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Fair data collection in wireless sensor networks: analysis and protocol

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Abstract In general, wireless sensor networks (WSNs) consist of many sensors which transmit data to a central node, called the sink, possibly over multiple hops. This many-to-one data routing paradigm leads to nonuniform traffic distribution for the different sensors (e.g., nodes closer to the sink transfer more traffic than those farther away). In this paper, we perform an analysis of the fairness issue by presenting a tree-based WSN and derive the throughput, delay, and energy distribution for each sensor under the fairness constraint. Based on the analysis, we design our fair data collection protocol in which each node decides its media access and packet forwarding strategies in a distributed manner. Finally, we demonstrate the effectiveness of our solution through simulations. The results for the proposed protocol show the accuracy of the analysis and show that the protocol ensures the fair delivery of packets and reduces end-to-end delay. Based on the analysis, we also quantitatively determine the energy required for each of the nodes and show that a nonuniform energy distribution can maximize the network lifetime for the WSN scenario under study.

Keywords Wireless sensor networks · Fair data collection · Source-to-sink delay · Network energy distribution · Analysis and protocol design

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1 Introduction

Wireless sensor networks (WSNs) are designed to enable a variety of applications including environmental monitoring, building and plant automation, homeland security, healthcare, etc. [1]. 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 [1]. The collection of sensor data from a field (or structure) is one of the predominant applications of sensor networks [2–7]. 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 [8], 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 are 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 nonuniform 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. Another important issue is the unbalanced energy consumption among the nodes in the network. Since the nodes closer to the sink have to forward more transit traffic, providing equal energy to all nodes poses a severe network lifetime problem. To alleviate these problems, three interrelated issues need to be addressed: (a) an appropriate media access strategy needs to be implemented so that radio resources for nodes are allocated according to traffic loads, (b) 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, and (c) an energy distribution strategy should be developed to maximize the network lifetime such that all nodes in the network have almost equal lifetimes, i.e., all nodes run out of their allocated energy at the same time.

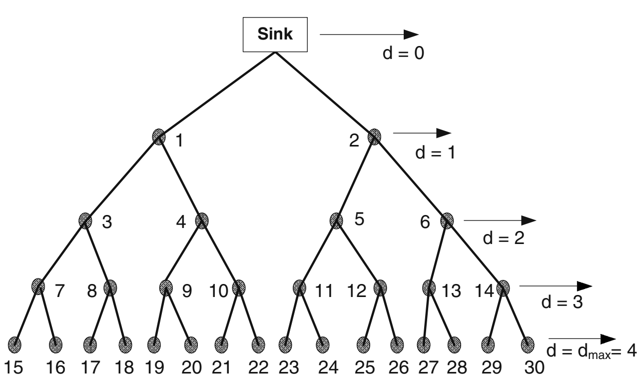

Fig. 1 Network model: a tree topology-based WSN that constitutes many-to-one data collection paradigm

In contention-based medium access protocols that use 802.11 distributed coordination function (DCF) [9] based on carrier sense multiple access with collision avoidance (CSMA/CA), 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. Regarding the network lifetime, intuitively far-away nodes require less energy due to their lower traffic levels than the nodes closer to the sink. As stated earlier, providing equal energy to all nodes may lead to network failure since the nodes with more traffic will consume their energy much earlier, thereby reducing the overall network lifetime. Thus, due to the nonuniform traffic pattern, a nonuniform energy distribution policy is required to maximize the network lifetime.

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. Motivated by the work presented in [10], we develop an analytical model which enables us to explore the arrival and service rates of packets for different nodes in the network and to derive the required frequency of media access and the packet selection strategy necessary to provide fairness to all nodes. We then investigate the throughput, delay, and energy distribution policy for each of the nodes with the fairness constraint. Based on the analysis, we design a protocol in which a sensor node can choose its minimum contention window CW_{min} and packet selection strategy in a distributed manner. We evaluate the performance through simulation and compare those results with the analytical results. The results show that the proposed design performs in concert with the analytical one, i.e., it provides equal throughput for all the sensors. The simulation results also demonstrate that the proposed technique effectively improves fairness, throughput, and delay compared to the case in which all nodes contend equally for the wireless media (i.e., all nodes have equal CW_{min}) and do not employ a packet selection strategy. We also quantitatively show the energy allocation to different nodes based on the analysis and show that nodes at different locations have different energy requirements to maximize the network lifetime.

The rest of the paper is organized as follows: Section 2 describes the network model under study and sets forth the assumptions made while constructing our analytical model. The analysis is presented in Section 3, and based on this analysis, we present our protocol design in Section 4. Section 5 presents the results obtained by solving the analytical model and compares them to the simulation results. Section 6 reviews related works, and in Section 7, we provide our conclusions and point out aspects that will be subject to future research.

2 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. 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. The sink is considered to be in a depth equal to zero.

We assume that the sensor nodes employ IEEE 802.11 DCF MAC [9] 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 and the other for relayed traffic. 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.

3 Fairness analysis

In this section, we present the approach to analyze the behavior of a sensor network that constitutes a many-to-one data collection paradigm. 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. Let $p(d)$ denote the successful channel-access probability of a sensor $s(d)$ at depth d. Let t_s denote the airtime occupied by the node $s(d)$ after successfully gaining access to the media. Our problem is to determine the values of $p(d)$ and $f(d)$ 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. To analyze the fairness problem, we first investigate the service and arrival rates of packets for the queues of a node. We then determine the throughput, source to sink packet delay, and the energy distribution policy using the fairness constraint.

