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Reduced Power Consumption in Wireless Sensor Networks with Min (N, T) Policy based M/G/1 Queue in Rayleigh Fading Channel

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ABSTRACT: The purpose of this study is to reduce the consumption of power at a wireless sensor node in a spectrum sharing environment by employing queuing theory. Spectrum is an expensive and scarce commodity. Spectrum sharing is an efficient way to utilize the under-utilized spectrum. To this effect, we first analyze the effect of number of primary users in a spectrum sharing environment on the average waiting time experienced by packets at any secondary user by utilizing the M/G/1 queuing model. Further, this scenario is extended to a Wireless Sensor Network operating in a spectrum sharing environment where the wireless sensor network is considered to be the secondary user. Due to presence of other users in the shared spectrum, the channel used by the sensor nodes suffers from fading effects. To counter and mitigate the effects of spectrum sharing, we propose using an M/G/1 queue with min (N, T) policy at the sensor node in a WSN. We analyze the power consumed by wireless sensor nodes by adopting an M/G/1 queue with min (N, T) policy by assuming that the wireless channel experiences Rayleigh fading. In this scenario, it is found that both the queuing policy and the constraint imposed on the peak interference power due to the presence of the primary user have a pronounced impact on the consumption of power at the wireless sensor node. The implementation of the Min (N, T) policy M/G/1 queue successfully reduces the average power consumption of a sensor node. The policy suggested in this paper helps reduce the power consumption at the sensor node in a spectrum sharing environment that operates in the presence of signal fading.

Keywords: energy, fading channels, probability, queuing analysis, radio spectrum, power consumption, Rayleigh channel, wireless sensor networks

Abbreviations: ACK, Acknowledgement; CSMA, Carrier Sense Multiple Access; EMBA, Efficient Multihop Broadcast; FIFO, First In First Out; QoS, Quality of Service; WSN, Wireless Sensor Node.

I. INTRODUCTION

A Wireless Sensor Node (WSN) is a collection of sensor nodes typically spread over a wide geographical area. Some of the nodes are responsible for collecting information that is gathered by the other sensor nodes. These sensor nodes are called sink nodes or just data sink. The typical composition of a sensor node consists of a sensor unit, a power supply unit and a radio transceiver. In certain applications, the sensor nodes may be located in geographically remote, inaccessible, and unattended environments in large numbers. It is also imperative in certain cases to keep the size of the sensor nodes as small as possible to ensure economy and secrecy. Applications may also demand that the sensor nodes may not be equipped with a sustainable power supply, leading to a limited lifetime [1]. The network interface is a primary source of power consumption which has led to considerable research in the field of low-power design of the network protocol stack of wireless networks to enhance energy efficiency [2]. Also, energy minimization is essential for wireless data transfer in wireless sensor networks [3]. These are the reasons which guide research in WSN to reduce the power consumption of the sensor nodes and in turn increase the lifetime of the sensor. This section should be succinct, with no subheadings.

The primary role of a sensor node is to sense specific parameters and transmit the sensed parameters in the form of data packets. In addition to sensing and transmitting data packets, sensor nodes are also responsible for routing the packets that it receives from other nodes. In a WSN, there is always a node which plays the role of a data sink to which all other sensor nodes transmit the packets generated by them or received by them from other nodes. This results in a traffic pattern in which there is a great deal of incoming packets to deal with for the nodes that are located closer to the data sink. As is obvious, this leads to faster depletion of energy for the nodes located closer to the sink and eventually results in the death of the node. This is what is known as the energy hole. The appearance of such an energy hole in a WSN will impact the delivery of packets to the data sink and may lead to the failure of the WSN. This leads us to believe that the sensor nodes located near the data sink determine the lifetime of the WSN. In recent years, the clustering approach has gained popularity and is widely employed to reduce the energy consumption and extend the lifetime of the network, where the sensed information is first aggregated and then sent to the base station or data sink.

Sensor nodes that receive data packets and subsequently forward it to other nodes have to frequently switch their radio transceivers between the ON and OFF state. Shih *et al.*, (2004) have shown that such frequent transitions of the radio transceiver state lead to a very high power consumption [4]. A way to tackle this high power consumption is to reduce the number of such transitions and time required for medium contention. Maheswar and Jayaparvathy (2010) have presented a queuing approach to tackle the problem of high power consumption [5]. They have developed a model of a WSN with a fixed buffer size which services the data packets using an M/M/1 queue with N-Policy. In their work, they have analyzed the efficiency of their model to reduce the power consumption of the sensor nodes. The operation of radio server in an M/M/1 queuing process that utilizes an N-policy is studied by us [6] and it was found that we can significantly reduce the power consumption of a sensor node in a WSN by reducing the number of transitions of the radio transceiver. This can be achieved by setting a threshold for the number of packets in the buffer before the radio can be switched ON to transmit the packets. Once the radio is switched ON, the node can transmit all the packets in the buffer in a burst till its empty.

