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M/G/1 QUEUE-BASED REDUCTION OF POWER CONSUMPTION AND LATENCY IN WIRELESS SENSOR NETWORKS

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Abstract

Longevity of wireless sensor networks (WSN) is dependent on the optimal utilization of power supply. To make optimal utilization of power and increase the operational life of the network, we present two techniques with the goal of decreasing the consumption of power in a sensor node by incorporating queuing theory. We analyze the performance of wireless sensor networks that implement a M/G/1 queue with two different queuing policies. The analysis is done with respect to two important aspects: power consumption and latency delay. The results of the analysis illustrate the fact that the power consumed at a wireless sensor node can be reduced significantly by optimal selection of thresholds. We also compare the two policies in terms of power consumption and latency and find that the Min (N, T) policy is better equipped to not only reduce the power consumption but also reduces the latency delay caused due to the introduction of the queuing thresholds. The results indicate that the schemes studied can be implemented in practical scenarios as they are effective in reducing power consumption and increasing the operational life of a WSN.

Keywords:

Energy, Latency, Probability, Queuing Analysis, Wireless Sensor Networks

1. INTRODUCTION

. A WSN is a collection of sensors that are sometimes located over a vast topographical area. Among other functions, one of the most essential functions of a sensor node is to sense and collect information and some of these nodes act as a central collection point (sink nodes) of all information. In many applications, it is imperative that the nodes be in unattended, and hostile environments. In some cases, the dimensions of the nodes are kept small to ensure stealth. Usually, the nodes have a battery as a source of energy, which cannot be replaced in some cases and, hence, have a limited lifetime [1]. The inability to replenish the energy source necessitates the efforts to lessen the use of power at a wireless node and hence lengthen the operational life of the WSN [2] [3].

Queuing theory presents a promising approach to lessen the utilization of power in a sensor node. Specifically, the M/G/1 queuing model with a *N*-Policy has been shown to be successful at reducing the power intake at a sensor node by a significant amount. However, some applications of WSN have real-time constraints, such as those involved in surveillance, control loops or event driven applications are sensitive to latency of the data delivery. In such applications a rare but critical event must be reported to the sink, to make an appropriate decision. Therefore, it is required that the delay experienced by the packets from sensors to sink must be bounded. The *N*-policy inadvertently introduces delay for the packets that are held up in the queue before being transmitted. To avoid this unnecessary delay, we need a *T* policy whenever the time taken for the queue to fill *N* packets is excessively long. In this article, we present the two techniques that aim to decrease the average utilization of power in a sensor node. We present numerical analysis of each of these systems and compare the two with respect to average consumed power and latency delay.

2. BACKGROUND

The primary function of a sensor node is to sense different parameters, and this activity leads to the collection of data and the formation of data packets. The sensor nodes are also responsible for forwarding data packets that are destined for other nodes. All the data generated at a node or received from other nodes need to be forwarded so that it reaches a central collection point, which may be a base station or a sink node. The generation and forwarding of data packets by a node lead to a many-to-one traffic pattern. Due to the convergent traffic pattern, the nodes located near the base station or data sink usually consume more power as their data forwarding burden is more. Jiang et al. [4] have mentioned this issue as the energy-hole problem. The appearance of any such energy-hole would mean that data cannot be forwarded to the base station or sink node anymore, leading to eventual failure of the network. Four main sources of power usage are reported in [5]: collision of the transmitted packets, radio consuming power during overhearing, and the power consumed to transmit additional control data, and power consumed during idle listening.

The radio receiver is in an ON state during overhearing other packets in the wireless medium and idle listening leading to a loss of power. As compared to other sources of energy utilization, packet collisions are responsible for significant energy expenditure at a wireless sensor node. In a wireless medium that is shared among many users, the sensor nodes can transmit the data packets only after gaining complete medium access. The process of gaining medium access is a primary reason for packet collisions. Another major contributor to energy consumption is the transition of a radio transmitter from on to off state and vice-versa [6].

We wish to apply queuing theory to resolve the problem of increased energy consumption. It is noticed that the speed of arrival of data packets at nodes closer to the data sink is higher than the nodes located away. The higher rate of arrival of packets at these nodes necessitates the need for the transmitter of a sensor node to switch between ON and OFF states more frequently. This frequent transition between the ON and OFF states leads to a faster depletion of the wireless sensor node's energy. A threshold *N* [7]-[9] is incorporated, thus forming a queue to reduce the transitions. The threshold ensures that the radio transmitter does not switch to the ON state unless there are at least *N* packets in the queue. After the accumulation of *N* packets in the buffer, the radio transmitter switches ON and transmits all the packets in the queue at one go, then switches back to the OFF state. The threshold in the queue does not let the radio transmitter switch to the ON state at every instance of packet arrival, thus effectively decreases the number of times the transmitter must switch between the ON and OFF states. This reduction in the transition leads to reduced consumption of energy at the wireless sensor node.

The incorporation of the threshold *N* in a queue-based approach leads to an inevitable extended wait time for the packets in the buffer. A threshold timer *T* [10] [11] can reduce the time for which the packets wait in the buffer. The timer *T* allows the radio transmitter to turn ON as soon as there are *N* packets in the queue, or the timer has reached *T* units since the transmitter was turned OFF last. If it takes a long time to collect *N* packets in the queue, then the timer *T* allows the radio server to turn ON as soon as *T* has elapsed, thus alleviating the unnecessary delay by the packets in the queue.