3.1 Service rate of packets

As stated earlier, each sensor transmits it own data as well as transit traffic from other sensors. Let q_R denote the queue for relayed traffic, and let q_L denote the queue for locally generated traffic. Let $T(d)$ denote the interarrival time of successfully accessing the media for the sensor node $s(d)$. Since within one time duration t_s, the probability of node $s(d)$ being granted access to the media is equal to $p(d)$, the probability that the node $s(d)$ does not successfully access the media for n time durations is given by

$$P[T(d) > nt_s] = (1 - p(d))^n. \tag{1}$$

By replacing with nt_s, we can rewrite Eq. 1 as

$$P[T(d) > t] = (1 - p(d))^{t/t_s}. \tag{2}$$

Since binomial probabilities can be approximated by Poisson probabilities using the appropriate parameters [11], we approximate the arrival process of successful media access as a Poisson process. In other words, we approximate the interarrival time $T(d)$ as an exponential random variable with a mean $1/\mu(d)$. Thus, we have

$$P[T(d) > t] = (1 - p(d))^{t/t_s} \approx \exp^{-\mu(d)t} \tag{3}$$
$$\Rightarrow\approx \frac{1}{t_s}\ln(\frac{1}{1-p(d)}).$$

where $\mu(d)$ represents the arrival rate of successful media access for the node $s(d)$ and is equivalent to the service rate of packets for $s(d)$. For q_R and q_L at the node $s(d)$, the service rate of packets for either queue is equal to the product of $\mu(d)$ and the probability that the queue is selected to send. Thus, the service rate, denoted by $\mu_R(d)$, of packets for q_R at $s(d)$ is given by

$$\mu_R(d) = \mu(d) f(d). \tag{4}$$

Since a node $s(d)$ transmits a packet from q_R only when q_R is not empty, the effective output rate, $\sigma_R(d)$, of packets from q_R is equal to the service rate multiplied by the probability of q_R being nonempty, i.e.,

$$\sigma_R(d) = \mu_R(d)(1 - P_e(d)), \tag{5}$$

where $P_e(d)$ denotes the probability of q_R being empty at $s(d)$. We will derive $P_e(d)$ in Section 3.2. When q_R is empty, $s(d)$ always transmits packets from q_L, so the service rate, $\mu_L(d)$, of packets from q_L at $s(d)$ is:

$$\mu_L(d) = \mu(d) - \sigma_R(d) = \mu(d) - \mu(d) f(d)(1 - P_e(d)). \tag{6}$$

Since, q_L for each node is assumed to be backlogged, the distribution of the time interval between two successive departures of packets from q_L is identical to the service time distribution of q_L. In other words, the effective output rate, $\sigma_L(d)$, of packets from q_L at $s(d)$ is equal to its service rate. Thus, we have

$$\sigma_L(d) = \mu_L(d). \tag{7}$$

From Eqs. 5 to 7, we obtain the aggregate effective output rate, $\sigma(d)$, for $s(d)$ as

$$\sigma(d) = \sigma_L(d) + \sigma_R(d) = \mu(d). \tag{8}$$

Equation 8 states that the effective output rate of $s(d)$ is equal to the arrival rate of the successful media access for this node. Therefore, the more a node gains access to the media, the higher its effective output rate becomes.

3.2 Arrival rate of packets

To analyze the behavior of the queues, we need to know the packet arrival rates for the queues. Since q_L is assumed to always be backlogged, we only need to determine the packet arrival rates for q_R at $s(d)$. Let $\lambda_R(d)$ denote the packet arrival rate for q_R at $s(d)$. In the context of the many-to-one data routing paradigm for WSNs, the total departures of packets from node $s(d+1)$ must be equal to the total arrival of packets to the q_R of $s(d)$. Therefore, $\lambda_R(d)$ can be given by

$$\lambda_R(d) = N_c(d)\sigma(d+1), \tag{9}$$

where $N_c(d)$ is the number of child nodes of $s(d)$. Substituting Eq. 8 into Eq. 9, we obtain

$$\lambda_R(d) = N_c(d)\mu(d+1), d = 1, 2, \ldots, d_{\max} - 1. \tag{10}$$

Since the node $s(d_{\max})$ is located at the edge of the network, the incoming rates of the transit packets are zero at this node, and therefore,

$$.\lambda_R(d_{\max}) = 0 \tag{11}$$

Summarizing Eqs. 10 and 11, we have

$$\lambda_R(d) = \begin{cases} N_c(d)\mu(d+1), & d = 1, 2, \ldots, d_{\max} - 1 \\ 0, & d = d_{\max} \end{cases}. \tag{12}$$

