Enforcing Fairness for Data Collection in Wireless Sensor Networks

Md. Abdul Hamid
Depatrtment of Information
& Communications Engineering,
Hankuk University of Foreign Studies,
Yongin, Gyeonggi, Korea, 449-791
E–mail: hamid@hufs.ac.kr

Muhammad Mahbub Alam, Md. Shariful Islam
and Choong Seon Hong
Networking Lab, Department of Computer Engineering
Kyung Hee University,
446-701, Korea
Email: {mahbub, sharif}@networking.khu.ac.kr, cshong@khu.ac.kr

***Abstract*—The well known many–to–one data routing paradigm [1] in wireless sensor networks (WSNs) demands non–uniform medium access and forwarding strategy to achieve the ultimate node level fairness. Since nodes closer to the sink have more traffic than that of far–away nodes, close–by nodes need to employ different frequency of media access and forwarding probability such that sink receives almost equal number of packets from all the nodes in the network. In this paper, we design a distributed fair data collection protocol where the nodes can decide their media access and packet forwarding strategies within the WSN such that a fair throughput can be enjoyed by each node irrespective of the node's distance from the sink. We demonstrate the effectiveness of our solution through simulations and results show that the proposed protocol ensures the fair delivery of packets, improves throughput and reduces end–to–end delay for the different WSN scenarios under study.**

***Index Terms*—Wireless Sensor Networks, Fair Data collection, Throughput and Delay, Protocol Design.**

I. Introduction

Wireless Sensor Networks (WSNs) are designed to enable a variety of applications including environmental monitoring, building and plant automation, homeland security, healthcare, etc [2]. Sensors are deployed over wide areas and transmit sensor data to one or more central nodes, called sinks or base stations. Due to the limited communication capability, the distance between a node and a sink may exceed the radio range. Therefore, relaying via intermediate nodes needs to be performed in order for the data to reach the sink. In a WSN, unlike traditional networks, the sensors themselves are the relaying devices, and are concurrently gathering and transmitting data [2]. The collection of sensor data from a field (or structure) is one of the predominant applications of sensor networks [3], [4], [5], [6], [7], [8]. For data–collection applications in sensor networks, it is important to ensure that all data sources have equal (or weighted) access to the network bandwidth so that the sink receives a complete picture about the monitored area. Certain applications of sensor networks (e.g., structural health monitoring) require that the information be collected from all the nodes, that the information not be aggregated, and that a minimum level of fidelity be maintained. In other words, the deployment space is considered to be equally important.

Due to the many–to–one nature of WSNs [1], it is well known that a sensor close to the sink tends to achieve a much higher throughput than a sensor that is far away from the sink. Given a WSN like that shown in Fig. 1, for example, if sensed data around the sink is not more important than the data far in the field, bias toward nearby sensors is undesirable. Ensuring fair access to the network bandwidth is critical to keeping the reporting channel open for distant sensors, so that the sink receives a complete view of the area being monitored. Fairness problems arise when nodes exercise improper media access techniques and/or forwarding strategies. Therefore, buffer overflow may happen frequently at nodes closer to the sink due to the non-uniform rates of packet arrival and departure. On the other hand, if all nodes are selfish and each node refuses to relay the other nodes' packets, the nodes farther away from the sink may suffer from starvation or an unacceptable end–to–end delay. To alleviate these problems, two inter–related issues need to be addressed: (i) an appropriate media access strategy needs to be implemented so that radio resources for nodes are allocated according to traffic loads, and (ii) a proper packet forwarding strategy must be developed in order to balance the selection of data packets to be transmitted, i.e., how many packets should be forwarded from local data vs. relayed traffic.

In this paper, our goal is to design a fair data collection protocol for wireless sensor networks. We consider a sensor network of stationary nodes, with each node conveying the gathered information to the sink node through multihop communications. We design a protocol in which a sensor node can choose its frequency of media access and appropriate packet forwarding strategy within the WSN such that a fair throughput can be enjoyed by each node irrespective of the node's distance from the sink. We evaluate the performance through simulation and results demonstrate that the proposed technique effectively improves fairness, throughput, and delay compared to the cases in which all nodes contend equally for the wireless media and do not employ a packet selection strategy.

