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MULTI-LAYER WSN WITH POWER EFFICIENT BUFFER MANAGEMENT POLICY

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Abstract—Power efficiency is a key issue in wireless sensor networks due to limited power supply. Buffer management is also crucially important in the scenario where the incoming traffic is higher than the output link capacity of the network since a buffer overflow causes power waste and information loss if a packet is dropped. There are many available buffer management schemes for traditional wireless networks. However, due to limited memory and power supply of sensor nodes, the existing schemes cannot be directly applied in wireless sensor networks (WSNs). In this work, we propose a multi-layer WSN with power efficient buffer management policy which simultaneously reduces the loss of relevant packets. Unlike the conventional WSNs which consider the whole network as single layer, we divide sensor network topology logically into multiple layers and give a three layer model as an example. In our proposed scheme, the layers are differentiated by the sensors' information. The buffer can then judge the packets from different layers and then make a decision on which packet to be dropped in case of overflow. We show that our proposed multi-layer WSN can reduce the relevant packet loss and power waste for retransmission of lost packets.

1. INTRODUCTION

Due to recent technological advances, the manufacturing of small and low cost wireless sensor nodes has become technically and economically feasible. However, as a result of their limited size, weight and ad-hoc method of deployment, the available power and memory size are limited. Wireless sensor networks (WSNs) are a set of small sensor nodes and the sink for data collection [1]. WSNs have a wide

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range of applications in environmental monitoring, habitat observation, health monitoring and so on [2]. In the monitoring applications, huge number of sensors are scattered in the application area and different sets of sensor nodes are assigned to collect the different readings from its sensing environment. Sensor nodes sense their environment periodically or on every predefined events and generate readings. Those sensor readings are forwarded towards the sink node for further processing by using store and forward method [1].

In WSNs, intermediate nodes (or sensors) need to forward the data originating from multiple sources. Due to its limited memory, the buffer of intermediate nodes may start overflowing and it will result in loss of valuable packets. As a consequence,retransmission of the same packet will be required and result in unnecessary power loss. Since battery power and memory are available in very limited amount, efficient use of available buffer and power is highly desirable in WSN. The packet format in WSN is somewhat similar to the packet used in ATM network since both of them have fixed length packets. However, the buffer management policies of ATM [3] cannot be applied to WSNs due to the limited memory and computational capabilities of sensor nodes. Thus, the important problem of buffer management for resource constrained WSNs remains largely open.

Current available buffer management schemes for WSN can be classified into *congestion avoidance* and *congestion control* [5, 6]. While *congestion avoidance* detects incipient congestion and prevents its occurrence, *congestion control* concentrates on enabling the network to recover from packet loss [4]. Most current congestion avoidance mechanisms [7–9] are not fitting to the network where multiple sensor nodes send their readings to a single sink node. The existence and the structure of optimal buffer management policy for congestion control was first investigated by Foschini and Gopinath [10]. They considered optimality within the class of policies that never drop a packet once they admit it in the buffer. Wei et al. [11] then suggested asharing policy, named *drop-on-demand* or DoD, which allows for the dropping of accepted packets. According to this policy, an arriving packet is always accepted if there is an empty buffer. In the case when the buffer has no available space for new arrival packet, buffer management policy decides whether to drop the new packet or to drop one of existing packets to have room for a new arriving packet. In general, policies which can accept an arriving packet by dropping another packet from the buffer are known as *push-out* policies. There has been a number of prior works which have proposed various push-out policies such as 1) *random* [12], 2) *first in first out* (FIFO) [13], 3) *drop tail* (LIFO) [14], and so on. In [15], a buffer management scheme called *most redundant drop* (MRD) was proposed that makes use of spatial information in sensor data to improve the network coverage. However, we are concerned with the environmental monitoring applications where different sets of sensors are assigned to collect the different information from its sensing environment. In this paper, we propose a multi-layer WSN with power efficient buffer management policy. The major difference between our scheme and MRD is in that we consider sensor network as multi-layer network, while MRD considers the whole network as a single layer network. The main idea of our buffer management policy is to maximize the overall throughput by means of minimizing the number of retransmitted packets required in the case of packet loss. Simulation results show that our proposed buffer management policy can ensure saving of relevant packets and thus it can outperform MRD in terms of recovery cost. The remaining of this paper is organized as follows. We first discuss the existing problems in Section 2. We then briefly present our network model in Section 3. Section 4 describes the key idea of our proposed methods for the efficient use of sensors' buffer. Simulation results and discussions are presented in Section 5. Finally, we conclude our paper in Section 6.