Since the distribution of the interarrival time of successful media access for $s(d)$ is exponential with a mean $1/\mu(d)$, the distribution of the time between two successive departures of packets from node $s(d)$ to the next node $s(d-1)$ is also exponential with a mean $1/\mu(d)$, which is equal to $1/\sigma(d)$ according to Eq. 8. Since the superposition of independent Poisson processes is still a Poisson process, the transit packets arriving at $s(d-1)$ obey a Poisson process with a mean given by Eq. 12. Therefore, the service and interarrival time distributions of packets for q_R at $s(d)$ are both exponential. Thus, q_R at node $s(d)$ can be analyzed as an $M/M/1/K$ queuing model [11], where K is the buffer size of q_R. Note that $P_e(d)$ denotes the probability of q_R

being empty at $s(d)$. With the service and arrival rates of packets for q_R at $s(d)$, we can get $P_e(d)$ by applying the $M/M/1/K$ queuing theory [11]. For $d = 1, 2, \ldots, d_{\max}$, we have

$$P_e(d) = \begin{cases} \frac{1-\rho(d)}{1-\rho(d)^{K+1}}, & \rho(d) \neq 1 \\ \frac{1}{K+1}, & \rho(d) = 1 \end{cases}, \tag{13}$$

where $\rho(d)$ is the traffic intensity for q_R at node $s(d)$, which is defined by

$$\rho(d) = \frac{\lambda_R(d)}{\mu_R(d)} = \begin{cases} \frac{N_c(d)(\mu(d+1))}{\mu(d) f(d)}, & d = 1, 2, \ldots, d_{\max}-1 \\ 0, & d = d_{\max} \end{cases}. \tag{14}$$

Note that traffic intensity at node $s(d_{\max})$ is zero since this node does not have any transit traffic, as shown in Eq. 14.

3.3 Achieving fairness

In this section, we derive the values of $p(d)$ and $f(d)$ for each node within the WSN such that a fair throughput can be experienced by all nodes. Based on the analysis of the service and arrival rate, we derive the condition under which the packets at node $s(d_{\max})$ are 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 effective output rate of q_R at $s(d_{\max} - 1)$ must be $N_C(d_{\max} - 1)$ times the effective output rate of q_L at $s(d_{\max})$. Therefore,

$$\sigma_R(d_{\max} - 1) = N_C(d_{\max} - 1)\sigma_L(d_{\max} - 1). \tag{15}$$

Since the number of child nodes, $N_C(d_{\max})$, for the nodes at $d_{\max}$ is zero, we can rewrite Eq. 15 as

$$\sigma_R(d_{\max} - 1) = (N_C(d_{\max} - 1) + N_C(d_{\max} - 1) N_C(d_{\max})) \times \sigma_L(d_{\max} - 1). \tag{16}$$

Similarly, packets of the nodes at depths $d_{\max}$ and $d_{\max} - 1$ are treated as fairly by the nodes at depth $d_{\max} - 2$ as the local packets of nodes at $d_{\max} - 2$. Therefore, the departure rate of packets coming from nodes at $d_{\max} - 1$ is equal to the departure rate of the nodes' own packets at $d_{\max} - 2$. Since the number of child nodes at depth $d_{\max} - 1$ for which the nodes at $d_{\max} - 2$ have to relay is $N_C(d_{\max} - 2)$, the total number of nodes for which the node at $d_{\max} - 2$ has to relay includes the nodes at $d_{\max}$ and $d_{\max} - 1$ and can be given by $N_C(d_{\max} - 2) + N_C(d_{\max} - 2)N_C(d_{\max} - 1)$, where $N_C(d_{\max} - 2)N_C(d_{\max} - 1)$ represents the number of nodes at $d_{\max}$ for which the node at $d_{\max} - 2$ has to relay (via the nodes' relaying at $d_{\max} - 1$). Consequently, the ratio of the effective output rate of q_L to that of q_R for the node at $d_{\max} - 2$ should satisfy the following

$$\sigma_R(d_{\max} - 2) = (N_C(d_{\max} - 2) + N_C(d_{\max} - 2)N_C(d_{\max} - 1)) \times \sigma_L(d_{\max} - 2) \tag{17}$$

Rewriting Eq. 17, we get

$$\sigma_R(d_{\max} - 2) = (N_C(d_{\max} - 2) + N_C(d_{\max} - 2) N_C(d_{\max} - 1) + N_C(d_{\max} - 2)N_C(d_{\max} - 1) N_C(d_{\max})) \times \sigma_L(d_{\max} - 2). \tag{18}$$

In general, we can derive the fairness condition under which an equal throughput is provided to all nodes in the network as follows

$$\sigma_R(d) = \sigma_L(d)W(d), \quad d = 1, 2, \ldots, d_{\max} - 1, \tag{19}$$

where $W(d)$ is the tree size of the node $s(d)$ (i.e., the total number of nodes for which $s(d)$ has to relay packets) and is given by Eq. 20

$$W(d) = \sum_{j=d}^{j=d_{\max}} \sum_{k=d}^{k=j} N_C(j), \quad d = 1, 2, \ldots, d_{\max} - 1. \tag{20}$$

By substituting Eqs. 5 and 7 into Eq. 19, we obtain

$$\mu(d) f(d)(1 - P_e(d)) = W(d)[\mu(d) - \mu(d) f(d)(1 - P_e(d)). \tag{21}$$

When $\rho(d) < 1$ and K (i.e., the buffer size of q_R) is large enough, we use Eq. 13 to derive the following approximation:

$$P_e(d) \approx 1 - \rho(d). \tag{22}$$

Substituting Eqs. 14 and 22 into Eq. 21, we get

$$N_C(d)\mu(d + 1) = W(d)[\mu(d) - N_C(d)\mu(d + 1)], \tag{23}$$

and by rearranging Eq. 23, we get

$$\frac{\mu(d)}{\mu(d + 1)} = N_C(d)(1 + \frac{1}{W(d)}). \tag{24}$$

Substituting Eq. 3 into Eq. 24, we obtain

$$\frac{ln(1 - p(d))}{ln(1 - p(d + 1))} = N_C(d)(1 + \frac{1}{W(d)}). \tag{25}$$

When the successful media access probability $p(d)$ is a small number, we have $ln(1 - p(d)) \approx -p(d)$. Thus, we can rewrite Eq. 25 as

$$\frac{p(d)}{p(d+1)} = N_C(d)\left(1 + \frac{1}{W(d)}\right), \quad d = 1, 2, \ldots, d_{\max} - 1. \tag{26}$$

Equation 26 shows that if the ratio of the successful media access probabilities is carefully controlled, it is possible to provide a fair throughput to the nodes despite their distances from the sink.