In this work, we present the numerical expression for power consumed at a sensor node and delay experienced in the case of the M/G/1 queue-based approach with *N*-policy applied to handle packets arriving at a wireless sensor node to that aims to lessen the expenditure of power at the node. We also present relevant expressions for the M/G/1 queue-based approach with Min (*N*, *T*) policy applied to handle packets arriving at a wireless sensor node. We have carried out the numerical analysis for both cases and provided a comparison of the two policies based on power utilization at the node and delay incurred by the packets while being queued at the wireless sensor node.

The remainder of the article is arranged as mentioned here: In part 2, we discuss the queuing model for the *N*-Policy and Min (*N*, *T*) Policy queuing systems. In part 3, we present the system parameters and state the mathematical expressions that quantify the sensor node power consumption, and delay for both the queuing systems. We discuss the findings of the analyses in part 4. We present a conclusion based on the analytical results in section 5.

3. QUEUING SYSTEM

In the following discussion, we shall refer to the M/G/1 queue with N-Policy as 'Queuing Strategy 1' and the M/G/1 queue with Min (*N*, *T*) policy as 'Queuing Strategy 2'.

3.1 QUEUING STRATEGY 1

For any wireless network that involves multiple transmitters and receivers, the sensors must contend with each other to gain access to the shared transmission medium in the case of a wireless sensor network. Keeping this in mind, we assume that any contention-based protocol meets the requirement of medium access, allowing the competing sensor nodes to access the medium automatically. The model described here requires the data packets to be queued in a buffer at the sensor node waiting to be transmitted by the sensor node's radio server. We make the following assumptions in this model: The data packets queue up in a buffer that operates in the FIFO mode. The data packets transmitted over the wireless medium do not encounter any error. This model also assumes that a group of sensor nodes transmit their packets to other nodes in a one-hop environment.

The assumption is that the packets arriving at a sensor node follow a Poisson process which is one of the most popular counting processes. The Poisson process can be utilized in situations where one wants to count the occurrences of certain events that appear to occur at a certain rate, but completely at random. The arrival rate of packets at a wireless sensor node also follow a similar pattern i.e., they arrive at a certain rate, but the exact instance of the arrival of a packet is not known. The symbol λ denotes the mean arrival rate (mar) of the packets. The radio server services the packets with the general distribution. The first moment and the second moment of the time taken for the service of the packets are designated by E_S and E_S^2, respectively.

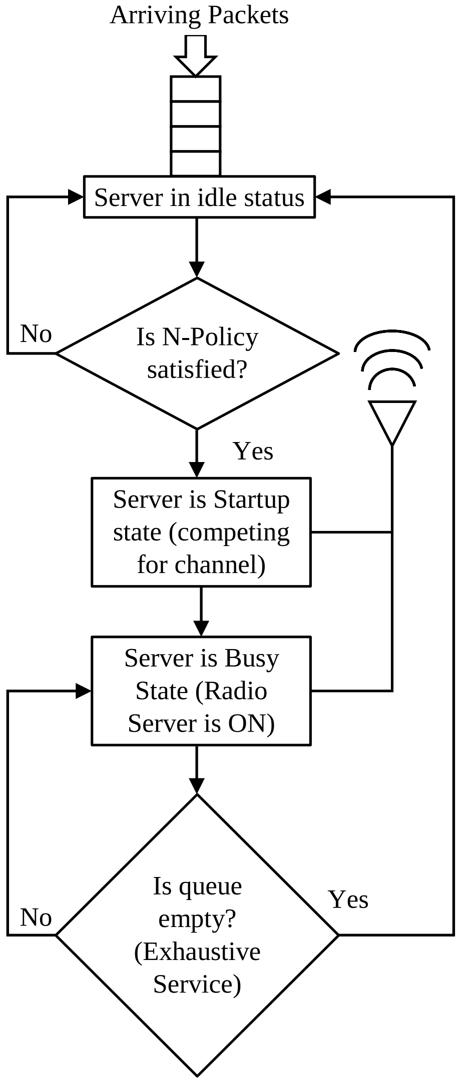

Fig.1. System model for 'Queuing Strategy 1'

We have assumed that the system has three major operational states: idle, busy, and startup.

- **Idle**: In this state, the transmitter remains in the OFF condition until the time the number of packets the queue does not reach *N* ($N \geqq 1$).
- **Startup**: In this state, the transmitter tries to gain access to the medium by contending with other transmitters. While in this state, the queue may have more than or equal to *N* packets.

- **Busy**: In this state, the transmitter is switched ON and transmits all packets in the queue till it becomes empty.

The random variable U denotes the startup time. The startup time is also assumed to follow some general distribution. The first moment of the startup time is denoted by E_U and second moment by E_U^2. For our study, we consider a single sensor node with the Queuing Strategy 1 in which the flow of operations is shown in Fig.1.