2. MOTIVATION AND PROBLEM STATEMENT

In the conventional sensor network as shown in Fig. 1, the whole WSN is considered as a single layer, and thus, each sensor node is responsible for relaying all the sensor data to the sink node. However, it is highly desirable to make efficient use of available resources such as memory and power in resource constrained WSNs. In addition, packet transmission is the most power consuming action for sensor nodes [1]. Thus, in order to reduce the number of packet transmissions, network coding became the promising technique for low-power sensor nodes. Network coding technique [16] allows an intermediate node to produce the linear combination of earlier received packets from different input links before sending the combined data to its output link. The operations are computed in the finite field and thus the result of the operation is also of the same length. Since the packet transmission is the most power consuming action for sensor nodes and the network coding technique reduces the number of packet transmissions, network coding becomes useful to reduce the power consumption in WSN [16]. However, it comes to a crisis in buffer portion. The original packets can be recovered by solving the set of linear equations just after receiving the required number of linearly independent packets. Thus, in the process of forwarding the packet to the sink node, an intermediate node may keep multiple packets

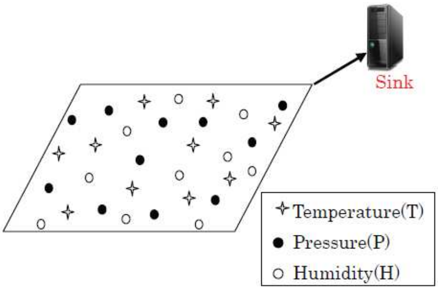


Figure 1. Monitoring sensor network application.

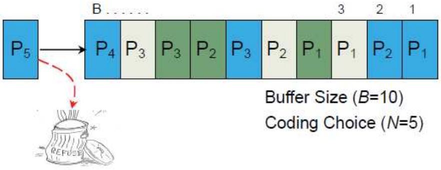


Figure 2. Buffer overflow problem at intermediate node.

before successfully decoding the original packet. Such nodes will be heavily loaded and due to limited memory size, the buffer may start overflowing as shown in Fig. 2. It is possible to perform the decoding in two manners. The first one is to perform the decoding in each receiver (relay) node and the other one is to recover the original packets only at the final destined node. The former provides better reliability since each node forwards the packets only after successfully recovered the original information. The latter is appropriate for delay-sensitive application since each node immediately forwards the received packets without doing any processing on received packets. It can also reduce computational complexity in decoding process. However, on the contrary, it may require the additional transmission of same packets to successfully recover the original information. As a compromise, we will use the combination of these two methods and take the benefits from both. Each node will perform decoding only on partial of received packets and for the rest of them, it will act just as a relay node.

3. PROPOSED MULTI-LAYER WSN

In this section, we will illustrate the network model of our study. We consider a simple environmental monitoring 3-layerWSN where hundreds of sensor nodes generate the readings on every unit time and send them to the sink. On the way from source to sink node, packets pass through intermediate nodes. In our network model, sensor nodes are designed to collect three different information (*temperature, pressure* and *humidity*) from the application area. Thus, the sensors which are assigned to collect the same information (e.g., *temperature*) will virtually form as a (*temperature*) layer. Sensors in each layer will accept the packets originating from the same layer as first priority. Complete sharing is applied to sensor's memory by which the total memory of each sensor is virtually shared between the different queues.