Now, along with the media access probability $p(d)$, each node needs to choose the appropriate forwarding probability $f(d)$ to ensure that Eq. 26 can used to provide fair throughput to all nodes. We derive Eq. 22 based on the assumption that the traffic intensity for each node is less than one, i.e.,

$$\rho(d) < 1. \tag{27}$$

The condition in Eq. 27 is desirable because when the traffic intensity for each node is larger than or equal to one, many packets may be blocked, leading to a waste of radio resource and poor system throughput. We derive the circumstances under which the condition in Eq. 27 is valid. Based on Eq. 14, we rewrite Eq. 27 as

$$\frac{N_C(d)(\mu(d+1))}{\mu(d) f(d)} < 1, \tag{28}$$

and accordingly, we have

$$f(d) > \frac{N_C(d)(\mu(d+1))}{\mu(d)} \approx \frac{N_C(d)(p(d+1))}{p(d)}. \tag{29}$$

Substituting Eq. 26 into Eq. 29, we get

$$f(d) > 1 - \frac{1}{1 + W(d)}. \tag{30}$$

$f(d)$ in Eq. 30 specifies the lower bound of the forwarding probability for the node at depth d, which ensures that the condition given in Eq. 27 is valid, and thus, Eq. 26 can be used to provide a fair throughput to all of the nodes irrespective of the depth of the tree from the sink.

3.4 Throughput with fairness constraint

In this section, we determine the per-node throughput and the system throughput using the fairness constraint derived in the previous section. Let $G(d)$ denote the per-node throughput for the node $s(d)$. $G(d)$ is then defined as the average number of locally generated packets successfully received by the sink per unit time. In other words, the throughput of the node $s(d)$ is the rate of packets that are sent from its local queue q_L which are not blocked by any of the intermediate nodes. Let $P_b(d)$ denote the blocking probability for q_R at the node $s(d)$ so that $1 - P_b(d)$ is the nonblocking probability for q_R at $s(d)$. For a given path, the nonblocking probability is the product of the nonblocking probabilities at all intermediate nodes. Thus, $G(d)$ is equal to the product of the effective output rate of q_L and the nonblocking probabilities at all intermediate nodes. Therefore, $G(d)$ is given by

$$G(d) = \begin{cases} \sigma_L(1), & d = 1 \\ \sigma_L(d) \prod_{i=1}^{i=d-1} (1 - P_b(i)), & d = 2, 3, \ldots, d_{\max} \end{cases}. \tag{31}$$

The blocking probability, $P_b(d)$, according to $M/M/1/K$ queuing formulas, is given by

$$P_b(d) = \begin{cases} \frac{(1-\rho(d))\rho(d)^K}{1-\rho(d)^{K+1}}, & \rho(d) \neq 1 \\ \frac{1}{K+1}, & \rho(d) = 1 \end{cases}, \tag{32}$$

where $\rho(d)$ is given by Eq. 14. Let G_{sys} denote the system throughput which can be defined as product of the number of nodes at depth 1 and the arrival rate of successful media access for those nodes. In other words, G_{sys} must be equal to the aggregate effective output rates of all nodes at depth 1 and is given by

$$G_{\text{sys}} = N(1)\sigma(1) = N(1)\mu(1). \tag{33}$$

Substituting Eq. 3 into Eq. 33, we get

$$G_{\text{sys}} = N(1)\frac{1}{t} ln\left(\frac{1}{1 - p(1)}\right). \tag{34}$$

The average throughput of a node, denoted by G_{avg}, is the system throughput divided by the total number of nodes in the network. Therefore, G_{avg} is given by

$$G_{\text{avg}} = \frac{G_{\text{sys}}}{N}. \tag{35}$$

To maximize the system throughput, the media access probability $p(1)$ in Eq. 34 should be maximized such that the constraint given in Eq. 26 is not violated to maintain the fairness.

3.5 End-to-end delay with fairness constraint

In this section, we determine the source to sink delay experienced by a packet with the constraint on fairness. Let $T_{\text{E2E}}(d)$ denote the delay experienced by a packet which is generated by the node $s(d)$. $T_{\text{E2E}}(d)$ is defined as the duration of time from when the first bit of a packet is sent by $s(d)$ until the packet is successfully received by the sink. Assuming that the propagation delay is negligible, $T_{\mathrm{E2E}}(d)$ is equal to the summation of the transmission time and the queuing delays at all intermediate nodes experienced by the packet. The queuing delay is equal to the duration of time from when this packet is pushed into the q_R of this node until this node starts sending the first bit of the packet to the next relaying node (or to the sink). Let $T_R(d)$ denote the queuing delay of a packet in q_R at $s(d)$. According to Little's formula [11], $T_R(d)$ is given by

$$T_R(d) = \frac{1}{\mu_R(d)} + \frac{L_R(d)}{\lambda_R(d)(1-P_b(d))}, \quad d = 1, 2, \ldots, d_{\max} - 1, \tag{36}$$