In this model, the packets that arrive at a sensor node queue up in a FIFO buffer. We consider a threshold N for the queue. Once the buffer has N packets, the radio server would turn on and try to gain access to the medium denoting the Startup state, as explained earlier. The data packets in the queue are transmitted at one go until there are no packets left in the buffer once the transmitter has gained access to the medium. The transmitter goes back to the idle state once the buffer is empty. This policy aims to lessen the number of switching between the idle and the busy state by employing a queue threshold. The reduced number of transitions leads to decreased energy consumption, increasing the lifetime of the node and the network.

The following notations are used for the analysis of our system:

L_N=quantum of packets in the system (average)

W_N=waiting time in system (average)

$W_{N,Q}$=waiting time in buffer (average)

$E[B_N]$=duration of the busy period (average)

$E[I_N]$=duration of the idle period (average)

$E[T_N]$=duration of the busy cycle (average)

The average quantum of customers (L_N) in the system with Queuing Strategy 1 is given by [7]:

$$L_N = \frac{1}{N+\rho_U}\left[\frac{N(N-1)}{2} + N\rho_U + \frac{\lambda^2 E_U^2}{2}\right] + \lambda E_S + \frac{\lambda^2 E_S^2}{2(1-\lambda E_S)} \quad (1)$$

From L_N in Eq.(1), we can calculate the average waiting time in the system, denoted by W_N

$$W_N = \frac{1}{\lambda}(L_N) \quad (2)$$

$$W_N = \frac{1}{N+\rho_U}\left[\frac{N(N-1)}{2\lambda} + NE_U + \frac{\lambda^2 E_U^2}{2}\right] + \lambda E_S + \frac{\lambda^2 E_S^2}{2(1-\lambda E_S)} \quad (3)$$

Since $W_N=W_{N,Q}+E_S$, the mean waiting time in the queue, represented by $W_{N,Q}$, can be found by the following expression

$$\begin{aligned} W_{N,Q} &= \frac{1}{\lambda}(L_N - \rho) \\ &= \frac{1}{N+\rho_U}\left[\frac{N(N-1)}{2\lambda} + NE_U + \frac{\lambda E_U^2}{2}\right] + \frac{\lambda E_S^2}{2(1-\lambda E_S)} \end{aligned} \quad (4)$$

The mean waiting time $W_{N,Q}$ represents the average delay experienced by packets waiting in the queue. The idle period (I_N) ends there are N packets in the queue. Currently, the radio transmitter switches ON and starts contending for the access to the medium. Once the radio transmitter has secured its right to transmit in the medium, it starts transmitting packets available in the queue, indicating the start of the busy period (B_N). The total length of time comprising the idle period and the busy period is called the busy cycle (T_N).

$$E[I_N] = \frac{N}{\lambda} \quad (5)$$

$$E[B_N] = \frac{(N+\lambda E_U)E_S}{1-\rho} \quad (6)$$

$$E[T_N] = E[I_N] + E_U + E[B_N] = \frac{(N+\lambda E_U)}{\lambda(1-\rho)} \quad (7)$$

Let,

C_s=energy required for setup per busy cycle

C_h=power required to hold each packet present in system

C_{id}=power consumed during the idle period

C_{sp}=power consumed during the startup period

C_b=power consumed during the busy period

The power consumed at the sensor node is calculated using the following expression:

$$P_C(N) = C_h L_N + \frac{C_S}{E[T_N]} + C_{id}\frac{E[I_N]}{E[T_N]} + C_b\frac{E[B_N]}{E[T_N]} + C_{sp}\frac{E_U}{E[T_N]} \quad (8)$$

Putting the relevant expressions in Eq.(8) gives us:

$$\begin{aligned} P_C(N) &= C_S\frac{\lambda(1-\rho)}{N+\rho_U} + \\ & C_h\left\{\frac{1}{N+\rho_U}\left[\frac{N(N-1)}{2} + N_{\rho_U} + \frac{\lambda^2 E_U^2}{2}\right] + \rho + \frac{\lambda^2 E_S^2}{2(1-\rho)}\right\} \\ & + C_{id}\frac{N(1-\rho)}{N+\rho_U} + C_b\rho + C_{sp}\frac{N(1-\rho)E_U}{N+\rho_U} \end{aligned} \quad (9)$$

where $\rho_U=\lambda E_U$;

The fact that the packets in the queue cannot be transmitted unless their number reaches the threshold N, introduces an unwanted delay in the transmission of the packets. The average latency delay experienced by the packets is given by Eq.(4). A smaller value of N would reduce the delay incurred by the packets.

3.2 QUEUING STRATEGY 2

We introduce a timer T to reduce the delay seen by the packets in the queue in Queuing Strategy 1. With the incorporation of the timer T, we now have the Queuing Strategy 2. Here, we discuss the Queuing Strategy 2 applied to a wireless sensor node. All the assumptions made in the case of the Queuing Strategy 1 also hold for this model. In the scheme studied here, we have assumed that the system has only two major operational states: busy state and idle state. The idle state is when the radio transmitter switches to the OFF state, and the busy state represents the time when the radio transmitter switches to the ON state to transmit the data packets in the queue at one go. For our study, we consider a single node with the Queuing Strategy 2 in which the flow of operation is as seen in Fig.2.