We define the *relevant* and *irrelevant* packets used in our scheme. Sensors in each layer will consider the packets originated from the same layer as *relevant* packets, and on the other hand, the packets originated from the different layers are treated as *irrelevant* packets. i.e., a sensor which is assigned to read the temperature will consider the packets which contain temperature readings as relevant packets and the packets which contain either pressure or humidity reading as irrelevant packets. Below we will consider the two different 3-layer WSNs. Sensors in 3-layer WSN type A accommodate to listen the packets originated from other layer sensors while that competence is not considered in 3-layer WSN type B.

3-layer WSN type A is illustrated in Fig. 3. In this WSN, whenever the buffer has available space, sensor will accept all arriving packets originated either from the same layer or different ones. When the buffer is full on arrival of new packets, a decision is made as to whether the next arriving packet should be accepted, rejected or accepted by pushing-out existing packet from buffer. The decision depends on the type of the arriving packet which can be identified by the packet header.

The network architecture of 3-layer WSN type B is illustrated in Fig. 4. Each sensor in 3-layer WSN type B listens only relevant information which come from the same layer instead of listening entire packets in its communication range. Thus, sensors in different layers will completely have no interaction. In our scheme, we use network coding as in-network processing in order to save the power in packet transmission. In network coding, each node needs to keep the previously arrived packets until receiving the sufficient number of packets for successfully decoding the original packets. This will lead to the problem of buffer flow for limited buffer of sensor node if the node keeps all arriving packets. Thus, we will perform network coding only on the relevant packets in order to make more efficient use of limited buffer. After successfully retrieving the original packet, node applies linear network coding on it along with its own generated readings if it has new sensor readings to send. Sensor nodes perform the encoding

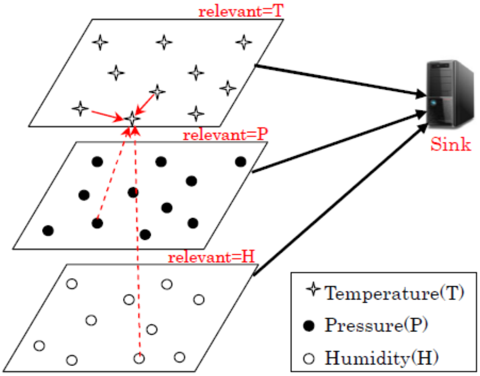


Figure 3. Proposed 3-layer WSN type A: listen all arriving packets whenever buffer has available space to accommodate them.

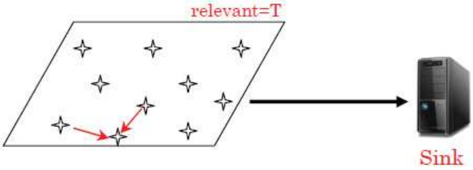


Figure 4. Proposed 3-layer WSN type B: listen only relevant packets.

process on the finite *Galois Field* GF(2) and then send the encoded packet to the network layer. For irrelevant packets, sensor will not perform any in-network processing and it will simply act as a relay node.

A good buffer management policy usually divides the buffer space logically into a number of queues. There are two ways to separate the total buffer space [17]:

1) Complete Partitioning, and 2) Complete Sharing.

The entire storage is permanently partitioned into number of queues and each queue gets a fixed amount of the buffer space in the first approach while all the storage space is fully shared between queues when necessary in the latter one. In our model,we use the complete sharing approach in order to obtain improved buffer efficiency. We assume that time is slotted. During one time slot, there can be one or more incoming packets and at most K packets may arrive at each node where K is the size of temporary input queue in each sensor node. At the end of the time slot, all the packets residing in the input queue will be transferred to the main buffer, or be dropped, according to buffer management policy. In every transmission slot, the transmitter of sensor node sends out packets from the output queue in FIFO manner.

4. PROPOSED BUFFER MANAGEMENT SCHEME

Several buffer management policies are available in literature for conventional data networks. However, those schemes cannot be applied in WSNs, since they are too complex to be implemented in low computation capable sensor nodes. We concentrate on the buffering mechanism for congestion control that can be implemented in each sensor node. Our goal is to identify a buffer management policy to efficiently share the available buffer space among packets of different types, so that the overall network throughput will be maximized. The basic elements of this mechanism include packet classification, buffer partitioning and a discard policy.