The policy discussed above has a drawback in which it results in delay for the packets staying in queue buffer. This may be counter-productive in cases where the data needs to be transmitted in real time. To avoid a large waiting time for the packets in the queue before being transmitted to the data sink, a T-policy [7] is proposed. In case of the T -policy, the radio transceiver is switched ON when the timer has reached predetermined T units since the time the transceiver was switched OFF. The incorporation of the timer T in the model eases the long waiting times that result in certain applications with a very low arrival rate of data packets. A Min (N, T) policy M/G/1 queuing model to elongate the lifetime of a sensor network has also been analyzed by us [8].

Some researchers have concentrated on developing algorithms to efficiently manage energy consumption at a wireless sensor node in a WSN. Bambere and Ghosh (2016) propose a Modified Efficient Multihop Broadcast Protocol for WSN (MEMBA) which is integration of EMBA protocol with overhear ability [9]. EMBA is an efficient multihop broadcast protocol for asynchronous duty-cycled wireless sensor networks where each node independently wakes up according to its own schedule. EMBA adopts two techniques of the forwarder's guidance and the overhearing of broadcast messages and ACKs.

In [10], the authors adopt a cross layer design methodology to design an energy efficient routing protocol entitled “Position Responsive Routing Protocol” (PRRP). PRRP is designed to minimize energy consumed in each node by, (1) reducing the amount of time in which a sensor node is in an idle listening state and (2) reducing the average communication distance over the network. Researchers have also used Neural Networks to reduce energy consumption in WSN. Bansal *et al.*, (2016) have implemented a back propagation neural network to figure out node failure in the network and reduce energy consumed by the network in deducting the failed node [11]. The authors optimize the performance metrics like energy consumption, throughput, end to end delay and error rate. The authors report that the proposed neural network optimizes energy consumption by 5J, throughput by 19%, error rate by 7.9 and end to end delay by 4.32ms.

WSNs usually operate in environments that are shared by other stationary/mobile devices. In such scenarios, the available radio spectrum becomes a scarce commodity. Radio spectrum is a very expensive and limited resource in wireless communications. Efficient spectrum utilization therefore presents itself as an important research area. In a radio spectrum sharing environment, two types of users: primary user (P-User) and secondary user (S-User) are typically found. The P-User has the license to use the spectrum and the S-User may be permitted to access the spectrum on the condition that it does not significantly interfere to compromise the quality of service (QoS) guaranteed to the P-User. It is essential while designing radio networks to take care to maintain the desirable QoS at the P-User while also allowing access to the S-User with a sufficiently high transmission rate. Tran *et al.*, (2012) analyze the time taken for packet transmission in systems sharing a common spectrum in which an S-User is allowed to access the radio spectrum that is owned by P-User [12]. The authors have assumed that the channel experiences Rayleigh fading and further examine the state where multiple P-Users impose a limit on the power transmitted by the S-User.

It is seen that when a wireless sensor node accesses a radio spectrum as an S-User it invariably encounters fading. Kabiri *et al.*, (2014) assess the power that is consumed by wireless sensor nodes that utilize the M/G/1 queue with min (N, T) policy under the assumption that the channel is affected by Nakagami-m fading [13]. Analysis of the system proposed is presented to demonstrate the effect of queuing on the power consumption of a sensor node in the presence of channel fading.

We study a spectrum sharing scheme in which a secondary transmitter (S-User-T) is transmitting packets to a secondary receiver (S-User-R) while a number of primary receivers (P-User-R) are operating on the primary network. It is assumed that the channel is affected by Rayleigh Fading. Under the considerations, the expressions for packet transmission time are presented here. Further, this scenario is extended to a WSN that shares the spectrum with a primary receiver (P-User-R). We consider a secondary network, in which wireless sensor nodes are secondary transmitter (S-User-T) as well as secondary receiver (S-User-R). We perform the analysis of the power consumed by wireless sensor nodes that utilize M/G/1 queue with Min (N, T) policy in a fading environment (Rayleigh fading). In this scenario, it is found that both the queuing policy and the constraint imposed on the peak interference by presence of the primary user have a considerable effect on the power consumed by the wireless sensor node.

II. SYSTEM MODEL

To effectively utilize licensed radio spectrum, it is suggested that spectrum sharing is a promising approach.

To limit the interference caused by the transmission of the secondary user, a predefined threshold can be imposed. In this model, it is assumed that packets arrive at the sensor node which we consider to be the S-User-

T, following a Poisson process. We have further assumed that the queuing model is an M/G/1 system in which service time follows a general distribution and a single server (node) processes the traffic.