The rest of the paper is organized as follows. Section II reviews related works. Section III describes the network model under study and sets forth the assumptions made while

978-0-7695-4041-2/10 $26.00 © 2010 IEEE
DOI 10.1109/CNSR.2010.36

constructing our fair data collection protocol. We present our protocol design in Section IV. Section V presents the results obtained from simulations. Finally, in Section VI we provide our conclusions and point out aspects that will be subject to future research.

II. Related Works

Tree–like sensor networks are studied in [9], where the authors present optimal strategies for data distribution and data collection, and analytically evaluate the time performance of their solution. [10] presents the first scaling laws on the worst-case capacity and on the price of worst–case node placement in sensor networks in the physical model. The results imply that if achieving a high data rate is a key concern, use of an involved power control mechanism at nodes is indispensable. In [11], the authors develop a Markov model of a sensor network in which the nodes may enter a sleep mode, and use this model to investigate system performance in terms of energy consumption, network capacity, and data delivery delay. Their analytical model specifically represents the sensor dynamics in sleep/active mode, while taking into account channel contention and routing issues. While many research results have been reported for the performance criteria (throughput, delay, energy consumption) of multihop wireless sensor networks, most of the efforts have been focused on the asymptotic case.

Many papers have studied MAC–layer fairness among one–hop flows within a neighborhood [12], [13], [14], [15], which is not directly applicable for multihop WSNs. In a WSN, data transmission is multihop in nature and it is completely different than single hop data transmission [1]. Recently there are several pioneering studies on congestion control in sensor networks [16], [17], [18]. However, these works either do not consider the fairness issue or have very restrictive assumptions on the routing structure, which limits their scope of applicability. In fact, no prior work provides a practical distributed solution to the fairness problem in a data–collection network where packets from a data source follow numerous different hops to the base stations. We have studied fairness among multiple hops of WSNs in which all nodes transmit data to a sink, and we have realized that nodes in the network should exercise two important aspects: appropriate media access and proper packet selection strategy. Combination of these two may achieve the ultimate node level fairness. Then, we have developed a fair data collection protocol to achieve the ultimate node level fairness in which our goal is to ensure that all the nodes in the network can have almost equal throughput.

III. Network Model And Assumptions

We consider a network composed of N stationary, identical sensor nodes, with each node uniquely identified by an integer in the range 1 to N. Each sensor node has an infinite amount of data to send to a single sink, i.e., each node always has data packets available for transmission. This data can traverse multiple hops before reaching the sink. Thus, each sensor node originates traffic and may forward traffic sent by other nodes.

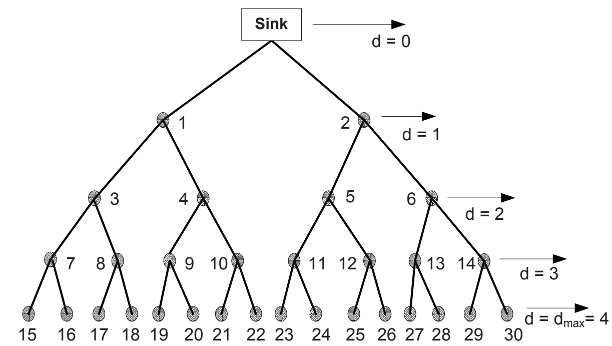

Fig. 1. Network model: a tree topology based wireless sensor network that constitutes a many–to–one data collection paradigm.

We also assume that the sensor nodes run a routing protocol that builds a tree to the sink. An example of this network topology is shown in Fig. 1 in the case of $N = 30$, in which the solid lines depict such a tree. The depth of the tree is denoted by d and $d = 0, 1, \ldots, d_{max}$, where d_{max} is the maximum depth of the tree (d_{max} specifies the maximum number of logical hops for a message from a node to reach the sink). We use $s(d)$ to denote a sensor node located at depth d in the tree, and $N_C(d)$ to denote the number of child nodes of $s(d)$. The sink is considered to be in a depth equal to zero.

We assume that the sensor nodes employ IEEE 802.11 DCF MAC [19] based on CSMA/CA to access the wireless medium. We assume that all nodes have a common radio range and are equipped with omnidirectional antennas. We also assume that only neighboring nodes are interfering nodes, and thus, nodes outside the transmission range do not interfere.