where $L_R(d)$ is the steady state queue size of q_R for the node $s(d)$. According to $M/M/1/K$ queuing formulas, $L_R(d)$ is given by

$$L_R(d) = \begin{cases} \frac{\rho(d)}{1-\rho(d)} - \frac{\rho(d)(K\rho(d)^K+1)}{1-\rho(d)^{K=1}}, & \rho(d) \neq 1 \\ \frac{K(K-1)}{2(K+1}, & \rho(d) = 1 \end{cases}, \tag{37}$$

and $P_b(d)$ is the blocking probability given in Eq. 32. Finally, we get the source to sink delay $T_{\mathrm{E2E}}(d)$ as

$$T_{\mathrm{E2E}}(d) = \begin{cases} T_{\mathrm{trans}}, & d = 1 \\ d \times T_{\mathrm{trans}} + \sum_{i=1}^{i=d-1} T_R(i), & d = 2, 3, \ldots, d_{\max} \end{cases}, \tag{38}$$

where T_{trans} is the transmission time of a packet.

Let T_{avg} denote the average end-to-end delay, which is the aggregate delay of the total number of packets generated by all nodes and successfully received by the sink divided by the total number of packets. Therefore, T_{avg} is given by

$$\begin{aligned} T_{\mathrm{avg}} &= \frac{\sum_{d=1}^{d=d_{\max}} N(d)G(d)T_{\mathrm{E2E}}(d)}{\sum_{d=1}^{d=d_{\max}} N(d)G(d)} \\ &= \frac{\sum_{d=1}^{d=d_{\max}} N(d)G(d)T_{\mathrm{E2E}}(d)}{G_{\mathrm{sys}}}, \end{aligned} \tag{39}$$

where $N(d)$ is the number of nodes at depth d.

3.6 Energy distribution with fairness constraint

Our goal is to distribute energy to nodes such that network lifetime is maximized. According to the sensor network model in Fig. 1, it is intuitive that the energy consumed at the sensor nodes closer to the sink is much higher than that at the nodes far away from the sink. The reason is that the node closer to the sink needs to relay all the traffic that are coming from its children nodes (i.e., far-away nodes from the sink) as well as its local traffic (generated by itself). Therefore, if all nodes in the network are allocated with equal amount of energy, then nodes closer to the sink will die before the nodes that are far away from the sink. If energy is allocated according to the traffic load of each sensor nodes, then all the nodes will exhaust their energy approximately at the same time. In other words, energy distribution should be performed in a way so that energy in all the depths of the tree is fully consumed almost at the same time. In the following, we present an explicit solution on the energy distribution for the nodes at different depths of the tree to achieve the prolonged network lifetime.

Let $E(d)$ be the energy consumption for the transmission of a data packet by a node $s(d)$. $E(d)$ can be given by

$$E(d) = \mathrm{packetsize} \times E_{\mathrm{bit}}, \tag{40}$$

where packetsize is the size of the data packet in bits and E_{bit} is the amount of energy consumed per bit transmission. For a simplified power consumption model of radio communication [12], E_{bit} is given by

$$E_{\mathrm{bit}} = E_{\mathrm{TE}} + E_{\mathrm{TA}} D^{\alpha} + E_{\mathrm{RE}}, \tag{41}$$

where E_{TE} is the energy per bit needed by the transmitter electronics, E_{TA} is the power consumption of the transmitting amplifier used to send one bit over one unit distance, E_{RE} is the energy used by the receiver electronics, D is the transmission distance, and α is the path loss factor that depends on the radio frequency environment and is generally between 2 and 4. Let $E_{\mathrm{total}}(d)$ denote the total initial energy at depth d, and Y be the duration of time after which a node at any depth runs out of its energy, so that Y can be defined as the network lifetime. We are interested in finding an optimal energy allocation criterion for the sensor network which maximizes the network lifetime.

Let $E^d_{\mathrm{resi}}(y)$ be the total residual energy at d after time y. We then have

$$E^d_{\mathrm{resi}}(y) = \begin{cases} E_{\mathrm{total}}(d) - E(d)N(d)\mu(d)y - \\ E(d)N(d)\lambda_R(d)y, \; d = 1, 2, \ldots, d_{\max} - 1 \\ E_{\mathrm{total}}(d) - E(d)N(d)\mu(d)y, \quad d = d_{\max} \end{cases}. \tag{42}$$

Let $Y(d)$ denote the time duration after which the nodes at depth d have fully consumed their energy. After time $Y(d)$, the residual energy will then be zero, i.e., $E^d_{\mathrm{resi}}(Y(d)) = 0$. Note that the sensor network model has the form of many-to-one data routing paradigm and the nodes closer to the sink transfer more traffic. If the equal energy allocation policy is used for each node, then the closer nodes (to the sink), nodes at depth 1, are always the first ones to exhaust their energy due to the largest amount of data transmission, leading to the failure of the network. However, at this time, the other nodes still have some residual energy, leading to unutilized energy in the network and a reduced value of network lifetime. So, the optimal energy allocation criterion is to make all nodes have the same exhaustion time and thus maximizes the network lifetime. From this criterion, using Eq. 42, we find the required energy distribution for nodes at different depths of the tree as

$$E_{\text{total}}(d) = \begin{cases} E(d)N(d)\mu(d)Y + E(d)N(d)\lambda_R(d)Y, \\ d = 1, 2, \ldots, d_{\max} - 1 \\ E(d)N(d)\mu(d)Y, \quad d = d_{\max} \end{cases} \tag{43}$$

Using Eq. 43, we can determine the required energy at individual depths of the tree topology shown in Fig. 1. Given the network energy, we can also determine the network lifetime using Eq. 43. In Section 5, we quantitatively show how much energy should be allocated at each depth of the tree such that lifetime Y is the same for all nodes in the network.