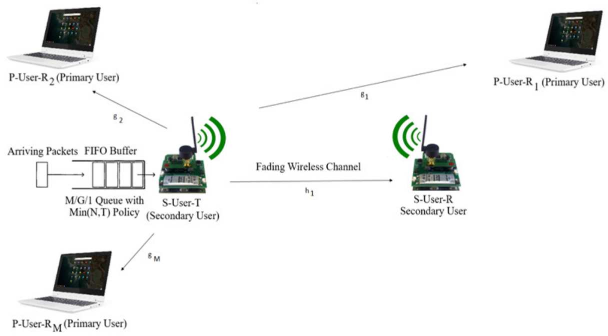

Fig. 1. System model under shared spectrum with multiple Primary Users.

A. Spectrum Design

The spectrum sharing scenario we have assumed is illustrated in Fig. 1. Here we consider that an S-User-T transmits data packets to an S-User-R in the presence of a number (M) of receivers in the primary network (P-User-R). This communication scenario is an example of point-to-point communication.

The following are the notations we have used:

h_1: Power gain of the S-User-T → S-User-R link

g_m: Power gain of the S-User-T → P-User-R$_m$ link, $m = 1, 2, \ldots, M$

We have assumed that the channel state information (CSI) of the secondary system is made available to the S-User-T using a feedback from the S-User-R. Also, the CSI of the S-User-T to the P-User-R can be made available by making use of a dedicated common control channel. In the scenario considered, the S-User-T is located near the P-User-R and the S-User-R is located at a considerable distance from the primary transmitters (P-User-T). With this set-up, we have assumed that only the S-User-T is a source of interference for the P-User-R. As the P-User-T and S-User-R are separated by a considerable distance, negligible amount of interference is caused by the primary transmitters to the S-User-R.

The S-User-T employs a buffer to store the incoming packets. The S-User-T also performs the task of breaking down the packets into bit streams and modifying its transmission power depending on the CSI which shall be denoted as (M+1)-tuple (g_1, g_2, . . ., g_M, h_1). We wish to minimize the transmission time of packets at the S-User while not interfering with the P-User-R.

A predefined timeout threshold t_{out} is considered to determine if a packet is transmitted successfully. A packet is considered successfully if the time required for transmission is less than t_{out}. The S-User-R sends an acknowledgement (ACK) after receiving a certain number of bits and reassembling them into packets successfully. The acknowledgement (ACK) packet that is transmitted by the S-User-R is assumed to be received by the S-User-T without any error and the delay involved is negligible. The ACK informs the S-User-T that the packet transmitted by it has been successfully received and it can proceed with transmitting the remaining packets in the buffer. The packets received by the S-User are stored in a buffer for further processing. The stored packets are serviced in a first-in first-out (FIFO) manner. As mentioned earlier, it is assumed the packets arrive at the S-User following a Poisson process with an arrival rate λ. The scenario considered is modeled as an M/G/1 queue in which the service time follows a general distribution and a single server (node) processes the traffic.

The S-User-T will want to avoid having a large number of dropped packets due to timeout and hence will want to transmit with maximum transmission rate. Also, the S-User-T needs to adapt its transmission power as a result of changes in the transmission medium and also ensure the QoS of any P-User-R located near it.

The outage probability (P_{out}) for the considered scenario is given by [12]

$$P_{out} = \sum_{m=0}^{M-1} \binom{M-1}{m} \frac{(-1)^m \left(\exp(\tilde{B}/t_{out} - 1)M\right)}{(1+m)(\exp(\tilde{B}/t_{out} + \dfrac{mQ_{pk}}{N_0} + G)} \quad (1)$$

The following are the parameters considered in the above expression:

$\tilde{B}$: System bandwidth

t_{out}: Timeout for packet transmission

M: Number of primary users

$Q^m{}_{pk}$: Peak interference power

$G = (Q_{pk}/N_0 - 1)$

The transmission time for a packet transmitted successfully is denoted by T_{suc}.

$$T_{suc} = \{T \mid T < t_{out}\} \quad (2)$$

The mean transmission time of packet transmitted successfully is given by [12]

$$E[T_{suc}] = \frac{MQ_{pk}}{(1-P_{out})} \psi_1\left(\exp\left(\frac{\tilde{B}}{t_{out}}\right), G\right) \quad (3)$$

where

$$\psi_1(a,b) = \sum_{m=0}^{M-1} \binom{M-1}{m} (-1)^m \times \int_a^\infty \frac{\tilde{B}}{(log_e t)\left(t + \dfrac{mQ_{pk}}{N_0} + b\right)^2} dt \quad (4)$$

For successfully transmitted packets, the second moment of packet transmission time is given by

$$E\left[T^2_{suc}\right] = \frac{MQ_{pk}}{(1-P_{out})N_0} \psi_2\left(\exp\left(\frac{\tilde{B}}{t_{out}}\right), G\right) \quad (5)$$

where

$$\psi_2(a,b) = \sum_{m=0}^{M-1} \binom{M-1}{m} (-1)^m \times \int_a^\infty \frac{\widetilde{B^2}}{(log_e^2 t)\left(t + \dfrac{mQ_{pk}}{N_0} + b\right)^2} dt \quad (6)$$

