Z-MAC AN ANALYTICAL MODEL FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

This paper presents an analytical model for estimating throughput and energy consumption in Z-MAC protocol for Wireless Sensor Networks. The analytical design includes transmission power control and transmission of frames through one hop, two hop and multi hop. Proposed model reduces collision under low contention level as well as high contention level with the use of explicit contention notification. The proposed protocol has been simulated using MATLAB. The simulations reveal better results for throughput and energy consumption of the proposed model as compared to Z-MAC protocol.

KEYWORDS

Wireless Sensor Networks, Trigonometry, Possion distribution and Energy efficiency.

1. INTRODUCTION

Time synchronization in Wireless Sensor Networks has been explored by researchers but there is no definite scheme that supports global time synchronization. Sensor Network may be employed in different conditions and locations, where clock drift play a vital role in creating synchronization errors. Therefore, the local clocks of a node and its one hop neighbour nodes needs to be synchronized. In this paper we have presented an analytical model proposed for Z-MAC protocol. This model discovers neighbours through synchronization and explicit contention notification as well as transmission power control of Z-MAC protocol. The rest of the 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 work presented in this paper in section 5.

2. RELATED WORK

Z-MAC is a hybrid protocol. It maintains high channel utilization using CSMA and TDMA under periods of low contention and high contention respectively. It consists of four sequential procedures- neighbour discovery, slot assignment, local frame exchange and global time synchronization. It only functions during the WSN's initialization period or after the significant changes in its topology of WSN. Z-MAC uses Dynamic-RAND algorithm for assigning time slot to each node. It requires updated time frames to be propagated throughout the network. To account for topology changes, Z-MAC's time frame rule allows each node to maintain its own local time frame that fits its two-hop neighbourhood. Z-MAC nodes operate in either a low contention level (LCL) or high contention level (HCL) mode. Z-MAC uses the backoff, CCA and LPL interfaces of berkeley-MAC to implement LCL and HCL [14].

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Berkeley Medium Access Control (B-MAC) is a link protocol that was designed assuming periodic frame transmission in short packets. It requires other services to be controlled by higher applications. The responsibility of optimizing power consumption, latency, throughput, fairness or reliability falls upon the node's applications. B-MAC acclimatizes more efficiently to dynamic topology of changing network conditions. B-MAC uses clear channel assessment (CCA) to determine the clear channel. Using CCA, a node estimates the noise floor by analyzing several signal strength samples of a channel. To conserve energy, nodes implement low power listening (LPL), whereby nodes cycle through stages and periodically sample the channel [16].

TRaffic-Adaptive Medium Access (TRAMA) protocol supports unicast, broadcast, and multicast traffic. It is inherently collision-free, due to Time Division Multiple Access, and uses a dynamic approach to switch nodes to low power based on traffic patterns. It consists of components like Neighbor Protocol (NP) and Schedule Exchange Protocol (SEP) [17].

In Neighbour Protocol approach information of one-hop neighbour is shared. Each node contends with neighbours to transmit data packets containing incremental neighbourhood updates in a randomly selected signalling slot. Every node has knowledge of two-hop neighbours and their information is broadcast across the network. A node is removed from that node's neighbourhood list if it fails to hear from a neighbour over a period of time. In order to prevent the early removal of active nodes even when there are no updates nodes send signalling packets during its time slot. With two-hop neighbour information known, Schedule Exchange Protocol creates and maintains traffic-based schedule information amongst neighbours. Each node generates its schedule by comparing an interval of slots with its two-hop neighbours. A node with highest priority slot can transmit the data. A node when ready for transmission announces to its neighbours by broadcasting a schedule packet containing a bitmap representing each one-hop neighbour. A neighbour is an intended receiver if its corresponding bit is set in the bit map of the sender. If a transmitting node does not have enough packets to fill its reserved slots, it declares this to its neighbours. Every node saves its last reserved slot to broadcast its schedule for the next interval. To maintain the schedule, a node's schedule is sent with every frame packet. Each schedule has an associated timeout, and nodes are not allowed to change the schedule until this timeout expires, ensuring consistency amongst one-hop neighbours.

3. Proposed Work

3.1. Neighbour Discovery

A node in the network before initiating the frame transmission, starts up by first running a neighbor discovery protocol where it periodically broadcasts a ping message to gather its one-hop neighbor list. Ping messages are transmitted by nodes at a random time after every fixed interval. A ping message contains the current list of its one-hop neighbors. Through this process, each node gathers the information received from the pings from its one-hop neighbors which essentially constitutes its two-hop neighbor information. Each sensor node has a certain area of coverage for which it can reliably and accurately report the particular quantity that it is observing. Nodes are mobile by nature, because of mobility the density of network may vary in different parts of the network.