According to the system illustrated in Fig.2, the radio transmitter is in switched off (idle state) condition until the number of data packets in the buffer is N or the timer T has not reached its threshold T. As soon as the N^{th} packet arrives at the node or the timer reaches T time units, the radio transmitter is turned ON, and all the packets in the queue are transmitted in an exhaustive manner.

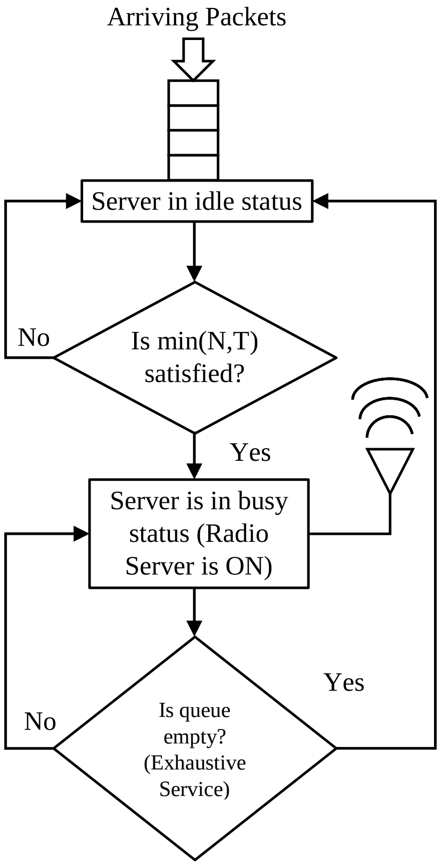

Fig.2. System model for 'Queuing Strategy 2'

The following notations are used for the analysis of our system:

L_{NT}=Average number of packets in the node

$E\ [B_{NT}]$=duration of the busy period (average)

$E\ [I_{NT}]$=duration of the idle period (average)

$E\ [T_{NT}]$=duration of the busy cycle (average)

The average number of packets (L_{NT}) is given by [8]:

$$L_{NT} = L_0 + \frac{E\left(X\left(X-1\right)\right)}{2E\left(X\right)} \tag{10}$$

$$L_{NT} = \rho + \frac{\lambda^2 E_S^2}{2\left(1-\rho\right)} + \sum_{n=1}^{N} \frac{\left(n-1\right)F_n\left(T\right)}{F_n\left(T\right)} \tag{11}$$

where L_0 represents the quantity of packets (average) present in the traditional M/G/1 queuing system that does not employ the N or T thresholds, X is a random variable that denotes the quantum of packets in the queue buffer when the radio transmitter switches on. $\rho=\lambda\ E_S$ is the parameter that denotes system utilization.

From L_{NT}, we can obtain other parameters like the mean waiting time in the queue, $W_{NT,Q}$, which is given by [12]:

$$W_{NT,Q} = \frac{1}{\lambda}\left(L_{NT} - \rho\right) \tag{12}$$

Putting relevant expressions in Eq.(12) gives us:

$$W_{NT,Q} = \frac{\lambda E_S^2}{2\left(1-\rho\right)} + \frac{\sum_{n=1}^{N}\left(n-1\right)F_n\left(T\right)}{\lambda\sum_{n=1}^{N}F_n\left(T\right)} \tag{13}$$

The average duration of the busy period, B_{NT}, as follows:

$$E\left[B_{NT}\right] = \frac{\sum_{n=1}^{N}F_n\left(T\right)}{\left(1-e^{-\lambda T}\right)} = \frac{E\left[X\right]E_S}{\left(1-\rho\right)} \tag{14}$$

where $E[B_0]$ denotes the average duration of the busy period of the traditional M/G/1 queue and $E[B_0]=E_S/(1-\rho)$. The average duration of the idle period, represented by I_{NT}, is as follows:

$$E\left[I_{NT}\right] = \frac{\sum_{n=1}^{N}F_n\left(T\right)}{\left(1-e^{-\lambda T}\right)}E\left[I_0\right] = \frac{E\left[X\right]}{\lambda} \tag{15}$$

where $E\ [I_{NT}]$ is the average duration of the radio transmitter in the OFF condition. E $[I_0]$ denotes the average length of idle period of a general M/G/1 queue without N or T policy. The mean duration of the busy cycle, T_{NT}, is given by:

$$E\left[T_{NT}\right] = E\left[I_{NT}\right] + E\left[B_{NT}\right] = \frac{E\left[X\right]E_S}{1-\rho} = \frac{E\left[X\right]}{\lambda} \tag{16}$$

The ratio of the time the radio transmitter is in busy state is denoted by P_B, given by:

$$P_B = \frac{E\left[B_{NT}\right]}{E\left[T_{NT}\right]} = \lambda E_S = \rho \tag{17}$$

The total energy consumed during every busy cycle is constant. The source of consumption is the switching between idle and busy states. This energy is denoted by C_s and called the setup energy expenditure factor (per busy cycle). Let C_h represent the power needed to hold each packet present in the system, C_b the power consumed in the busy state, and C_i the power needed in idle state.