In general, the first and the second moment for packet transmission time is given by

$$E\left[T^i\right] = (1-P_{out})\, E\left[T^i_{suc}\right] + t^i_{suc} P_{out}, \qquad i = 1, 2 \quad (7)$$

B. Power Consumption in Spectrum Sharing Systems

For the second stage of analysis, we consider a spectrum sharing scenario as illustrated in Fig. 2. Here, the consideration is that a sensor node shares the spectrum with a primary receiver (P-User-R) of the primary network. The secondary network we have considered is pretty simple and comprises of a secondary transmitter (S-User-T) and a secondary receiver (S-User-R), both of which are wireless sensor nodes. The data packets arriving at the S-User-T follow a Poisson process with an arrival rate λ and are stored in a buffer in the S-User-T. The S-User-T considered is a single server and the packets stored in the buffer are serviced in first-in first-out (FIFO) manner. The service time is assumed to have a general distribution. Since the WSN operates in the presence of a primary network, the transmission of the sensor nodes will be subject to fading in the wireless environment. We have assumed that the channel will undergo Rayleigh fading.

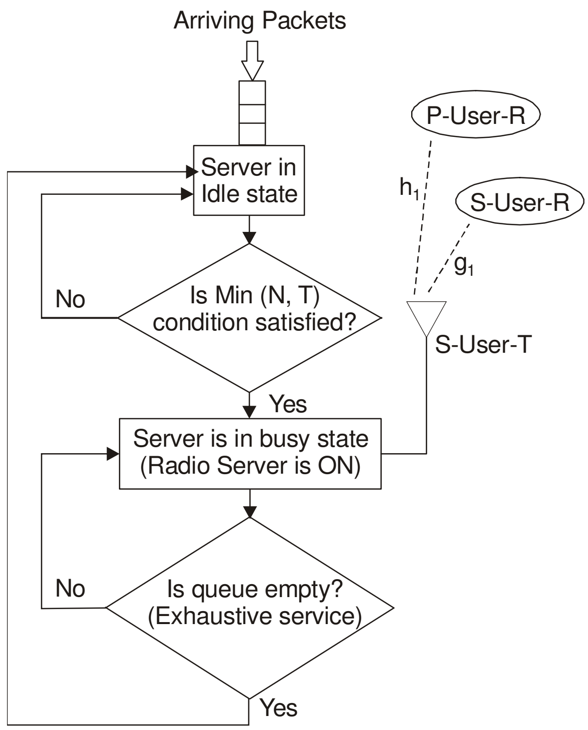

Fig. 2. WSN model in a spectrum sharing environment with an M/G/1 queue and Min (N, T) policy.

A data packet that arrives at a sensor node is stored in a buffer for transmission by the radio server at a later stage. This situation is akin to a customer arriving at a bank and standing in a queue in order to be served by the teller. The buffer at the sensor node is a FIFO queue. We have assumed that no errors in transmission take place over the wireless medium. It is also assumed that the scenario depicted follows a many-to-one communication pattern one-hop manner. For the wireless sensor node, the packets are transmitted to a destination node which is a data sink. The medium access protocol is assumed to be a contention-based protocol like CSMA.

There are two primary states of the sensor node that we have considered i.e. idle state or busy state. The radio transmitter is in the switched OFF condition when the sensor node is in the idle state whereas it is switched ON when in the busy state. In general, when packets arrive at a sensor node, the radio transmitter is switched ON and the packets are transmitted and the transmitter is switched OFF again. This leads to frequent transitions of the state of the transmitter leading to a higher power consumption. The *N* and *T* policy as depicted in Fig. 2 keeps the radio transmitter in OFF state even when there are packets in the buffer to be transmitted but the number of packets is less than *N* or the time elapsed since the radio was last switched OFF is less than *T* time units. Once the number of packets in the queue reaches the threshold *N* or the time elapsed since the last busy period is T, the radio transmitter of the server is switched ON (busy) and all the packets in the buffer are transmitted at once in a burst.

The amount of energy is consumed per busy cycle is assumed to be the same during switching from idle mode to busy mode and vice versa. The total energy consumed to switch from idle mode to busy mode and from busy mode to idle mode is called the setup energy, given by C_s. C_h denotes the power consumed while holding each packet in the queue. Let C_b denote the power consumed in the busy state, and finally, let C_i denote the power consumed when the radio is in the idle state. The total power consumption of the system is given by [13]:

$$P_C(N,T) = C_h\left[\rho + \frac{\lambda^2 E[T^2]}{2(1-\rho)} + \frac{\sum_{n=1}^{N}(n-1)F_n(T)}{\sum_{n=1}^{N}F_n(T)}\right] + C_s\frac{\lambda(1-\rho)}{E[X]} + C_b\rho + C_i(1-\rho) \quad (8)$$

where

$$F_n(t) = \int_{x=0}^{t}\frac{\lambda(\lambda x)^{n-1}}{(n-1)!}e^{-\lambda t} \quad (9)$$

$$E(X) = \frac{\sum_{n=1}^{N}F_n(T)}{F_1(T)} \quad (10)$$

Note that the parameter $\rho = \lambda E[T]$ implies the system utilization. Thus, using the expression in (8), the power consumption can be computed.