4.1. Packet Classification

Each sensor will classify the receiving packets into three different types and thus each packet is said to be of type i, $1 \leq i \leq 3$. First type of packets is termed as *relevant packets* which contain same type of sensor reading and those packets are originated from the same layer sensor nodes. Sensors will treat the packets originated from different layer sensors as *irrelevant packets* as they are carrying the different type of sensor readings. Last type of packets is called as *normal packets* which may include *hello* packets and other regular packets which are generated at regular interval of time. In any case, we will make sure that we are not losing any relevant packets and we permit other types of packets to be dropped.

4.2. Buffer Partitioning

Buffer partitioning delineates the amount of storage space available to a given queue and defines how space is shared among the different queues. We have selected the complete sharing buffering scheme [18] for our approach because it is efficient and simple. In our network scenario, each node consists of a total buffer size, B, shared by T different types of queues. The entire buffer space is divided into T queues according to the intended receiving packet type.

In 3-layer WSN type A, the main buffer will be partitioned into three queues (*relevant, irrelevant* and *normal*) as in Fig. 5, and each queue accepts packets with the corresponding type only. The capacities

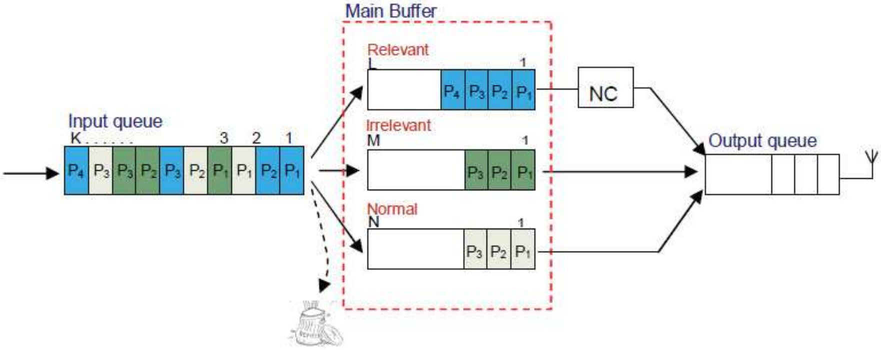


Figure 5. Buffer management policy for 3 layer WSN type A.

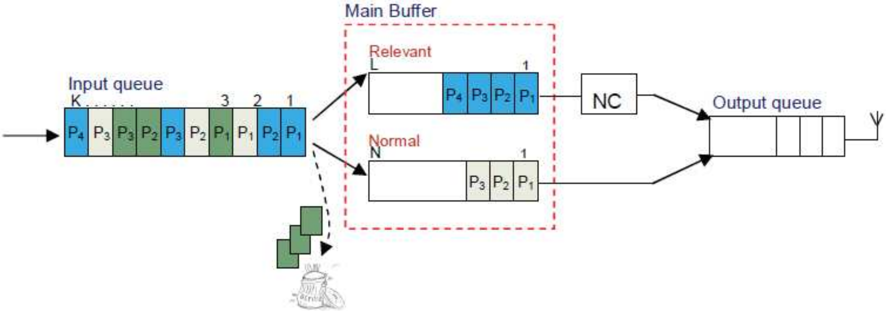


Figure 6. Buffer management policy for 3-layer WSN type B.

of *relevant, irrelevant* and *normal* queues are L, M and N, respectively. Thus, the total capacities of these three queues will not exceed the total capacity of main buffer, $L + M + N \leq B$. In one time slot, all incoming packets will be temporarily stored in input queue whose size K is usually less than the main buffer, i.e., $K < B$. Then, the packets in input queue are inputted to the tail of dedicated queues in main buffer or drop according to specified policy. The capacities of the queues can be adjusted dynamically and therefore a packet does not have to be dropped if there is any available space in the buffer.