The nodes are deployed in a sensor field with the predefined communication range. Due to mobility of nodes, any ongoing transmission may be disrupted. A sender node with the help of its one hop neighbors communicates with receiver and measures the Angle of arrival (AoA) to determine the direction of arrival. It also calculates the Distance of Arrival (DOA). Trigonometric function is used to find out the angle of arrival.

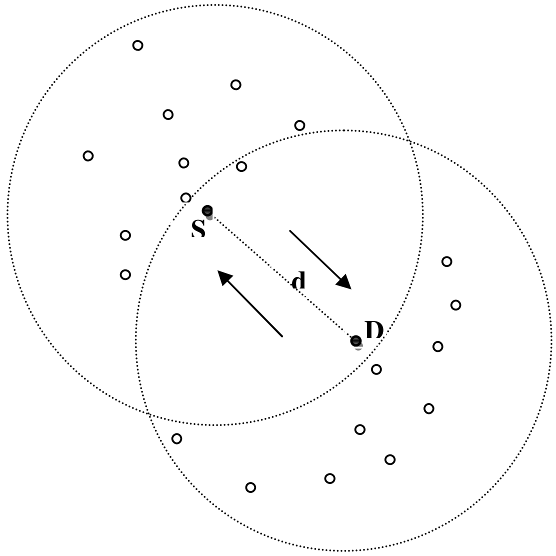

Figure 1 Nodes with direct transmission

In figure 1source S and destination node D are in the sensing range of each other and they are involved in direct transmission of frames and acknowledgements.

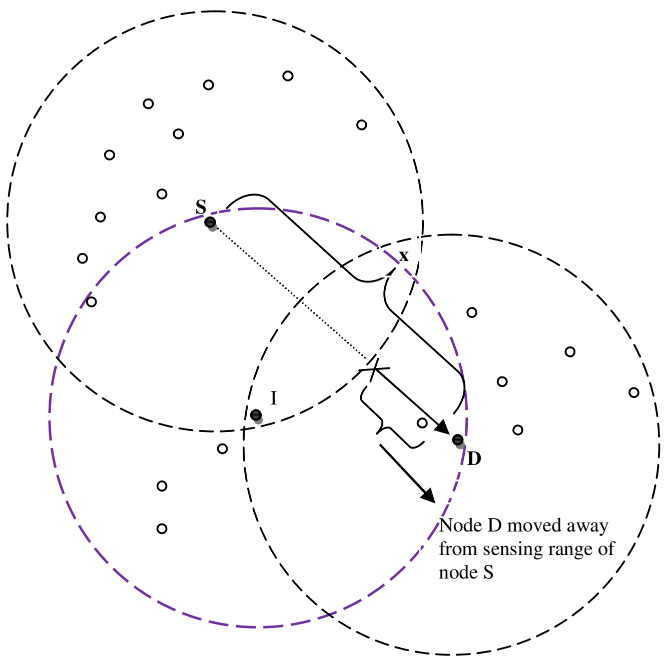

Figure 2 Dislocated nodes of direct transmission

In figure 2 destination node D has moved away from the sensing range of the source node S. Therefore, the ongoing transmission comes to an end without transmitting all the frames. A new node I that has moved in the sensing range of both the source and destination, assumed to be in the right angle of both the nodes. X is the latest distances to be calculated between nodes S and D.