III. RESULTS AND DISCUSSION

A. Delay Performance in a Spectrum Sharing Environment

To measure the effect of the spectrum sharing approach discussed in the previous sections, we evaluated the expressions in Eqns. (1) and (7). We have analyzed the effect of the constraint on the peak interference power and the number of primary users on the outage probability. We have also analyzed its effect on the mean transmission time of the packets in the secondary system. The parameters selected for the model are as follows:

System bandwidth: B = 1 MHz
Packet size: L = 4096 bits (512 bytes)
Time out: t_{out} = 10 ms
Noise Power Spectral Density: $N0$ = 1W/Hz

Eqn. (1) is the expression for the outage probability. In the expression, we have varied the number of Primary Users (M) and also the peak interference power (Q_{pk}). We have considered the number of Primary users to be between 1 and 20. The outage probability has been evaluated for three different values of peak interference power: 5 dB, 10 dB and 15 dB. The evaluated outage probability for the considered values of number of primary users and peak interference power has been tabulated in Table 1. The same has also been graphically illustrated in Fig. 3.

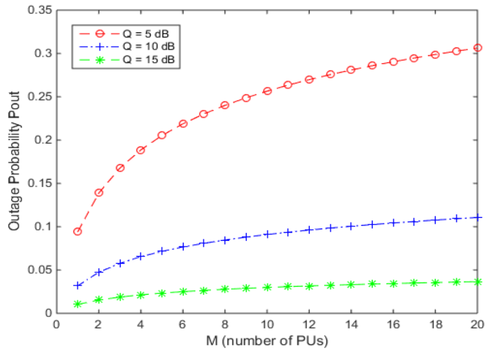

Fig. 3. Impact of the number of Primary Users on the outage probability P_{out}.

Table 1: Outage Probability P_{out} for a number of Primary Users (M).

	Outage Probability Pout for a number of Primary Users (M)				
Q_{pk}	M = 1	M = 5	M = 10	M = 15	M = 20
5 dB	0.094	0.205	0.256	0.286	0.306
10 dB	0.032	0.072	0.091	0.102	0.111
15 dB	0.010	0.023	0.030	0.034	0.037

In Table 1, we have shown the probability values for only a select few values of primary users due to space constraint. We see the effect the number of primary users, M has on the outage probability for given peak interference power of 5, 10, and 15 dB. It can be seen that the outage probability rapidly increases with a rise in M when the peak interference power is set to a lower value of 5 dB. It is also seen that there is an increase in outage probability albeit slowly when the peak interference power is set to a higher value of 10 or 15 dB and it saturates fast in the case when peak interference power is 15 dB. A higher peak interference power allows an S-User-T to transmit with a relatively high transmission power resulting in an increased transmission rate. This in turn means that the transmission time for the packets reduces leading to a lower of outage probability. It is also seen the outage probability increases with increase in the number of primary users for a constant peak interference power, as it imposes a more stringent constraint on the transmission power of an S-User-T.

Table 2: Mean Transmission time of packets $E[T^1]$.

	Mean Transmission time of packets $E[T^1]$ in sec.				
M	Q_{pk} = 1 dB	Q_{pk} = 5 dB	Q_{pk} = 10 dB	Q_{pk} = 15 dB	Q_{pk} = 20 dB
1	0.00516	0.00258	0.00188	0.00158	0.00140
4	0.00743	0.00394	0.00284	0.00234	0.00205
7	0.00804	0.00441	0.00319	0.00263	0.00229
10	0.00836	0.00469	0.00339	0.00280	0.00244

Eqn. (7) is the expression for mean transmission time of packets, when i = 1. The mean transmission time has been evaluated by varying the peak interference power between 1 and 20 dB for different number of primary users (M = 1, 4, 7 and 10). The evaluated mean transmission time for the considered values of number of primary users and peak interference power has been tabulated in Table 2. The same has also been graphically illustrated in Fig. 4.

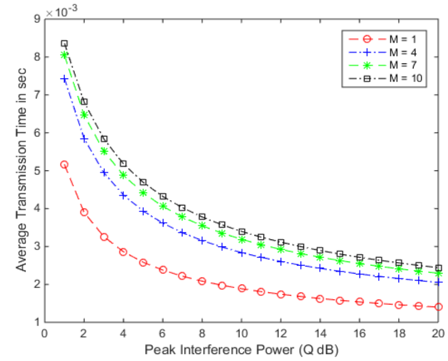

Fig. 4. Mean transmission time of packets versus peak interference power for different number of Primary Users.