On the other hand, in 3-layer WSN type B since sensors are designed to listen only relevant packets, sensors' main buffer will be divided into only $T = 2$ different queues as shown in Fig. 6, where $L + N \leq B$. The first queue is corresponding to the relevant packets and the second one is served to store the normal type of packets and irrelevant packets will simply be dropped. Each node can identify the type of received packets by information provided in packet header.

4.3. Discard Policy

Discard policy concerns with the rules including accepting or rejecting an arriving packet as well as pushing out an already stored packet to accommodate an arriving one. The decision is made based on the types of arriving packets. In this paper, we propose a new push-out policy. Our goal is to find the policy which maximizes the overall throughput or equivalently minimizes the overall loss probability. As mentioned earlier, we explicitly classify the arrived packets into three types, *relevant, irrelevant* and *normal*, in WSN type A and two types, *relevant* and *normal*, in WSN type B. Incoming packets will always be inputted to corresponding queues whenever the buffer is not full, and discard policy will be invoked when the buffer is full.

In case when the main buffer has no available space on arrival of new packet, our proposed push-out policy works as follows. If the arriving packet is of normal type and there is some packets in normal queue, then it replaces the oldest one in the normal queue with the new arriving packet. However, if the length of normal queue is zero ($N = 0$), i.e., there is no existing normal packet to replace, then it simply drops the arriving packet. However in the case if the arriving packet is relevant, it drops existing one either from relevant or normal queue to accept the new arriving relevant packet. If the arriving packet is irrelevant, then a packet is dropped from normal queue to have room for an arriving packet. The same policy is applied in both WSN type A and B with the exception of irrelevant packet type. While all irrelevant packets are rejected in WSN type B, on the contrary, accepting or rejecting of irrelevant packets in WSN type A depends on the current availability of the buffer space.

5. PERFORMANCE EVALUATION

5.1. Simulation Setting

We perform computer simulation using NS-2, a standard tool in sensor network simulation. We have implemented a simple environmental application in which three sets of sensor nodes sense their immediate surroundings and forward those readings to the sink node by using store and forward method. The default parameter setting for the simulation is shown in Table 1. In our simulation, wireless nodes are randomly deployed in 100 m × 100 m area. For the sake of simplicity, we assume that MAC protocol assigns a unique channel for every node to prevent possible collisions and each node receives the packets within its communication area without any failure. We also assumed that it is the responsibility of routing protocol to forward the packet towards

Table 1. Simulation parameters.

Number of nodes	100–500
Area (m^2)	100×100
Layers' deployment	Balanced layers
	Unbalanced layers
Packet size	30 bytes
Transmission range	25 m
No. of sensor classification	3
Coding choice for relevant packet	5

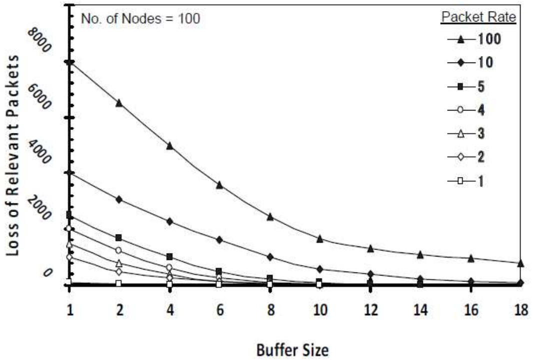


Figure 7. Loss of relevant packets vs. buffer size for 3-layer WSN type A.

the sink node. For all the results presented below, we use the average result of 10 simulation runs for each scenario.

5.2. Impact of Design Parameters

In order to be taken into account in determining an optimal design parameters for WSN, we study the impact of design parameters on buffer management, such as buffer size, packet rate and time. First, we discuss the impact of the buffer size on the loss of relevant packets in order to select an optimal buffer size for subsequent simulations. The results in Fig. 7 indicate the buffer size 10 is optimal for the packet rates of less than 5 packets per unit time to maintain the minimum loss of relevant packets. In addition, according to the nature of low data rate WSN, the sustainable rate of sensor node is supposed not to exceed 5 packets per unit time. Using the values obtained from above figure, we will use buffer size of 10 in our simulation.