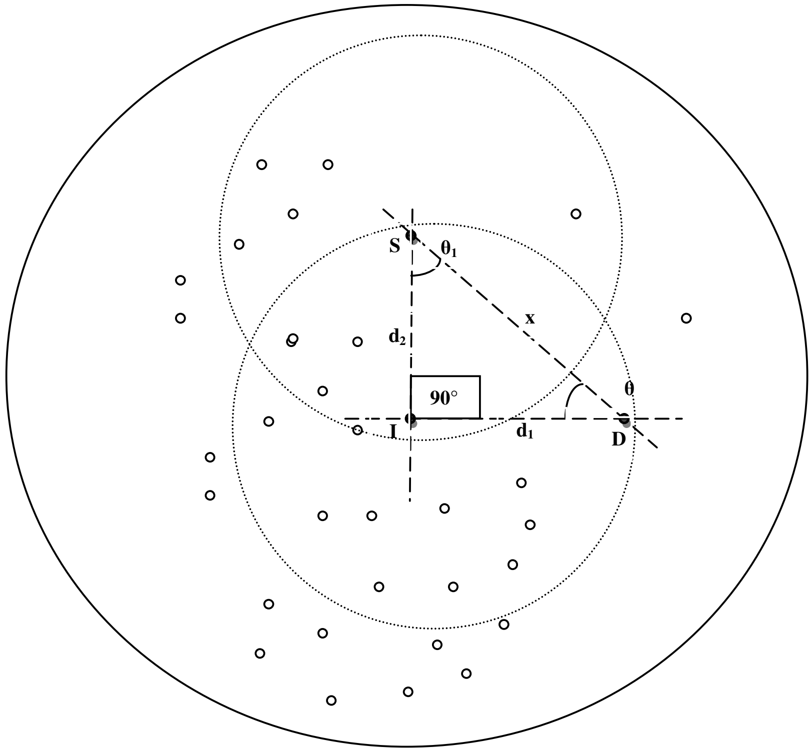

Figure 3 Angle of arrival

$$\sin\theta_1 = d_1/x$$
$$\cos\theta_1 = d_2/x$$
$$x^2 = (d_1)^2 + (d_2)^2$$

$x^2 = (v_1)^2$ // sum of two values is assumed to be v_1

$$x = v_1$$
$$\tan\theta_1 = d_1/d_2$$
$$\theta_1 = \tan^{-1}\left(d_1/d_2\right) \quad (1)$$

$\theta_1 = \tan^{-1}(v_2)$ // division of d_1 and d_2 values is assumed to be v_2

$$\theta_2 = 180^\bullet - (\theta_1 + 90^\bullet)$$
$$\theta_2 = 90^\bullet - \theta_1 \quad (2)$$

In figure 3 the source node *S* is assumed to form an angle θ_1 and the destination node *D* is assumed to form angle θ_2. Both the nodes are away from each other's communication range. As ping messages are transmitted by nodes to their neighbours after every fixed interval (for knowledge of topology change in the network). When a new node exchanges the ping message both the source and destination nodes receive it. Node *S* on receiving the information, initiates its request to the new node to transmit the unsent frames to node *D*. The source node resumes its transmission with *D* through intermediate node *I*. As nodes are dynamic by nature they move apart over a period of time. The angle of arrival is estimated trigonometrically and shared among all the one hop neighbours through ping message to avoid link failure.

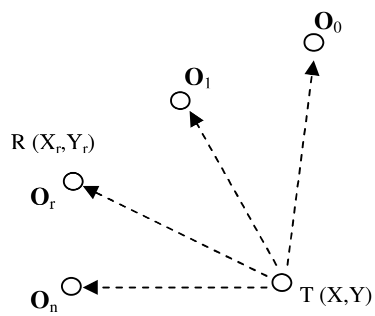

Figure 4 Distance of Arrival

Consider a transmitter at an unknown location vector $T = (x, y)$. The source is located within the range of $N+1$ receiver at known locations $O_0, O_1, ..., O_r, ..., O_N$. The subscript r refers to any one of the receivers $O_r = (x_r, y_r)$ where $0 \le r \le N$. The distance (d) from the transmitter to one of the receivers in terms of the coordinates is

$$d_r = \left| \vec{R}_r - \vec{T}_t \right| = \sqrt{(x_r - x_t)^2 + (y_r - y_t)^2}$$

$$d_r = \sqrt{(x_{r-t})^2 + (y_{r-t})^2}$$

Strength of the received frame is calculated with the use of log normal model of radio signal propagation between the source and destination with an intermediated node. Let (x_s,y_s), (x_d,y_d) and (x_i,y_i) be the location of source node, destination node and intermediate node.

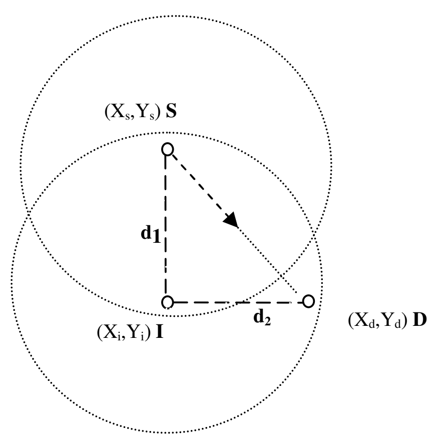

Figure 5 Received Signal strength

$$ss_D = t_p(S) - p_L(d) - 10_n \log\left(\frac{d_1}{d_2}\right) \qquad (3)$$

ss_D is the signal strength of the receiver.
$t_p(S)$ is the transmitted power of source node.
$P_L(d)$ is the distance covered from source through intermediate node I.

n is the path loss exponent.
d_1 is the distance from source to intermediate node.
d_2 is the distance from intermediate node to designation node.

$$ss_S = t_p(D) - p_L(d) - 10_n \log\left(\frac{d_2}{d_1}\right) \quad (4)$$

ss_s is the signal strength of the source node.
$t_p(D)$ is the transmitted power of destination node.
d_2 is the distance from designation node to intermediate node.
d_1 is the distance from intermediate node to source.
The signal strength is exchanged among one hop neighbours of both sender and the receiver.