Each node is associated with two queues at the network layer: one for its local data, denoted by q_L, and the other for relayed traffic, denoted by q_R. Each time a node gets a chance to access the media, the node forwards (transmits) one packet from one of the two queues according to a probabilistic forwarding strategy. That is, a node at depth d forwards a relayed packet to the next hop with a forwarding probability of $f(d)$ or sends a locally generated packet with a probability of $1-f(d)$. When one queue is empty, it will forward a packet from the other queue with a probability of one. The wireless channel is assumed to be error–free, although our model could be easily extended to represent a channel error process.

IV. Proposed Protocol: Provisioning Fairness

A. Protocol Overview

As stated earlier, our goal is to provide fair delivery of packets by each node, i.e., the sink should receive an approximately equal number of locally generated packets from each node. Each node contends for access to the wireless medium to transmit data. Our problem is to determine the frequency of media access and appropriate packet forwarding strategy for each node within the WSN such that a fair throughput can be enjoyed by each node irrespective of the node's distance from the sink.

In contention–based medium access protocols that use 802.11 DCF (Distributed Coordination Function) [19] based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), the frequency of media access for nodes is determined by the minimum contention window CW_{min}. At a given node for its first transmission, a packet is transmitted after waiting the number of slots randomly selected from $\{0, 1, \ldots, CW_{min} - 1\}$, where CW_{min} is an integer representing the minimum contention window size. Every time a node's packet is involved in a collision, the contention window size for that node is doubled, up to a maximum value CW_{max}. In 801.11 DCF with CSMA/CA, this operation is equivalent to randomly selecting a number from the range $[0, 2^i CW_{min} - 1]$ with equal probability $1/2^i CW_{min}$, where i represents the number of transmission attempts. To achieve fairness for the many–to–one traffic pattern in a WSN, the CW_{min} can be adjusted such that nodes with different loads may have different frequencies of media access. However, resolving the required frequency of media access does not guarantee fairness. Since a node has to transmit transit traffic as well as its own data in addition to contending with other nodes for the same destination (i.e., the sink), there is inevitable contention between its own and transit traffic. Note that this type of contention is not prevalent in wireless LANs in infrastructure mode in which the nodes are always at a one–hop distance from the access point. Therefore, along with the modified frequency of media access, a balance should be maintained by each node between forwarding its own data and transmitting transit traffic.

Consider Fig. 1, packets at node $s(d_{max})$ should be treated as fairly by the node $s(d_{max} - 1)$ as the local packets of the node $s(d_{max} - 1)$, so that $s(d_{max})$ has the same throughput as the node $s(d_{max} - 1)$. Since the number of child nodes for which $s(d_{max} - 1)$ has to relay packets is $N_C(d_{max} - 1)$, to provide a fair throughput to nodes $s(d_{max})$ and $s(d_{max} - 1)$, the output rate of packets from queue q_R at $s(d_{max} - 1)$ must be $N_C(d_{max} - 1)$ times the output rate of packets from queue q_L at $s(d_{max})$. Similarly, packets of the nodes at depths d_{max} and $d_{max} - 1$ should be treated as fairly by the nodes at depth $d_{max} - 2$ as the local packets of nodes at $d_{max} - 2$ and so on. Therefore, nodes closer to the sink need more frequent access to the media and higher forwarding probability compared to the nodes that are farther away from the sink. With these observations, we design the protocol in which a node can determine its required frequency of media access and forwarding probability such that each node may achieve a fair share of wireless medium (i.e., fair throughput) irrespective of the node's distance from the sink.

Our design consists of four components: (i) queue management: since each node (except the leaf node(s)) transmits two types of traffic (i.e., locally generated traffic and relayed traffic), each node maintains separate queues for storing local and relayed packets, (ii) determining tree–size: since each node (except the leaf node(s)) forwards traffic of other nodes, it needs to determine the number of nodes for which it relays the packets, (iii) determining the minimum contention window size: depending on the traffic intensity, each node needs to determine the required frequency of media access, and (iv) determining the forwarding probability: each node (except the leaf node(s)) needs to determine the required packet selection probability that tells exactly how many packets should be forwarded from the local queue and the relayed queue to the next hop node. We describe each of the components in detail in the following section.

B. Protocol Detail

In what follows, we present the detailed design of the proposed protocol for fairness to be achieved by the nodes in the network. We describe our protocol based on the network topology shown in Fig. 1.