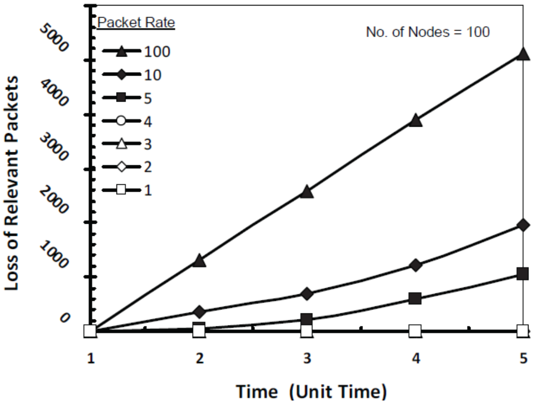
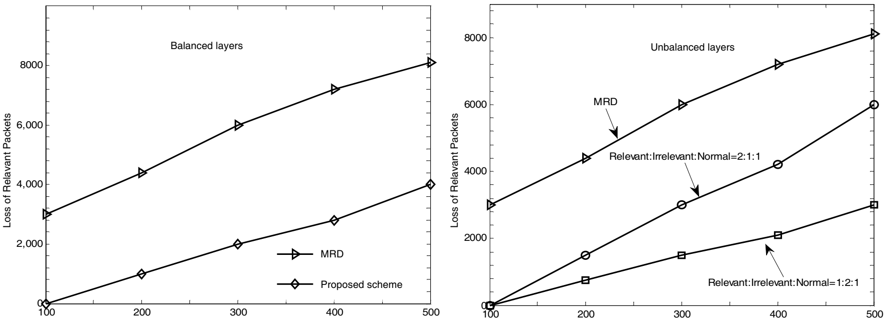


Figure 8. Loss of relevant packets vs. time for 3-layer WSN type A.

Another factor to be considered is the time and thus we also evaluate the loss of relevant packets as a function of time. We use 100 sensor nodes and the memory of each sensor node can hold up to 10 packets. The result in Fig. 8 shows that the loss of relevant packets is linearly proportional with the time. This is due to the fact that sensors' buffer suffer overflow from time to time.

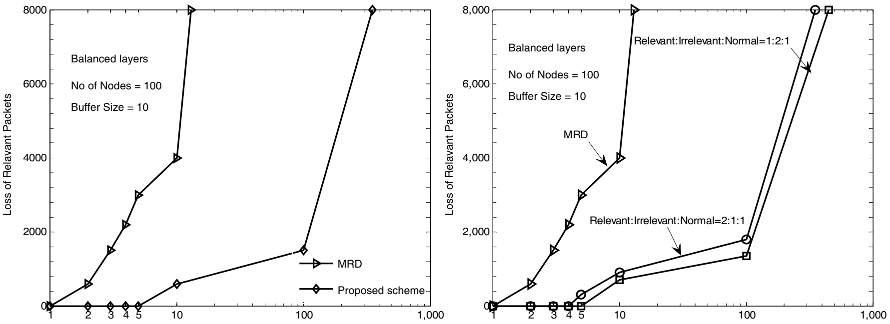
5.3. Simulation Results

In order to evaluate the performance of our proposed buffer management policy, we computed the packet loss with a period of 5 unit time under the proposed policy and compared our proposed buffer management scheme with MRD scheme. Performance parameters of interest are relevant packet loss, retransmission cost and overall power consumption. For the three layers' deployment, balanced layers and unbalanced layers are considered. In the balanced-layers case, the probabilities of the relevant, irrelevant and normal layers are assumed to be the same. While in the unbalanced-layers case, the probability ratio between the three layers is set to be 2:1:1 and 1:2:1 as two examples. In Fig. 9(a) and Fig. 9(b), the loss of relevant packets is plotted as a function of the number of network nodes for balanced layers and unbalanced layers respectively. The figures show that as the network node (N) increases, the loss of relevant packets increases in both the proposed scheme and the MRD scheme. However,the rate of increase in MRD is much greater than in our proposed scheme. Besides, it is also observed that the layers deployment is not effective to the MRD scheme. While for our proposed scheme, the loss of relevant packets will increase as the probability of relevant layer's packets increases.