3.2. Clock Synchronization

Synchronization of local clocks is required among neighbouring senders and also when they are under high contention. Synchronization is performed locally among neighbouring senders, and the frequency of synchronization can be adjusted according to the transmission rates of sender. Sender with higher frame rate transmits more frequent synchronization messages. Receiver synchronizes their clocks to the sender clock. Every node transmits a synchronization message containing its current clock value. On receiving a synchronization message, the node updates its clock value by taking a weighted moving average of its current value and the newly received value. Nodes may be positioned in hide outs where the clock value drifts from other nodes which are located in a plan surface. Nodes whose clock value may vary with other neighbour clocks rarely transmit frames. When a node is sending frames after a long time, its clock could be drifted far apart from other synchronized clocks. But as it increases its rate and its frames being routed to the sink, its clock value comes closer to the clock values of other routing nodes. Therefore, resynchronizations with the other nodes in the network are performed periodically.

3.3. Explicit Contention Notification

Explicit Contention Notification (ECN) messages alert the two-hop neighbours not to act as hidden terminals when contention is high. Every node makes a local decision to send an ECN message based on its local estimates of the contention level.
The two ways of estimating two-hop contention is either by receiving acknowledgment from the one-hop receiver or by measuring the packet loss rate. Packet loss may occur due to low signal to noise ratio between the source and destination. The packet loss is represented by

$$P_L \Rightarrow SNR_{s\to d} = \left(\frac{p * p_l(d_{s\to d})}{n} > th\right) \quad (5)$$

Where *p* is power,
$p_l(d_{s\text{->}d})$is a path loss factor,
s and *d* be the source and destination nodes.
n is the noise power and
th is the threshold value of SNR.
The second way of estimation 2-hop contention is by measuring the noise level of the channel. Any node in the network that has a frame to transmit senses the channel with the Clear Channel Assessment algorithm before initiating the transmission. When the noise level of the channel is higher than CCA threshold, the node takes random backoff. A node starts transmitting only when the noise level of the channel is smaller than CCA threshold. Noise level of a channel is measured by carrier to noise ratio (C/N),

$$\frac{C}{N} = (E_f / n) * \frac{R}{B} \quad (6)$$

where E_f is the energy consumption in one frame transmission,

n is the noise level of current frame transmission,
R is the rate at which a frame is transmitted and
B is the channel bandwidth.

3.4. Transmission control of Z-MAC

The function of a node begins when it senses an event and network function begins when a node starts transmitting the sensed event in the form of message, data, frame or packet etc. All the nodes in the network are randomly deployed. A node is licensed to sense for events, share the data with other nodes, forward the data to a head node or sink node all the time until the battery power drains.

At a given time, either a node or few nodes may transmit out of N number of nodes. Therefore, the probability of a node involved in transmission is $p_{n=1}(t) = 1/N$ likewise the probability of more than one node involved in transmission is $p_{n=2,\ldots,N-1}(t) = N - 1/N$. The probability of transmitting nodes may vary over time. At the initial stage of the network function all the nodes are equipped with full battery power (equal energy). Therefore, more number of nodes is expected for sensing the events. As nodes with sensed events are involved in forwarding of frames, it leads to increase in high contention level among neighbours. Any node before initiating a transmission estimates contention level to avoid collision of frames.

$$C_L = M_N - \sum_{i=1}^{n} \pi r^2 * \frac{n_t}{N} \tag{7}$$

C_L is the contention level
M_N is the measurement node (a node which estimates the contention level is called measurement node),
$\sum_{i=1\ to\ n}$ are the contenders.
πr^2 is the circular area where all the contending nodes reside.
n_t is the number of nodes contending at time t and
N is total number of nodes in a given area.

A node that wins the contention starts transmitting. Once the transmission is over the node goes to listen state. Further, nodes which are in the backoff mode wake up once the timers expire.

The authors of Hybrid MAC suggest that a node may be in one of two modes - Low Contention Level (LCL) or High Contention Level (HCL). In Low Contention Level a node can compete to transmit in any slot. A node is in High Contention Level only when it receives Explicit Contention Notification (ECN). In both the modes, the concerned node has higher priority over other nodes. If a node does not have frames to transmit, the neighbor nodes compete to utilize the slot for transmission of frames.