The power consumed by a wireless sensor node is given by the following expression:

$$P_C\left(N,T\right) = C_h L_{NT} + \frac{C_S}{E\left[T_{NT}\right]} + C_b\frac{E\left[B_{NT}\right]}{E\left[T_{NT}\right]} + C_i\frac{E\left[I_{NT}\right]}{E\left[T_{NT}\right]} \tag{18}$$

Putting relevant expressions in Eq.(18) yields:

$$\begin{aligned} P_C\left(N,T\right) = {} & C_h\left[\rho + \frac{\lambda^2 E_S^2}{2\left(1-\rho\right)} + \sum_{n=1}^{N}\frac{\left(n-1\right)F_n\left(T\right)}{F_n\left(T\right)}\right] \\ & + C_S\frac{\lambda\left(1-\rho\right)}{E\left[X\right]} + C_b\rho + C_i\left(1-\rho\right) \end{aligned} \tag{19}$$

The expression in Eq.(19) can be used to compute the power consumption in a sensor node.

Although the T-Policy incorporated in the scheme reduces the latency delay, some latency is still introduced into the system. The expression in Eq.(13) defines this latency delay function.

4. NUMERICAL ANALYSIS

4.1 QUEUING STRATEGY 1

We carried out a numerical analysis of the model presented here by evaluating the expressions in Eq.(9) and Eq.(4). We have written custom MATLAB scripts to compute the power consumption and delay. We have considered the following values for the system parameters:

Packets arrive with an average arrival rate (mar): λ (1.0 to 5.0)

- E_U=0.2, and E_U^2 =0.54.
- E_S=0.05 and E_S^2 =0.03.
- Power utilization factors: C_s=40, C_h=1, C_{id}=5, $C_{sp=}$100, and C_b=100.

4.2 QUEUING STRATEGY 2

We carried out a numerical analysis of the model presented here by evaluating the expressions in (19) and (13). We have written custom MATLAB scripts to compute the power consumption and delay. We have considered the following values for the system parameters:

- Packets are received with mar: λ=1.0.
- First moment of service time of transmitter E_S=0.05 and the second moment E_S^2 =0.03.
- Power utilization factors: C_s=40, C_h=1, C_b=100 and C_{id}=5

4.3 COMPARISON OF THE TWO STRATEGIES

Both the schemes presented in the previous sections aim to lessen the power expenditure at a wireless sensor node by introducing a queue threshold *N*. However, with the introduction of the queue threshold, we also come across another phenomenon, which is the unnecessary latency delay that the packets experience while waiting in the queue before they are transmitted further. To mitigate this latency delay, the Queuing Strategy 2 introduced a timer *T*. The timer's introduction facilitates the reduction in the latency delay as proposed by the scheme. To understand the effectiveness of the Queuing Strategy 2 for power consumption and latency delay, we compare its performance with the Queuing Strategy 1. It is important to note that the Queuing Strategy 1 has three states as defined earlier i.e., idle, startup, and busy. In contrast, the Queuing Strategy 2 has only two primary states i.e., idle, and busy. We carry out this comparison with the assumption that the startup state in the case of the Queuing Strategy 1 will not significantly affect the power consumption and latency delay. The value of the timer threshold in the Queuing Strategy 2 is considered to be *T*=4 and 8 for this comparison, as we see in the results section that *T*=4 and 8 offer the best tradeoff for power consumption and delay. The other parameters in the two systems have the following values for this comparison.

Packets arrive with an average arrival rate (mar): λ=1;

- E_U=0.2, and E_U^2 =0.54;
- E_S=0.05 and E_S^2 =0.03;
- Power utilization factors: C_s=40, C_h=1, C_{id}=5, $C_{sp=}$100 and C_b=100;

5. RESULTS AND DISCUSSION

In this section, we present the results of Numerical Analysis carried out for the Queuing Strategies 1 and 2 discussed previously.

5.1 QUEUING STRATEGY 1

Here, we present the results of the evaluation of expressions in Eq.(9) and Eq.(4). We have varied the mean arrival rate (mar) (from 1.0 to 5.0) to study the effect the queue threshold has on power utilization and delay. The power utilization (consumption) values are presented in Table.1 for selective values of the threshold *N*. The queue threshold *N* has been varied between 1 and 20. Due to space constraints, the power consumption for all values of *N* is not presented in the table.

If we observe the values of power consumption in Table.1, we notice that for the mar of λ=1, the power consumption decreases sharply when the threshold *N* changes from 1 to 3 and after that reducing slowly before rising again at *N*=15 onwards. A similar trend is seen for other values of λ. We also observe that the consumption of power increases as λ increases because a higher arrival rate of packets fills the buffer faster, resulting in faster and more frequent transitions between idle and busy states.

The lowest point represents the point of least power consumption and gives the corresponding optimal value of *N*. It is seen that this point keeps shifting to the right with an increase in the mean arrival rate (mar). For example, if we observe the three curves corresponding to mar=1.0, 2.0, and 3.0, we see that the points at which the least power is consumed are located at *N**=10, 14, and 17, respectively.