In Table 2, we have shown the mean transmission time of packets for only a select few values of peak interference power due to space constraint. Table 2 shows the mean transmission time of packets at the S-User-T as a function of the peak interference power. The number of P-Users are varied with M = 1, 4, 7, 10. It is evident that a rise in the peak interference power reduces the mean transmission time for the packets from the S-User-T. It is noted that the mean transmission time decreases rapidly when the peak interference power is greater than 16 dB as seen in Fig. 4. An increase in peak interference power results in a higher transmission rate which leads to a fall in the time taken to transmit packets at the S-User-T. As is seen from Table 2, the mean transmission time of packets increases with an increase in the number of Primary users, which is obvious, as a higher number of primary users will impose a more stringent constraint of peak interference power on the S-User-T.

Table 3 gives the evaluated results of the same expression in Eqn. (7) with i = 1, which is nothing but the mean transmission time of packets. The same results are plotted in Fig. 5. Results in Table 3 show the effect that the number of primary users has on the mean transmission time of packets at the S-User-T.

Table 3: Mean Transmission time of packets $E[T^1]$.

	Mean Transmission time of packets $E[T^1]$ in sec.				
Q_{pk}	M = 1	M = 5	M = 10	M = 15	M = 20
5 dB	0.00318	0.00507	0.005718	0.006049	0.006265
10 dB	0.00189	0.002983	0.003399	0.003624	0.003776
15 dB	0.00117	0.001748	0.001974	0.002097	0.002182

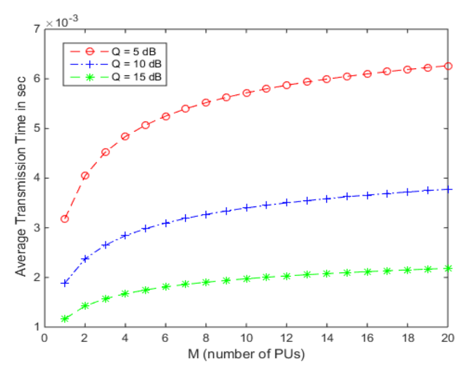

Fig. 5. Mean transmission time of packets at the Secondary User Transmitter versus number of Primary Users.

We have chosen the values for the number of primary users from 1 to 20. All the evaluated results are not tabulated due to lack of space. It is seen that for smaller values of the peak interference power (5 dB), the number of primary users plays an important role in determining the average time taken for packet transmission. A higher value of peak interference power, results in a slower rise in the average time taken for transmission of packets when the number of primary users increases and has almost no impact for peak interference power of 15 dB once the number of primary users goes beyond 4. The results depicted in Fig. 5 are similar to the ones we see in the case of outage probability.

B. Power Consumption in Spectrum Sharing Systems

In this section, evaluate the power consumption function $P_C(N, T)$ given by the expression in Eqn. (8). We have evaluated the power consumption function twice, once while keeping T constant and varying N and the second time while keeping N constant and varying T. The parametric values are as follows:

System bandwidth: B = 1 MHz

Packet size: L = 4096 bits (512 bytes)

Timeout: t_{out} = 10 ms

Noise Power Spectral Density: N_0: 1W/Hz

C_h= 1 mW, C_s = 40 mWs, C_h= 100 mW, C_i = 5 mW

In the first set of analysis, the power consumption for fixed *T* and varying *N* has been computed and tabulated in Table 4 and 5. The same results have been plotted and are shown in Fig. 6 & 7. The power consumption has been calculated also by considering varying number of Primary Users and variable peak interference that can be tolerated by the Primary users. Table 4 and Fig. 6 give the power consumption when the number of primary users is 1 and the peak interference power is 5 dB. Table 5 and Fig. 7 show the results for the number of primary users set to 3 and peak interference power set to 10 dB.

Table 4: Power Consumption when M = 1 and Q_{pk} = 5 dB.

	Power Consumption (mW).				
	N **=1**	***N*** **= 5**	***N*** **= 10**	***N*** **= 15**	***N*** **= 20**
T = 4	45.17948	11.39661	11.34439	11.35712	11.35717
T = 8	45.17948	9.042661	11.46768	12.34468	12.41533
T = 12	45.17948	8.936574	12.69238	15.28168	16.19237
T = 16	45.17948	8.989188	13.25883	16.90585	19.27638
T = 20	45.1795	9.042703	13.54776	17.70694	21.12903

Table 5: Power Consumption when M = 3 and Q_{pk} = 10 dB.