As a node acquires frame to transmit, it checks whether it is the owner of the current slot. If it is the owner of the slot, it takes a random time within a fixed time period. During this random time the node keeps the frame into ready state, checks for the status of one and two hop neighbours, and performs local synchronization among neighbours. When the timer expires, it runs Clear Channel Assessment (CCA). If the channel is clear, it transmits a message to one hop neighbours. The message contains information such as type of data in the frame, frame size, routing information, origin of the frame, route through which the frame is to traverse and the destination ID. On receiving the message a receiver calculates the distance from the source, angle of arrival, packet loss ratio and transmits it along with the ACK message. On receiving an acknowledgement message, the source node calculates the distance of arrival, and transmits DOA along with the first frame. If the channel is not clear, then it waits until the channel becomes free.

If a node is not an owner of the current slot, and is in LCL, or in HCL, and the current slot is not owned by its two-hop neighbours, it waits and back off within a contention window. When the timer expires, it runs CCA. In case it finds the channel clear, it starts transmission. If the channel is not clear, it waits until the channel becomes clear, and then repeats the above process.

Further, if a node is not an owner of the current slot, and it receives ECN message from its two hop neighbours, it checks its neighbours for a node with LCL, since a node with HCL can always avail the current slot of LCL node to perform higher priority task. The node with LCL gives current transmitting slot to HCL and goes into sleep mode and postpones its transmission until it finds a time slot that is not owned by a one hop and two hop neighbours. ECN message is generated by one hop neighbours of a final destination node [14].

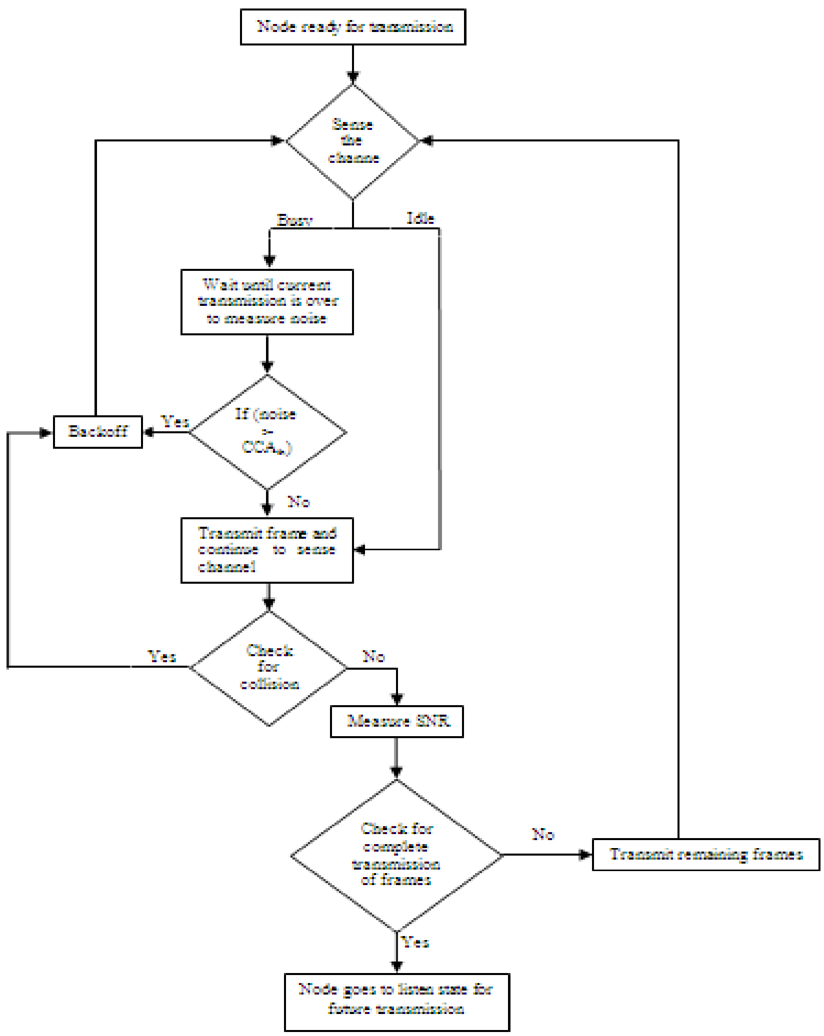

Figure 6 Work flow of a node

As explained in section 3.1 at any time mobility may dislocate a pair of node involved in exchange of frames. In section 3.1 a displaced node D resumed communication with an intermediate node which is one hop away from the source node S. Likewise any ongoing transmission may be blocked by dislocating the pair of nodes which are multi-hop away from each other. Nodes which are one hop away from each other uses Request to send (RTS) and Clear to Send (CTS) as like IEEE 802.11 protocol. Explicit contention notification (explained in section 3.3) is used for communication of nodes which are dislocated multi-hop away from each other. Explicit contention notification message has information of packet loss rate, carrier to noise ratio, transmission slot and contention level of nodes in different areas, and routing path through which transmission occurs.