1) Queue management: In every node, the queues q_R and q_L at the network layer are created for storing the relayed and generated packets, respectively. A field in each packet header holds the identifier of the source node that generates the packet. Each node inserts the generated packets into q_L and the relayed packets (received from its child) into q_R. In this paper, we implement First–In First–Out ((FIFO) queues. However, it can be adjusted if the proportional delay needs to be addressed.

2) Determining tree size: Each node $s(d)$ obtains its tree size $W(d)$, the number of nodes for which it relays the packets, in the following manner. The tree size of the transmitting node is stored in the packet header for that node. Upon receiving a packet from a child node, the parent node retrieves and stores the tree recorded in the packet header of the child node. The parent node then stores the sum of all child nodes' tree sizes, and adds the number of child nodes $N_C(d)$ to the sum. Referring to Fig. 1, sensor nodes 15 and 16 will record tree sizes of 0 in the packets they transmit. Node 7 stores these sizes, and when it transmits packets to Node 3, it records 0 + 0 + 2 = 2 in the packet header. Similarly, when Node 8 transmits packets to Node 3, it records 2 in the packet header. Then, Node 3 records its tree size as 2 + 2 + 2 = 6. In the similar manner, Node 4 records its tree size as 2 + 2 + 2 = 6. Finally, Node 1 records its tree size as 6 + 6 + 2 = 14. So, storing the tree sizes in the data packet headers allows the network to easily determine those tree sizes. Also, the network can dynamically adjust itself depending on topological changes, including the addition of new nodes, the dying of old ones, or the mobility of current nodes. In this paper, we do not consider the effects of topology changes in the network.

3) Determining the minimum contention window size: Intuitively, to provide fairness to all nodes in the network, a node closer to the sink should have a higher probability of successful media access because it experiences a heavier amount of transit traffic. As stated earlier, in a contention–based media access mechanism, such as IEEE 802.11 DCF, a node gets higher access to the wireless media if its minimum contention window size CW_{min} is smaller than that of the other contending node(s). Since the number of medium access of a node is approximately inversely proportional to its CW_{min} value, i.e., the higher the probability of a node's successfully accessing the media, the lower the CW_{min} value. This is used to guide the direction of CW_{min} adjustment for each of the nodes in the network. Let $CW_{min}(d)$ and $CW_{min}(d+1)$ denote the minimum contention window sizes for nodes at depths d and $d+1$, respectively. The ratio of the minimum contention window for nodes $s(d)$ and $s(d+1)$ is then set according to

$$\frac{CW_{min}(d+1)}{CW_{min}(d)} \approx N_C(d)(1+\frac{1}{W(d)}), \quad d = 1, 2, \ldots, d_{max}-1, \tag{1}$$

where $N_C(d)$ is the number of child nodes of $s(d)$, and $W(d)$ is the number of nodes (i.e., the tree size) for which $s(d)$ relays packets. Knowing the $CW_{min}(d)$ of $s(d)$, node $s(d+1)$ can set its $CW_{min}(d+1)$ using Eq. 1.

We need to know the CW_{min} for the nodes at depth 1 so that other nodes can determine their respective CW_{min} values. To determine the CW_{min} of a node at depth 1, we use the concept presented in [20]. With a fixed number of contending nodes n, each of which always has packets available for transmission, the maximum throughput can be expressed as a function of the probability p_s that a node successfully accesses the media and transmits a packet. According to [20] p_s can be given by

$$p_s = \frac{2(1-2p_c)}{(1-2p_c)(CW_{min}+1)+p_c CW_{min}(1-(2p_c)^m)}, \tag{2}$$

where p_c is the collision probability and m is the retransmit limit. To find the value of p_c, it is sufficient to note that the probability p_c that a transmitted packet experiences a collision, is the probability that at least one of the $n-1$ remaining nodes transmits at the same time. Since at steady state, each remaining node transmits a packet with probability p_c, according to [20], p_c is given by