Table.1. Power Consumption in system with Queuing Strategy 1

mar	Queue Threshold					
	***N*=1**	***N*=3**	***N*=5**	***N*=10**	***N*=15**	***N*=20**
λ=1	56.91	28.54	22.76	19.94	20.62	22.20
λ=2	91.58	47.45	36.75	29.69	28.84	29.63
λ=3	115.4	63.35	49.18	38.79	36.66	36.78
λ=4	132.2	76.74	60.21	47.28	44.12	43.68
λ=5	144.0	88.00	70.00	55.22	51.25	50.35

We also analyze the effect of the threshold *N* by evaluating the expression in Eq.(4). We vary the mar (from 1.0 to 5.0) and the queue threshold *N* between 1 and 20 to study the effect of the queue threshold. The latency delay calculated in seconds has been presented in Table.2. As before, we present these values only for limited values of *N* due to space constraints.

Table.2. Latency Delay in in system with Queuing Strategy 1 (sec)

mar	Queue Threshold					
	***N*=1**	***N*=3**	***N*=5**	***N*=10**	***N*=15**	***N*=20**
λ=1	0.40	1.21	2.17	4.64	7.12	9.62
λ=2	0.55	0.79	1.22	2.41	3.64	4.88
λ=3	0.66	0.68	0.93	1.69	2.49	3.31
λ=4	0.75	0.66	0.80	1.33	1.92	2.53

λ=5	0.83	0.66	0.74	1.13	1.59	2.07

Let us consider the first row of Table.2, which corresponds to mar of λ=1. We see that the latency increases linearly with an increase in the value of the queue threshold *N*. As the threshold increases, the packets are held up in the queue for a long time before the radio transmitter switches on, and all the packets are transmitted in a burst. The same trend is seen for other values of λ. We also see that as the mar increases, the latency delay reduces. The fact that a faster rate of arrival of the packets fills up the buffer faster, leading to an earlier transmission of the packets, explains the fall in latency delay with an increase in the mean arrival rate. This trend tells us that in cases where the data packets arrive at a very slow rate, the delay experienced by the packets at a node with a Queuing Strategy 1 waiting to be transmitted further is high and thus warrants the introduction of the timer threshold *T*.

5.2 QUEUING STRATEGY 2

In this part, the results of the evaluation of expressions in Eq.(19) and Eq.(13) are seen. We have carried out the analysis in two different ways. Initially, we have varied the value of *N* with *T* constant. With this setting, we have then computed the power consumption using the expression in Eq.(19). Later, we have varied the value of *T* while keeping *N* constant and carried out the same computation. The results of both computations are presented in tabular form in Table.3 and Table.4, respectively.

Table.3. Power Consumption in system with Queuing Strategy 2 and *T* Constant

Time Threshold	Queue threshold					
	***N*=1**	***N*=3**	***N*=5**	***N*=10**	***N*=15**	***N*=20**
T=4	47.82	24.80	21.77	21.14	21.14	21.14
T=8	47.82	23.55	19.61	18.43	18.55	18.56
T=12	47.82	23.48	19.43	18.14	18.73	18.96
T=16	47.82	23.48	19.42	18.12	19.12	19.93
T=20	47.82	23.48	19.42	18.12	19.29	20.68

The Table.3 gives us the results of the computation of power consumption using the expression in Eq.(19) when we vary the queue threshold *N* between 1 and 20 by keeping *T* constant. Each row of Table.3 represents the power consumed by the wireless sensor node for a different value of the timer threshold *T*. Every curve represents the power consumed by the node for a different value of *T*.

Let us consider the first row of Table.3, which represents the power consumed when *T*=4 sec. We see that power consumption reduces sharply with an increase in the queue threshold value of *N* from 1 to 3. We further see that the power consumption becomes constant after the queue threshold of *N*=5. A similar trend is seen for the other cases when the timer threshold is varied from *T*=8 to 20. However, we also notice that for higher values of *T*, mainly *T*=12 and above, the power consumption increases after decreasing for queue threshold values of *N*=10 or higher. Power consumption increases at higher values of *N* and *T* because of the increased overhead of holding the packets in the queue, outweighing the benefits of the queue threshold. The lowest power consumption occurs when the value of *N* is around 8 or 9 for different *T* values. Thus, the addition of the second threshold *T* has improved the viability of the proposed Queuing Strategy 2.

The Table.4 gives us the power consumed at a wireless sensor node using the Queuing Strategy 2 when we vary the timer threshold *T* between 1 and 20 by keeping *N* constant. Each row of Table.4 represents the power consumed by the wireless sensor node for a different value of the queue threshold *N*. Every curve represents the power consumed by the node for a different value of *N*.

Table.4. Power Consumption in system with Queuing Strategy 2 and *N* Constant

Queue Threshold	Timer Threshold					
	***T*=1**	***T*=3**	***T*=5**	***T*=10**	***T*=15**	***T*=20**
N=2	36.91	30.89	29.63	29.32	29.32	29.32
N=4	34.43	24.41	21.79	20.84	20.82	20.82
N=8	34.34	23.36	19.90	18.20	18.07	18.07
N=12	34.34	23.35	19.86	18.36	18.44	18.48
N=16	34.34	23.35	19.86	18.57	19.22	19.59
N=20	34.34	23.35	19.86	18.61	19.69	20.68

As can be seen from Table.4, if we consider any row from the table, the power consumption reduces sharply with an increase in the value of *T*. The power consumption then becomes almost constant after *T* =8. However, it is seen that for values of *N*=12 or higher, the power consumption decreases and then increases after *T*=8, which is consistent with the results seen in Table.3. If we look at the results, we find that the best possible values of *N** and *T** are 8 and 10 respectively for the given set of parameters that result in the lowest power expenditure at a wireless sensor node using the Queuing Strategy 2.