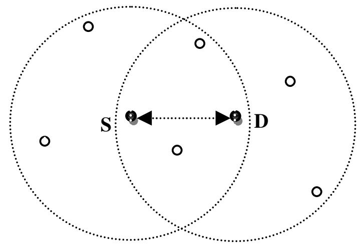

Figure 7 1-Hop Communication

Let, assume that a source node acquires frames for transmission at the rate λ_r and arrival follows Poisson distribution. The acquired frame is forwarded to its one hop neighbor that is a destination node. The frames are forwarded at the rate λ_r. Therefore, the power consumption for transmission of source node is

$$P_t = p_r \lambda_r + \frac{e^{-(1/f)} * (1/f)^n}{n!} \quad (8)$$

$e^{-(1/f)} * (1/f)^n / n!$ is the probability of receiving a frame,

p_r is the total power consumed in receiving a frame.

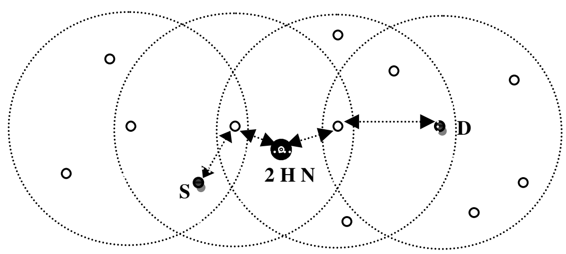

Figure 8 Multi-Hop Communication

Figure 8 shows the dislocated source and destination nodes that are at 1-hop from each other (figure 7). The sender node initiates a broadcast message to its neighbor nodes with information of contention levels of its vicinity and information of next frame to be transmitted. To transmit a message a node takes τ time. Therefore, $\lambda_t = 1/\tau$. The power consumed by a node while broadcasting the message is expressed as

$$P_b = \sum_{i=1}^{n} \frac{e^{-(1/\tau)} * (1/\tau)^1}{1!} * P_{\max} \quad (9)$$

Among '*n*' nodes receiving the message one of them is an indented receiver. The receiver traces path and number of hops through which the message has arrived from the transmitter node. On tracing the required information the receiver sets every 2-hop nodes as measurement node to check the contention level of nodes which are local to measurement node. The task of measurement node is to generate ECN message over every fixed time interval *t*.

The destination node transmits a request message containing route information and number of frames to be received by 1-hop neighbours. On receiving request message a 1 hop neighbour forwards to 2-hop nodes. Information of 2-hop nodes and ECN message are forwarded to sender's 1-hop nodes.
The power consumption of a node at 2-hop can be calculated as

$$P_{2HN} = p_r \lambda_r + \frac{e^{-(1/1h)} * (1/1h)^1}{1!} + p_t \lambda_r \frac{e^{-(1/t_{ECN})} * (1/t_{ECN})^1}{1!} \quad (10)$$

$e^{-(1/1h)} * (1/1h)^1 / 1!$ is the probability of receiving a request message from receiver's1-hop neighbour node

$e^{-(1/t_{ECN})} * (1/t_{ECN})^1 / 1!$ is the probability of transmitting an ECN message to sender's 1-hop node.

p_r is the power consumed for receiving a request, p_t is the power consumed for transmitting

Power consumption of source node while receiving its 1-hop information along with ECN message of 2-hop node is

$$P_S = p_r \lambda_r + \frac{e^{-(1/1h)} * (1/1h)^1}{1!} + p_r \lambda_r \frac{e^{-(1/t_{ECN})} * (1/t_{ECN})^1}{1!} \quad (11)$$

$e^{-(1/1h)} * (1/1h)^1 / 1!$ is the probability of receiving 1-hop neighbour's vicinity, p_r is the power consumed for receiving from sender's 1-hop node.

$e^{-(1/t_{ECN})} * (1/t_{ECN})^1 / 1!$ is the probability of receiving a forwarded ECN message of 2-hop node from the sender's one hop node.

p_r is the power consumed for receiving a request, λ_r is the data rate.

