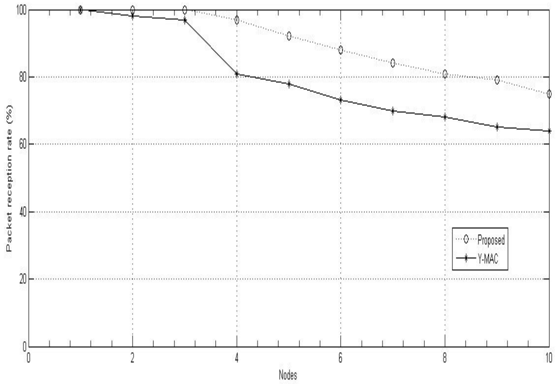

Fig. 6 Multi hop average Data reception

Fig 3 shows the average data reception rate at the sink node for multi-hop transmission. Nodes in Y-MAC protocol generate messages after a fixed time interval, whereas in this work messages can be generated at any time. From the figure, it is clear that data reception rate declines faster than the proposed protocol. Therefore, we can infer that under heavy traffic conditions the data reception rate of proposed protocol is better than Y-MAC protocol.

5. Conclusions

In this work, we have proposed analytical model for estimating energy consumption in Y-MAC protocol for Wireless Sensor Networks. The power consumption for an individual node is calculated for both unicast and broadcast transmission with multichannel transmission of frames. A node in the network saves its energy by changing its mode periodically. The proposed protocol calculates active, listen and sleep time of a node and shows results comparable with Y-MAC protocol in terms of energy consumption. However, analytical model as expected performance marginally better since it does include the complexities of the system.

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