To understand the effect of that the timer threshold *T* on the latency delay we evaluate the expression in Eq.(13). We first study the effect of the latency delay by varying the value of the threshold *N* and, at the same time keeping *T* constant. We also compute the latency delay by considering different values of *T* while simultaneously keeping the value of *N* constant. The latency delay in both cases has been evaluated, and the results are tabulated in Table.5 and Table.6.

Table.5. Latency Delay (sec) in system with Queuing Strategy 2 and *T* Constant

Time Threshold	Queue threshold					
	***N*=1**	***N*=3**	***N*=5**	***N*=10**	***N*=15**	***N*=20**
T=4	0.016	0.933	1.580	2.007	2.016	2.016
T=8	0.016	1.011	1.967	3.613	3.994	4.015
T=12	0.016	1.016	2.012	4.312	5.655	5.987
T=16	0.016	1.016	2.016	4.485	6.582	7.696
T=20	0.016	1.016	2.016	4.513	6.917	8.799

The Table.5 gives us the computed latency delay that the data packets must endure while waiting in a queue at a wireless sensor node using Queuing Strategy 2 when we vary the queue threshold *N* between 1 and 20 by keeping *T* constant. Each row of Table.5 represents the latency delay for a different value of the timer threshold *T*. Every curve represents the latency delay experienced by the data packets while waiting to be serviced by the sensor node's radio server for a different value of *T*.

From Table.5, we observe that for *T*=4, the latency delay increases with an increase in the value of the queue threshold till *N*=8, after which the delay becomes almost constant. For higher values of *T*, the delay becomes almost constant for values of *N* greater than 8. In short, we can say that the point at which the delay becomes almost constant keeps moving to the right (higher value of *N*) with an increase in the value of *T*. However, for *T*=20, the latency delay keeps on increasing linearly with an increase in the value of *N*. This evaluation tells us that latency delay is the least when *T*=4 which is self-explanatory as a lower value of the timer threshold leads to lower waiting time for the packets waiting to be serviced by the radio server of the wireless sensor node.

The Table.6 gives us the computed values of latency delay that the data packets must endure while waiting in a queue at a wireless sensor node using the Queuing Strategy 2 when we vary the timer threshold *T* between 1 and 20 by keeping *N* constant. Each row of Table.6 represents the latency delay for a specific value of the threshold *N*. Every curve represents the latency delay experienced by the data packets while waiting to be serviced by the transmitter of the wireless sensor node for a different value of *N*.

Table.6. Latency Delay (sec) in system with Queuing Strategy 2 and *N* Constant

Queue Threshold	Timer Threshold					
	***T*=1**	***T*=3**	***T*=5**	***T*=10**	***T*=15**	***T*=20**
N=2	0.311	0.473	0.507	0.516	0.516	0.516
N=4	0.500	1.140	1.395	1.512	1.516	1.516
N=8	0.516	1.504	2.360	3.357	3.505	3.515
N=12	0.516	1.516	2.510	4.547	5.350	5.500
N=16	0.516	1.516	2.516	4.950	6.686	7.355
N=20	0.516	1.516	2.516	5.011	7.316	8.799

If we observe Table.6, we see that the latency delay is higher for higher values of *N*, which is pretty evident as a higher value of *N* would mean that it would take more time for the buffer to fill up and that would result in a more significant delay. For lower values of the queue threshold *N*=2 or 4, we see that the timer threshold *T* does not affect the latency delay after values of *T*=5 and *T*=7, respectively. This tells us that lower values of the queue threshold result in smaller latency delay, and the timer threshold does not influence the latency delay. In other words, the timer threshold *T* is effective in reducing the latency delay only when the queue threshold is high.

It is seen that the selection of optimal values of *N* and *T* is of utmost importance from all the discussion on the results of evaluating the expression for power consumption and delay. A higher value of *N* would mean more significant power saving but would also lead to a higher latency delay. That is where the timer threshold *T* comes into the picture. The network administrator must select an optimal value of *T* that would reduce the latency delay without significantly increasing the power consumption.

5.3 COMPARISON OF THE TWO STRATEGIES

In this part, we compare the two models concerning power consumption and latency delay. The value of the timer threshold in the Queuing Strategy 2 is *T*=4 and 8 for this comparison as *T*=4 and 8 offer the best tradeoff concerning power consumption and delay. The results of this comparison are presented graphically in Fig.3 and Fig.4.