$$p_c = 1-(1-p_s)^{n-1}. \tag{3}$$

Equations 2 and 3 represent a nonlinear system in the two unknowns p_s and p_c, which can be solved using numerical techniques. Using 2 and 3, we find the CW_{min} value of the one hop node(s) (i.e., nodes 1 and 2) as follows. In Fig. 1, the number of contending nodes n is equal to 6 (i.e., nodes 1 to 6). In other words, only one node out of 6 can transmit at a given time (assuming that only neighboring nodes are interfering nodes). Keeping p_c at approximately 22%, with $m = 4$, we get $p_s = 0.057$ with $CW_{min} = 24$. We use this value for the nodes at depth 1 and according to Eq. 1, the CW_{min} values are calculated for the other nodes at different depths using the topology in Fig. 1 (Table 1). In a similar manner, we get $p_s = 0.0456$ with $CW_{min} = 32$ for the nodes at depth 1.

TABLE I
$CW_{min}(d)$ AND $f(d)$ USED IN THE SIMULATION (SCENARIO 1). VALUES ARE CALCULATED BASED ON THE TOPOLOGY GIVEN IN FIG. 1

		Proposed		Equal for all nodes	
Depth	Node ID	CW_{min}	f	CW_{min}	f
1	1–2	24	0.958	32	0.75
2	3–6	51	0.882	32	0.75
3	7–14	119	0.691	32	0.75
4	15–30	358	0.0	32	0.0

4) Obtaining the forwarding probability $f(d)$: Recall that each node maintains two queues; q_L for the locally generated traffic, and q_R for transit traffic. Each node can determine its $f(d)$ value according to Eq. 4 after obtaining $W(d)$ as described in Section III-B.2.

$$f(d) = 1 - \frac{1}{1+W(d)}. \tag{4}$$

Choosing the value of $f(d)$ using Eq. 4 ensures that the packets from all nodes have equal probability of being transmitted. For example, consider a node at depth 1 such as, Node 1. There are 14 nodes for which Node 1 has to forward transit traffic. So, including Node 1, there are 15 nodes, and the probability that packets from each child and Node 1 itself will be transmitted from Node 1 is $1/15$, i.e., $1/(1+W(d))$. Therefore, the probability that Node 1 will select a packet from q_R is $1-1/(1+W(d))$. Using the topology given in Fig. 1, the calculated values of $f(d)$ are shown in Table 1.

V. PERFORMANCE EVALUATION

In this section, we evaluate our scheme through extensive simulation using ns–2 [21]. Note that the RTS/CTS/DATA/ACK structure in 802.11 DCF [19] is used by the nodes to contend for the medium. Although these control packets can collide and some non–colliding transmissions may be stopped, the RTS/CTS exchange eliminates most data packet collisions. The added cost of the RTS/CTS exchange is worthwhile when the data packets are substantially larger than the control packets. However, in sensor networks, data packets are usually small [22], and on some platforms the RTS/CTS exchange would incur a 40% overhead [23]. Consequently, we will use only DATA/ACK in our simulation. Furthermore as stated earlier, we assume that only neighboring nodes are interfering nodes, and thus, nodes outside the transmission range do not interfere. Though this is a simple assumption, it is sufficient for us to assess our protocol.

We consider two scenarios in the simulation. In the first scenario, we use the network topology shown in Fig. 1 (the total number of nodes in the network to be 30 and a single sink). In the second scenario, we have simulated the proposed mechanism in a network of 80 nodes and a sink, where nodes are distributed with uniform random distribution. We measure the throughput of individual nodes and source–to–sink delay experienced by data packets in the network. The performance of the proposed protocol is compared with the cases when

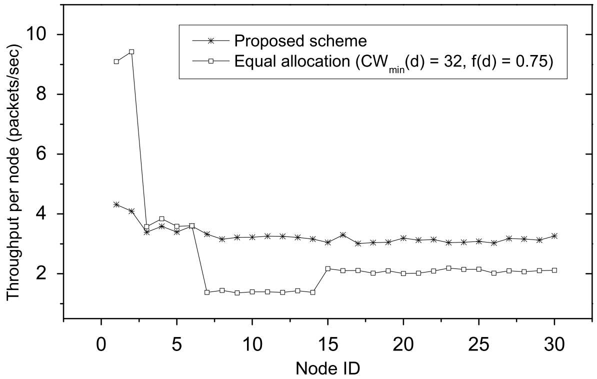

Fig. 2. Throughput for individual nodes in the network.