4 Protocol design

In this section, we design the protocol to achieve fairness based on the analysis presented in Section 3. In the context of fair data collection, our design consists of four components: (a) queue management, (b) determining tree size, (c) determining the minimum contention window size, and (d) determining the forwarding probability. We describe each of the components in the sequel.

4.1 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 queues. However, it can be adjusted if the proportional delay needs to be addressed.

4.2 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 $6 + 6 + 2 = 14$. 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.

4.3 Determining the minimum contention window size

Based on the analysis, we found in Eq. 26 that 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 of 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

$$\frac{CW_{\min}(d+1)}{CW_{\min}(d)} \approx N_C(d)\left(1 + \frac{1}{W(d)}\right), \quad d = 1, 2, \ldots, d_{\max} - 1, \tag{44}$$

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. 44.

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 [13]. 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 [13] p_s can be given by

$$p_s = \frac{2(1-2p_c)}{(1-2p_c)(CW_{\min}+1)+p_c CW_{\min}(1-(2p_c)^m)}, \tag{45}$$

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 [13], p_c is given by

$$p_c = 1-(1-p_s)^{n-1}. \tag{46}$$

Equations 45 and 46 represent a nonlinear system in the two unknowns p_s and p_c, which can be solved using numerical techniques. Using 45 and 46, 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 six can transmit at a given time (assuming that there is no interference from nodes more than a depth away). Keeping p_c at approximately 20%, 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. 44, 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 1 $p(d)$, $CW_{\min}$, $f(d)$ used in analysis and simulation

		Proposed			Equal for all nodes		
Depth	Node ID	p	$CW_{\min}$	f	p	$CW_{\min}$	f
1	1–2	0.057	24	0.958	0.0456	32	0.75
2	3–6	0.0266	51	0.882	0.0456	32	0.75
3	7–14	0.0114	119	0.691	0.0456	32	0.75
4	15–30	0.0038	358	0.0	0.0456	32	0.0

4.4 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. 30 after obtaining $W(d)$ as described in Section 4.2. Choosing the value of $f(d)$ using Eq. 30 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.

5 Performance evaluation

In this section, we evaluate our scheme through extensive simulation using ns–2 [14]. Note that the RTS/CTS/DATA/ACK structure in 802.11 DCF [9] is used by the nodes to contend for the medium. Although these control packets can collide and some noncolliding 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 [15], and on some platforms, the RTS/CTS exchange would incur a 40% overhead [16]. 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 ran our simulation for 100 s, and the results are averaged over ten runs.

5.1 Scenario 1

In this scenario, the topology used in the simulation is shown in Fig. 1. 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. Therefore, the wireless medium is occupied by the node for a time equal to the transmission time of a packet, i.e., $t_s = T_{\text{trans}}$ = 256 Kbps/36 bytes = 1.125 ×

10^{-3} s. 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. The analytical results are calculated using the values of $p(d)$ and $f(d)$, and the simulations are performed using the values of $CW_{\min}$ and $f(d)$. Results are obtained for two cases: First, the $p(d)$, $CW_{\min}$, and $f(d)$ 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 analytical results of the proposed protocol are justified as can be observed from the simulated results as depicted in 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. Figure 3 presents the average throughput, which shows that the proposed protocol has a 36% improvement compared to the approach in which all nodes use equal $CW_{\min}$ and $f(d)$. As depicted in Fig. 3, lines parallel to the Y-axis represent the maximum and the minimum values of each case found in analysis and simulations.

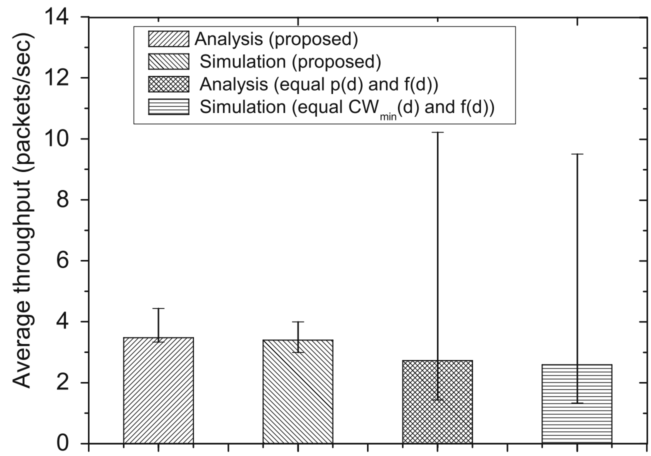

Fig. 3 Average throughput (G_{avg}) of a node

Figure 4 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 probabilities. The average packet delay for the proposed protocol is reduced by more than 27% compared with the protocol using equal $CW_{\min}$ and $f(d)$ for all nodes as shown in Fig. 5. As depicted in Fig. 5, lines parallel to the Y-axis represent the maximum and the minimum delays found in analysis and simulations.