	Power Consumption (mW).				
	N **=1**	***N*** **= 5**	***N*** **= 10**	***N*** **= 15**	***N*** **= 20**
T = 4	45.15006	11.34786	11.2952	11.30792	11.30797
T = 8	45.15006	8.992167	11.41696	12.29394	12.3646
T = 12	45.15006	8.885858	12.64159	15.23089	16.14158
T = 16	45.15006	8.938423	13.20803	16.85506	19.22559
T = 20	45.15010	8.991922	13.49697	17.65615	21.07824

If we observe the power consumption values in Table 4 and 5, we notice that there is negligible difference in power consumption when the number of primary users is varied or the peak interference power is varied. So, it can be said that the number of primary users and the peak interference tolerable by these Primary users do not change the power consumption pattern of a wireless sensor node significantly. So, we can restrict our discussion to the results in either Table 4 and 5. Let us consider Table 4, where the power consumption of a single node has been tabulated for varying *N* for fixed values of *T*.

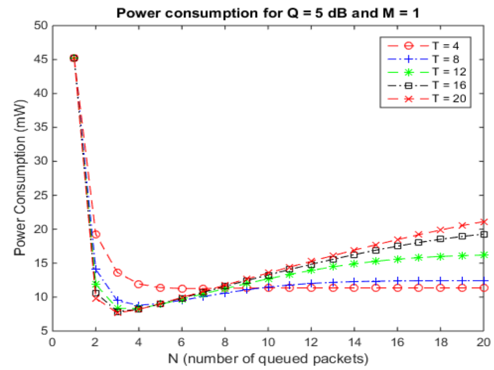

Fig. 6. Power consumption with T constant.

In Table 4 & Fig. 6 we see that the power consumption of the wireless sensor node decreases sharply and then reaches a constant floor with a rise in the threshold for the number of packets in the queue for a given threshold of waiting time T = 4 in the queue. It is also seen that a threshold value of *N* = 6 packets in the queue is sufficient for reducing the power consumption (11. 21725 mW) of the wireless sensor node in this scenario. For other values of *T*, it can be seen that there is a sharp fall in the power consumption with a rise in the number of packets *N* from 1 to 3. However, the power consumption of the wireless sensor node increases again for higher values of *N*. Even if we consider higher waiting thresholds of *T* = 8, 12, 16 and 20, the reduction in power consumption is not significant to warrant the associated delay experienced by the packets due to the higher waiting thresholds in the queue. So, it can be safely said that the optimum values of *N* and *T* are 6 and 4 respectively to reduce the power consumption in a wireless sensor node for the considered scenario.

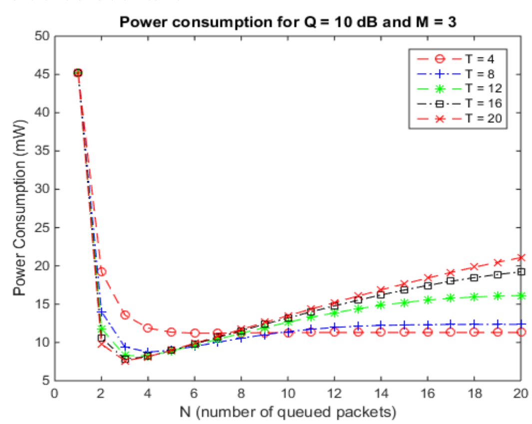

Fig. 7. Power consumption with T constant.

In the second set of analysis, the power consumption for fixed N and varying T has been computed and tabulated in Table 6 and 7. Fig. 8 & 9 show the plot of the results obtained in Table 6 and 7 respectively. As we have done earlier, the power consumption has been calculated also by considering varying number of primary users and variable peak interference that can be tolerated by the Primary users. Table 6 and Fig. 8 give the power consumption when the number of primary users is 1 and the peak interference power is 5 dB. Table 7 and Fig. 9 show the results for the number of primary users set to 3 and peak interference power set to 10 dB.

As seen previously, if we observe the results in Table 6 and 7, it is seen that the power consumption of a single wireless sensor node differs negligibly when we vary either the number of Primary Users or the peak interference is. So, it can be safely said that the number of primary users and the peak interference tolerable by these Primary users do not affect the power consumption pattern of a wireless sensor node significantly. So, we can restrict our discussion to the results in either Table 6 or 7.

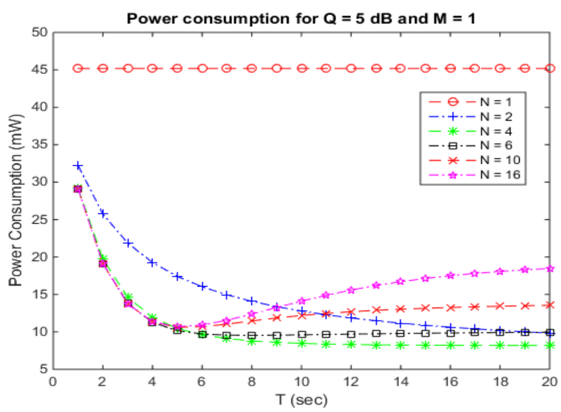

Fig. 8. Power consumption with N constant.