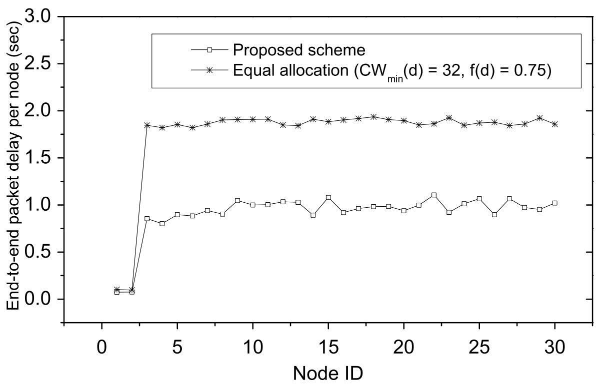

Fig. 3. Source–to–sink delay experienced by packets of nodes in the network.

all the nodes share the same access probability, (i.e., same minimum contention window size) and forwarding probability. We ran our simulation for 100 seconds, and the results are averaged over 10 runs.

A. Scenario 1

In this scenario, our simulation is performed with 30 sensor nodes and a single sink, with a maximum network depth of 4 as depicted in Fig. 1. We consider the channel bandwidth to be 256 Kbps, each data packet to be 36 bytes, and the control packet ACK to be 4 bytes. When a node gets access to the media, it transmits one packet. For each sensor, q_L and q_R are set to hold a maximum of 12 and 56 packets, respectively. We measure the throughput and delay of individual nodes without considering the control packets. Only data packets that are received by the sink are recorded for the calculations. As mentioned earlier, results are obtained for two cases: first, the minimum contention window size $CW_{min}(d)$ and the forwarding probability $f(d)$ values are set according to the proposed protocol, and secondly, these values are set equal for all nodes (i.e., when nodes employ no media access and forwarding strategies), as shown in Table 1.

Figure 2 presents the throughput of the individual nodes in the network. The results of the proposed protocol are justified as can be observed from Fig. 2, i.e., all nodes in the network enjoy almost equal throughput. However, when all the nodes use equal media access (and equal contention window) and forwarding probabilities, the throughputs of individual nodes are reduced quickly as the depth of the tree increases. Furthermore, we can see that nodes at depth 4 (sensors 15 to 30) have a higher throughput than the nodes at depth 3. The reason behind this is that nodes closer to the sink may be busy forwarding packets of other nodes and consequently, they get less opportunity to transmit their locally generated packets. With the proposed protocol, the throughputs are almost equal for all the nodes, so the nodes need to exercise modified media access and packet selection techniques to achieve fair throughput. Also, the proposed protocol has more than 26% performance improvement compared to the approach in which all nodes use equal media access (i.e., equal CW_{min}) and employ no packet forwarding strategy (i.e., equal $f(d)$).

Figure 3 presents the source to sink (i.e., end–to–end) delay of packets for all nodes. The proposed protocol has much less delay compared with the settings using a common media access and packet forwarding strategy. The average packet delay for the proposed protocol is reduced by more than 48% compared with the protocol using equal CW_{min} and $f(d)$ for all nodes.

B. Scenario 2

In this scenario, we have simulated the proposed mechanism in a network of 80 nodes and a single sink as shown in Fig. 4. The nodes are placed in a square area with uniform random distribution. We have used the Ad hoc On–Demand Distance Vector (AODV) routing protocol [24], where each node creates a path to the sink. The paths created by the nodes ultimately become a tree rooted at the sink. Due to changes in wireless link quality over time, the routing tree changes. Therefore, we have modified the AODV routing protocol to terminate the route computation after an initial, reasonable tree is found. Then, we ran the simulation for the proposed mechanism as well as the simulations for two cases when the channel access and forwarding probability are equal for all nodes in the network. Like scenario 1, we have considered same channel bandwidth, packet size and the control packet.

Figure 5 presents the throughput of the individual nodes in the network. The simulation results of the proposed protocol depicted in Fig. 5 show that all nodes in the network enjoy almost equal throughput. However, when all the nodes use equal media access (i.e., equal contention window) and forwarding probability, the throughputs of individual nodes are reduced quickly. Furthermore, when the forwarding probability is increased, individual throughput of each node decreased. This is because most of the time nodes are busy transmitting transit traffic. The proposed protocol has around 32% and 41.6% average throughput improvement compared to the cases when all nodes have equal media access and forwarding probability.