Next, Fig. 6 presents the energy required at different depths of the tree such that all the nodes in the network have the same lifetime. We set the same distance among the depths of the tree and the energy consumption per data transmission to $E(d) = 1$ unit. We check the energy required for the different depths of the tree (Fig. 1) by setting the lifetime Y to 100 s. The energy consumption is higher for the nodes closer to the sink since the nearby nodes transmit more data packets. Therefore, nodes closer to the sink need more energy

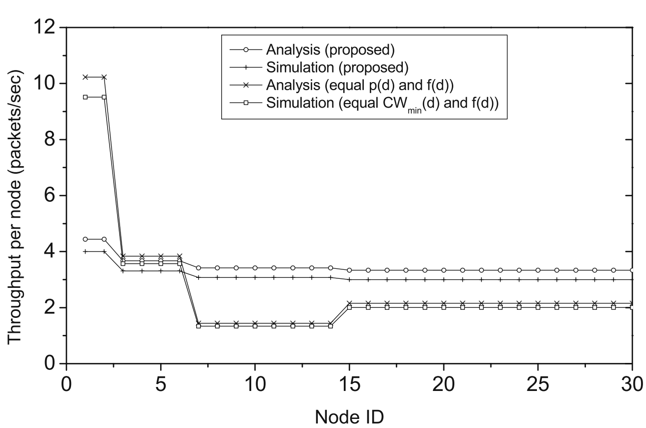

Fig. 2 Throughput for individual nodes in the network

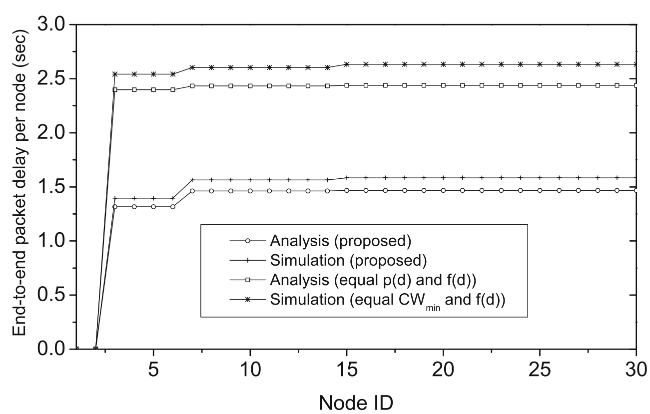

Fig. 4 Source-to-sink delay ($T_{\text{E2E}}(d)$) experienced by packets of nodes in the network

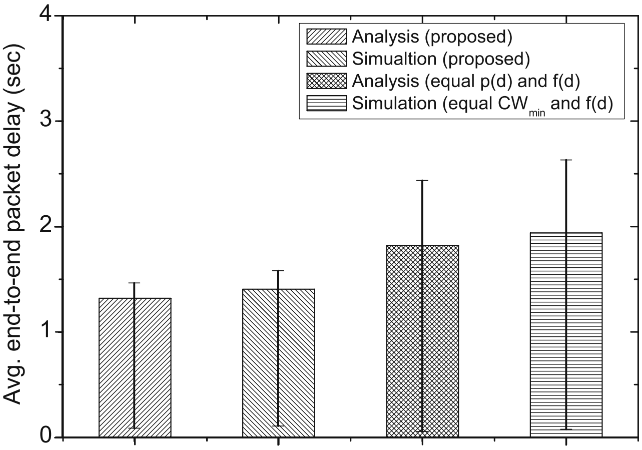

Fig. 5 Average end-to-end delay (T_{avg})

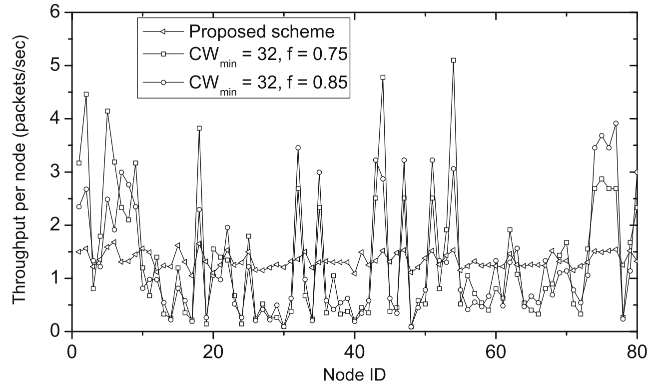

Fig. 7 Throughput for individual nodes in the network

than nodes that are farther away in order to achieve efficient energy utilization and to maximize the lifetime of the network, as depicted in Fig. 6.

5.2 Scenario 2

In this scenario, we have simulated the proposed mechanism in a network of 80 nodes and a single sink. 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 [17], 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 the channel bandwidth to be 256 Kbps, each data packet to be 36 bytes, and the control packet ACK to be 4 bytes. We ran the simulation ten times for each of the mechanisms and measure the average results for both throughput and delay.

Figure 7 presents the throughput of the individual nodes in the network. The simulation results of the proposed protocol depicted in Fig. 7 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.