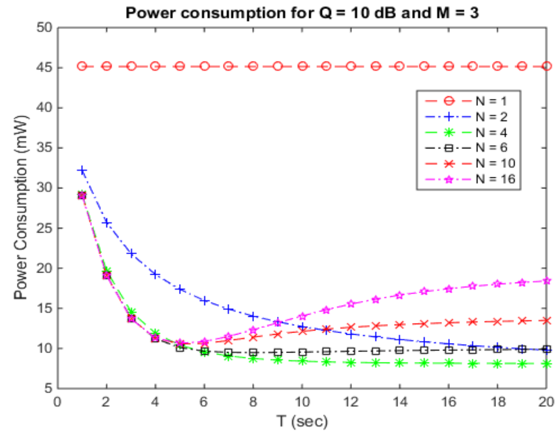

Fig. 9. Power consumption with N constant.

Let us consider Table 6, where the power consumption of a single node has been tabulated for varying T for fixed values of N. In Table 6 (Fig. 8) we can see that if the threshold for the number of packets in the queue is set to $N = 1$, then the time threshold T has no effect on the power consumption and the power consumed is the largest among all observed scenarios. Choosing the right threshold for the number of packets in the queue is paramount as can be seen in the case when $N = 4$ or 6. Higher values of N do not reduce the power consumption of the wireless sensor node. An increase in the value of the time threshold T to around 6s will further decrease the power consumption whereas any larger thresholds of T do not reduce the power consumption significantly. However, a time threshold value of 4s is optimal as higher values of T lead to more delay in packet transmission without any significant reduction in power consumption. When we combine the results seen in Table 4 and 6, the Min (6, 4) policy appears to be the optimal solution for minimum power consumption in case of all channels that are affected by Rayleigh fading without significantly causing delay in the transmission of packets under the considered scenario.

Table 6: Power Consumption when $M = 1$ and $Q_{pk} = 5$ Db.

	Power Consumption (mW).				
	T =1	T = 4	T = 10	T = 15	T= 20
N = 1	45.17948	45.17948	45.17948	45.17948	45.17948
N = 2	32.22194	19.26441	12.78564	10.88012	9.840743
N = 4	29.20791	11.93158	8.465511	8.223133	8.185716
N = 6	29.09610	11.26625	9.602664	9.8194	9.950559
N = 10	29.0938	11.34439	12.19271	13.15333	13.54776
N = 16	29.0938	11.35716	14.10291	17.13812	18.46621

Table 7: Power Consumption when $M = 3$ and $Q_{pk} = 10$ dB.

	Power Consumption (mW).				
	T =1	T = 4	T = 10	T = 15	T= 20
N = 1	45.1501	45.15006	45.15006	45.15006	45.15006
N = 2	32.1854	19.22074	12.73841	10.83184	9.791892
N = 4	29.1696	11.88335	8.41505	8.172454	8.134974
N = 6	29.0577	11.21725	9.551945	9.76862	9.899769
N = 10	29.0554	11.2952	12.14193	13.10254	13.49697
N = 16	29.0554	11.30796	14.05213	17.08733	18.41541

IV. CONCLUSION

The energy-hole problem (EHP) is a serious threat to the longevity of a wireless sensor network. The focus of this work is to prolong the lifetime of the wireless sensor nodes that are closest to the data sink node by reducing the power consumed by them. We have considered an M/G/1 queuing model with Min (N, T) policy in order to reduce the power consumption.

We have considered the scenario of a spectrum sharing system and analysed the delay incurred in the transmission of packets. We have presented mathematical expressions for outage probability and mean transmission time for point-to-point communications. We have implemented the M/G/1 queuing model to analyse the mean transmission time.

We have also performed an analysis of the power consumption in the case of wireless sensor nodes with Min (N, T) policy and M/G/1 queue in a spectrum sharing environment subject to signal fading.

The power consumption in a wireless sensor node is a function of the service time of the data packets, the different queuing parameters, and also depends on the Rayleigh fading experienced by the transmission channel. The numerical analysis we carried out, illustrates how the parameters N and T impact the power consumption in a wireless sensor node for a given fading scenario. Overall, it can be safely concluded that the power consumption in a wireless sensor node in a spectrum sharing environment in the presence of signal fading can be significantly reduced by implementing the M/G/1 queue with Min (N, T) policy by choosing appropriate values for the parameters N and T.

V. FUTURE SCOPE

We have also performed an analysis of the power consumption in the case of wireless sensor nodes with Min (N, T) policy and M/G/1 queue in a spectrum sharing environment subject to signal fading. The fading considered in this study is Rayleigh fading. The study can be extended to include other fading models.

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Conflict of Interest. The authors declare no conflict of interest.

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