4. Simulations and Results

The proposed analytical model for estimating energy consumption in Z-MAC protocol is implemented in MATLAB. This protocol has been designed to support high priority transmission requests. The proposed protocol has been tested for one hop, two hop and multi-hop transmission of frames. The protocol also supports irregular time interval. The Simulation parameters used in the work are listed in the table below:

Parameter	**Value**
Number of nodes	50
Simulation time	120 Seconds
Contention window per slot duration	400 µs
ECN refresh period (t_{ECN})	10 Seconds
Communication bandwidth	15 Kbps
Transmission Range	22 meters
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	VBR
Initial Energy	500 Joule

The performance of the proposed work is analyzed and compared with Z-MAC protocol. The performance is evaluated in terms of two metrics - energy efficiency and Throughput. The number of transmitting nodes is varied to analyze the relationship between performance and node density. Energy saving by a sink node in Z-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.

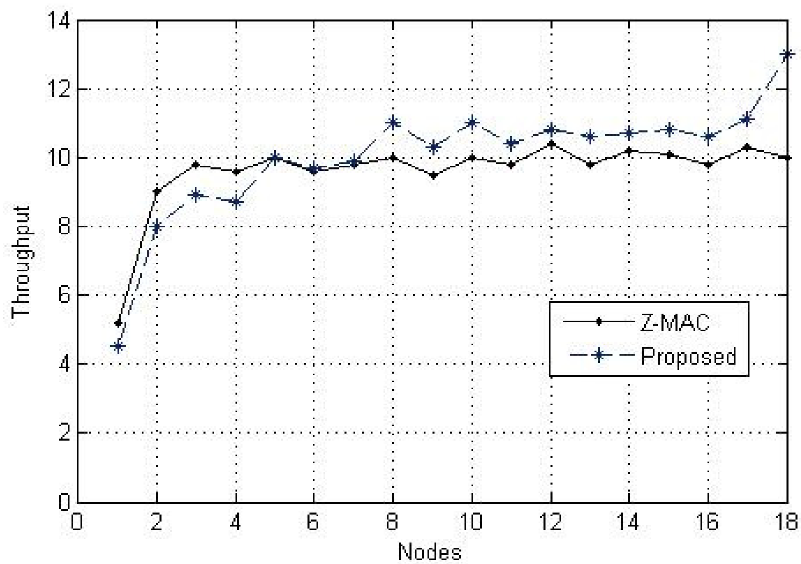

Figure 9: 1-Hop Throughput

The above figure shows the comparison of one hop throughput between Z-MAC and proposed analytical model of Z-MAC protocol. This figure shows-the impact of Low Contention Level between one hop transmitting nodes. For One-hop throughput measurement, we fix the frame size and vary the number of senders. High Contention Level is disabled because the performance of HCL and LCL is more or less the same when all nodes are in a one-hop distance from each other. Before the execution of analytical model of Z-MAC protocol, DRAND (Dynamic Random algorithm) is executed to synchronize the clocks of the senders. The 1-hop throughput of proposed analytical model out performs the existing work.

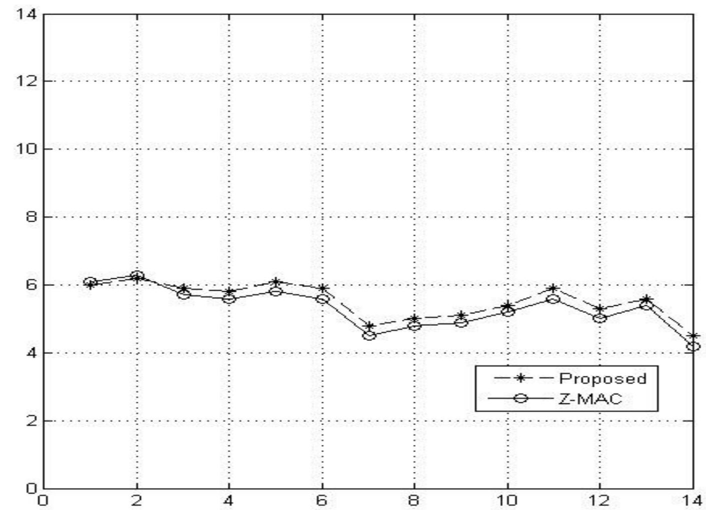

Figure 10: 2-Hop Throughput

The above figure shows the comparison of two hop throughput between Z-MAC and proposed analytical model of Z-MAC protocol. This figure shows-the impact of High Contention Level of two hop transmitting nodes. As the number of hidden terminals increases along with more senders High Contention Level of the proposed model performs well and proves that the overhead of Explicit Contention Notification is much lower. It is observed that the throughput of the Z-MAC drops under high contention than the proposed protocol.