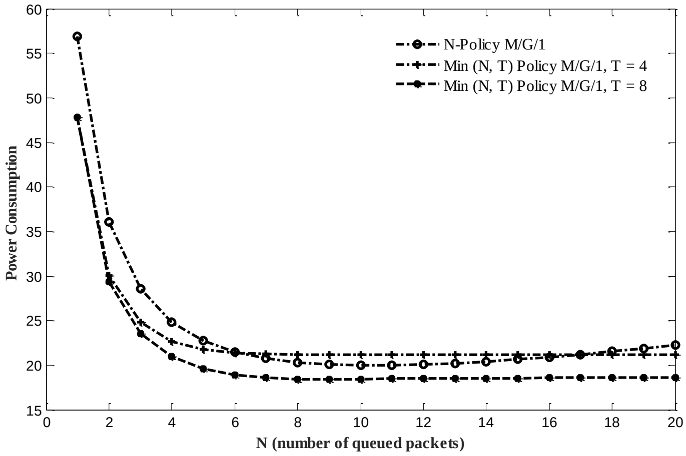

Fig.3. Power consumption comparison of systems with Queuing Strategy 1 and Queuing Strategy 2

The Fig.3 shows the graphical representation of power consumption at a wireless sensor node that employs Queuing Strategy 1 and another one that employs Queuing Strategy 2. We see that power consumption reduces significantly when we increase the value of *N* from 1 to 3, and, after that, it continues decreasing but at a slower rate. The power consumption in both the systems is almost similar and reaches the lowest value at around *N*=8 or 9 for both the systems. From this illustration, we understand that the Queuing Strategy 2 offers a similar decrease in power consumption as the Queuing Strategy 1.

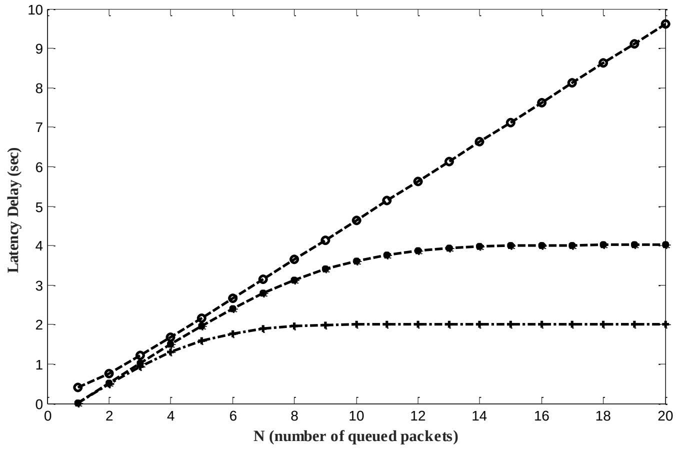

Fig.4. Latency delay comparison of systems with Queuing Strategy 1 and Queuing Strategy 2

The Fig.4 illustrates the delay that the data packets waiting in the queue must endure at a wireless sensor node that employs Queuing Strategy 1 and another one that employs Queuing Strategy 2. We see that the latency delay increases when we increase the value of *N* from 1 to 4 and after that continues increasing but at a slower rate. The latency delay keeps rising linearly for the Queuing Strategy 1 with an increase in *N*. From this illustration we understand that the Queuing Strategy 2 causes a much lesser delay for the packets in the queue as compared to Queuing Strategy 1 for higher values on *N*.

From the discussion on Fig.3 and Fig.4, we understand that the Queuing Strategy 2 offers a similar reduction in power consumption to Queuing Strategy 1 but is much better in terms of latency delay i.e., it does not cause as much delay as the Queuing Strategy 1. The Queuing Strategy 2 is better for real-time applications where the data cannot tolerate the delay caused by wireless sensor nodes employing the Queuing Strategy 1.

6. CONCLUSION

In our present work, we have presented and analyzed two schemes which can be made a part of existing MAC protocols to lessen the utilization of power at a wireless sensor node. We have presented the expressions for power consumption and delay for the M/G/1 queue with *N*-Policy (Queuing Strategy 1) as well as the M/G/1 queue with Min (*N,T*) Policy (Queuing Strategy 2). Using these mathematical expressions, we have carried out numerical analysis of the power consumed at a wireless node and the subsequent delay introduced due to packets waiting in the queue of a wireless node. The analysis results tell us that the power consumption of a wireless sensor is significantly reduced by incorporating a queue threshold (*N*). This threshold value is used to hold the packets in the buffer to prevent frequent switching of states of the transmitter. By employing a queue threshold, we ensure that the number of transitions the radio transmitter must undergo between idle and busy states reduces. A drawback of this technique is that it causes an unnecessary delay, which may not be acceptable in time-sensitive applications. In such scenarios, a timer (*T*) can reduce the critical parameter of latency delay. With the help of numerical analysis, we can also indicate the optimal values of *N* and *T*, which would ensure a reduction in power consumption and not cause unnecessary delay.

We have also compared the two systems based on power consumption and delay. There is a slight reduction in power consumption for Queuing Strategy 2 as compared to Queuing Strategy 1. But the Queuing Strategy 2 shows significantly better performance in terms of latency delay i.e., the delay incurred in the transmission reduces significantly. The Queuing Strategy 2 is better for real-time applications where the data cannot tolerate the delay that would be caused in the case of wireless sensor nodes employing the Queuing Strategy 1. Overall, the analysis of the system with Queuing Strategy 2 enables us to select optimal *N* and *T* values that would reduce the average power consumption without causing unnecessary latency delay caused by the Queuing Strategy 1. The study indicates that the schemes studied are valid and can be implemented easily in practical scenarios.

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