Figure 6 presents the source to sink (i.e., end–to–end) delay of packets for all nodes. The proposed protocol has much less delay than when there are equal media access and forwarding

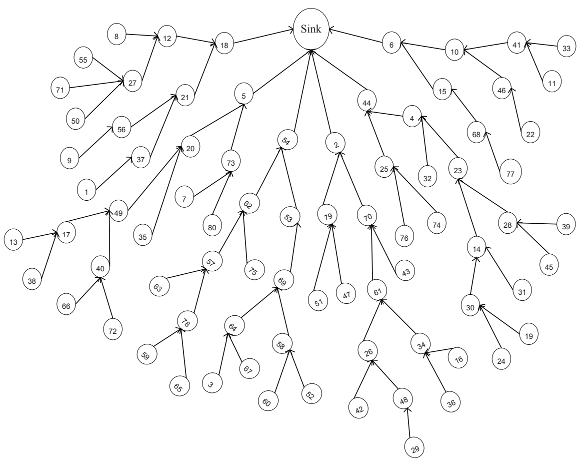

Fig. 4. A snapshot of routing topology used in the simulation (for Scenario 2).

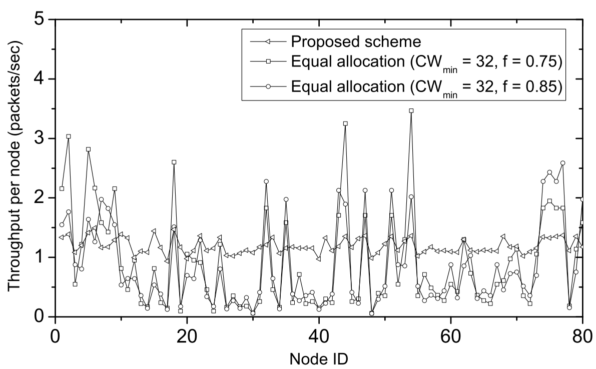

Fig. 5. Throughput for individual nodes in the network.

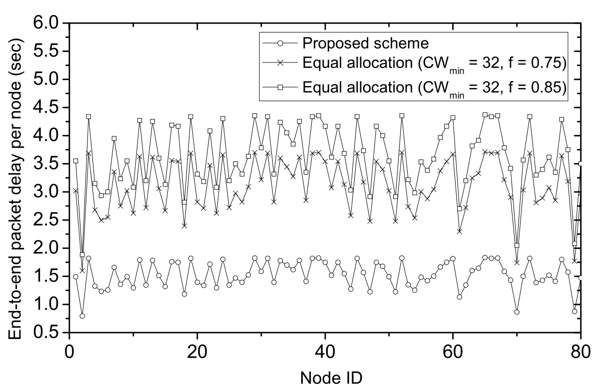

Fig. 6. Source–to–sink delay experienced by packets of nodes in the network.

probabilities. Furthermore, when the forwarding probability is increased, delay is also increased since nodes are busy forwarding transit traffic. Our strategy adjusts the successful channel access and forwarding probability according to the expected load of the node such that the service and arrival rates of packets for each node can be balanced. The average packet delay for the proposed protocol is reduced by more than 50% and 58% compared with the cases when nodes employ no media access and packet forwarding strategy.

VI. Conclusion

In this paper, we have presented a fair data collection protocol for the many–to–one communication architecture of wireless sensor networks. We have considered a sensor network in which the nodes send their data to a sink node using multihop transmissions. We have designed the protocol to address the non–uniform traffic flow behavior for different nodes in the network, and shown that unless a sensor network, operating under load, has some means of controlling frequency of media access and packet forwarding strategy, it will face significant degradation in efficiency and fairness. We have also shown that throughput and delay can be improved significantly with our design. Finally, the network model could be easily modified to take into account some aspects that have not been addressed in this work and that can be interesting subjects for future research. For instance, a model of the error process over the wireless channel and multipath data forwarding would be good subject for further research.

Acknowledgment

This work was supported by the IT R&D program of MKE/KEIT [2009-S-014-01, On the development of Sensing based Emotive Service Mobile Handheld Devices]. Dr. CS Hong is the corresponding author.

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