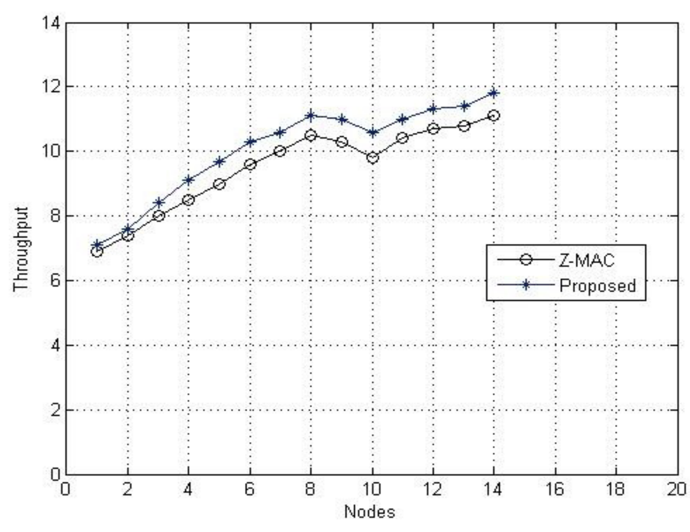

Figure 11: Multi hop Throughput

Figure 11 shows multi-hop throughput of existing Z-MAC protocol and the proposed analytical model. Under low transmission rate both protocols deliver all the packets and achieves approximately same throughput. Analytical model of Z-MAC shows slightly better throughput than the existing work. This is because the back-off congestion window value for non-owners of slot is smaller than proposed work. The back-off value makes the difference because contention is low and most transmissions in Z-MAC are done by nodes as non-owners. It is observed that proposed work achieves better throughput. Figures 9, 10 and 11 shows that analytical model of Z-MAC out performs the Z-MAC (hybrid MAC) protocol.

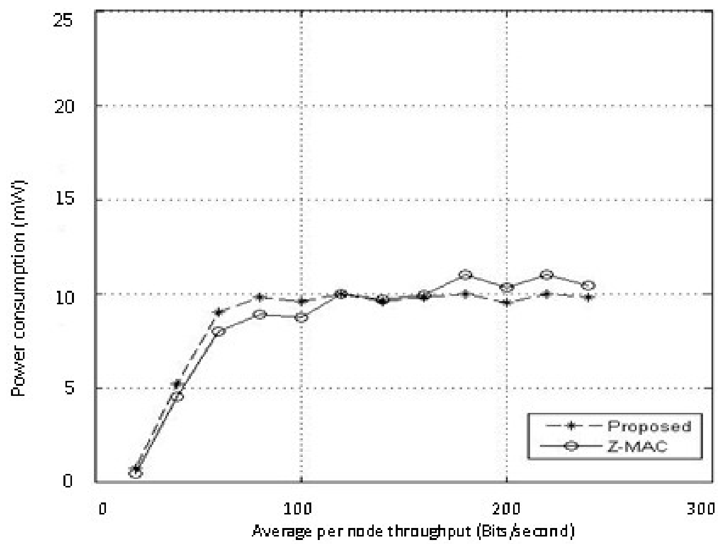

Figure 12: Energy Consumption

The above figure shows the comparison of energy consumption between Z-MAC and proposed protocol. Energy efficiency is measured based on 1-hop, 2-hop and multi-hop transmission of frames. While measuring the efficiency, sending rates are varied in estimating 1-hop, 2-hop and multi-hop throughput over power. The above figure presents the energy consumption of nodes involved in different duty cycles. As we observe in the multi-hop throughput, under low data rates, existing MAC has slightly lower throughput. This is because of Z-MAC has a smaller contention window size than the proposed model. Z-MAC's idle time is smaller under low transmission rates. As the transmission rate increases, we find that energy efficiency of analytical model of Z-MAC improves than that of Z-MAC because when ECN is sent, it blocks other senders not to transmit during the slots owned by two-hop neighbours. The figure also shows the impact of the bits transmitted per second and power consumption of nodes in milli-watts. It is quite clear from the figure that the proposed protocol out performs the Z-MAC in energy consumption. It consumes approximate of 50 milli-joules lesser than the energy consumed by Z-MAC protocol.

5. Conclusion

In this work, we have proposed analytical model for estimating throughput of different hops and energy consumption in Z-MAC protocol for Wireless Sensor Networks. The power consumption for an individual node is calculated for one hop two hop and multi-hop communication. A node in the network saves its energy by changing its mode periodically. The proposed protocol shows better results than Z-MAC protocol in terms of energy consumption. While designing the analytical model for Z-MAC, utilization variation in synchronization errors and transmission fairness are not focused. The variation in noise level over a period was focused with limitations. This can be explored in the future work as an extension of the current work.

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