(a) Balanced layers (b) Unbalanced layers

Figure 9. Loss of relevant packets vs. no. of nodes for 3-layer WSN type A.



(a) Balanced layers (b) Unbalanced layers

Figure 10. Loss of relevant packets vs. packet rate for 3-layer WSN type A.

We then plot the loss of relevant packets as a function of the source packet rate in Fig. 10. This measurement was done assuming 100 network nodes where each node has fixed buffer size of 10. From the results, we conclude that our proposed schemes were able to optimize the recovery cost since MRD has more loss of relevant packets in the network compared to our proposed scheme. When the source rate is less than 5, our scheme can guarantee not to drop any relevant packets, while MRD drops significant number of relevant packets.

There is no difference with the loss of relevant packets in both of our proposed schemes, Model-A and Model-B. Thus, in order to evaluate the performance of our proposed schemes, as in Fig. 11, we computed the total number of dropped packets in our schemes for the same scenario. We found that the total number of dropped packets is bigger in Model-B since Model-B never accepts the packets from different layers and therefore always drops packets originating from different layers.

In addition, it is also desirable to measure the delay of each model and compare the results. Fig. 12 shows the average delay as a function of time. As previously discussed, intermediate sensors need to keep the certain number of encoded packets before receiving the required number of packets to recover the original packets. The delay of Model-B is caused due to the lack of sufficient number of received packets from its neighbor nodes. The Model-A also sustains a delay although it is less than the Model-B since it can benefit by accepting all the packets from its communication range and acting as a relay node.

Thus, we can conclude here that Model-A is better for delay sensitive applications.

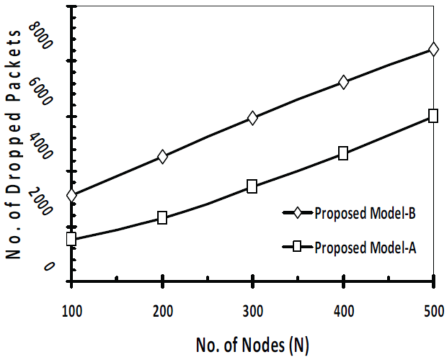


Figure 11. No. of dropped packets vs. no. of nodes.

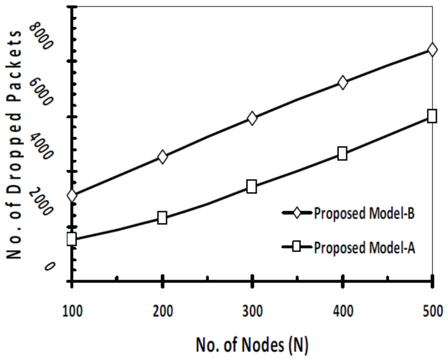


Figure 12. Average delay as a function of time.

6. CONCLUSION

In this paper, we proposed two types of multi-layer WSN with a power efficient buffer management policy to efficiently share the storage space in each sensor node. In our proposed scheme, the conventional one layer WSN is remodeled and the sensor nodes are layered according to the information and sensing environment. The buffer can then judge a data packet according to their layer information and make a decision to keep or drop the packet. In this way, the overall network throughput can be maximized while recovery cost of packet loss can be minimized. Compared to MRD, our proposed buffer management scheme has minimum number of dropped packets for the type of relevant packets. This is due to the fact that our multi-layer WSN topologies allow each sensor node to treat the different packet types in different manner. Our simulation showed that the proposed buffer management policy can ensure not to lose any relevant packet and thus it can outperform the MRD in terms of retransmission cost. As a main contribution of our paper, we showed that, significant power savings can be achieved by reducing the retransmission power for the loss of relevant packets.

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