Figure 8 presents the source to sink (i.e., end-to-end) delay of packets for all nodes. The proposed protocol

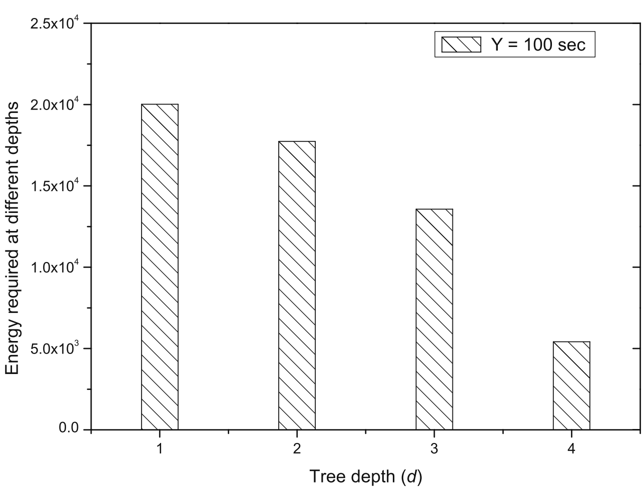

Fig. 6 Energy allocation at individual depths of the tree topology shown in Fig. 1

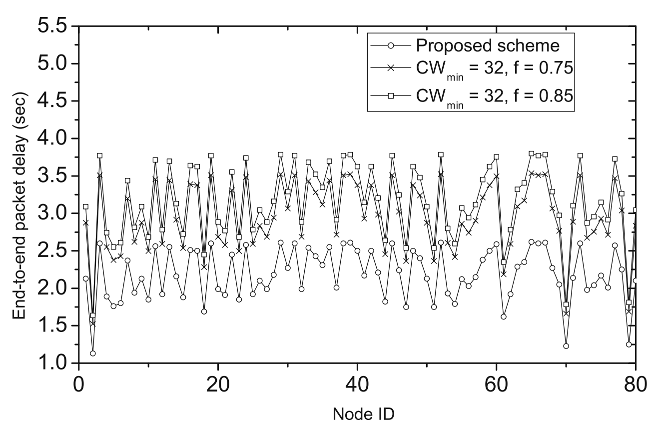

Fig. 8 Source-to-sink delay experienced by packets of nodes in the network

has much less delay than when there are equal media access and forwarding 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.

6 Related works

Tree-like sensor networks are studied in [18], where the authors have presented optimal strategies for data distribution and data collection and analytically evaluated the time performance of their solution. In [19], authors have presented 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, the use of an involved power control mechanism at nodes is indispensable. In [20], the authors have developed a Markov model of a sensor network in which the nodes may enter a sleep mode and used this model to investigate system performance in terms of energy consumption, network capacity, and data delivery delay. Their analytical model specifically represented the sensor dynamics in sleep/active mode, while taking channel contention and routing issues into account. Though 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 [21–24], 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 [8]. Recently, there are several pioneering studies on congestion control and fairness in sensor networks [25–29].

Chen and Zhang [25] have proposed a new aggregate fairness model and a localized algorithm called AFA. AFA is design to work with any routing protocol. In particular, it allows the packets from a data source to follow an arbitrary set of forwarding paths to the base stations. However, AFA needs the knowledge of source distribution at prior, and they have not taken into account the aggregation of flows from multiple sources and it is impractical to distinguish among them. A tree-based fairness scheme is proposed in [26], in which each sensor learns the number of upstream data sources in the subtree rooted at itself. It measures the maximum downstream forwarding rate and divides up the available capacity among upstream neighbors, which is propagated upstream to limit data rate. However, each sensor allocates bandwidth only based on the size of its subtree and has not considered the effect of other interferers to congested node.

Rangwala et al. [27] have proposed an interference-aware fair rate control model (IFRC) to share congestion among all potential interferers and converge to a fair and efficient rate using an additive increase multiplicative decrease control law for tree based communication in WSNs. IFRC is closer in spirit to prior work on sensor network congestion control. However, since IFRC only takes effect after congestion happen, it cannot mitigate congestion and avoid packet drops. Fan et al. [28] have developed algorithms for achieving fair and high throughput data extraction from all nodes in presence of renewable energy sources. Specifically, they have designed their protocol to compute the lexicographically maximum data collection rate for each node, such that no node will ever run out of energy. They have proposed a centralized algorithm and an asynchronous distributed algorithm to compute the optimal lexicographic rate assignment for all nodes. However, centralized algorithm poses a heavy burden for the sensor nodes and authors pointed out that distributed solutions need to be developed to jointly determine the optimum rates for all nodes and the flows on each link.

A fairness model is presented in [29] to allocate congested bandwidth based on the credit of each sensor source instead of uniform distribution. There are two problems to be solved: One is the computation of credit that is how to represent and compute the credit of original packet and aggregated packet; the other is rate allocation that is how to allocate bandwidth among all upstream neighbors of congested node and how to share bandwidth among congested node and its interferers. However, to achieve fair rate control, all nodes in interference set need to exchange their average credit and rate with each other, which incurs significant control overhead for the resource constrained sensor nodes.

The problem of max–min fair rate control has been looked at in the context of WSNs [30, 31]. In an earlier work [30], an additive increase-based rate allocation scheme is proposed that guarantees a weaker notion of max–min fairness. A TDMA-based MAC is developed in [30], which guarantees a max–min rate allocation by assigning slots to various sources. Authors in [31] have formulated the problem of maximizing the network utilization subject to a max–min fair rate allocation constraint in the form of two coupled linear programs. They have shown how the max–min rate can be computed efficiently for a given network. Then they have adopted a dual-based approach to maximize the network utilization. The analysis shows the suboptimality of previously proposed additive increase algorithms with respect to bandwidth efficiency. However, in theory a dual-based subgradient search algorithm can take a long time to converge.

In this paper, we have studied the fairness problem 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 strategies. Combination of these two may achieve the ultimate node level fairness. We have developed a statistical model to derive the exact condition that will enable us to achieve fairness at the network nodes. Starting from the service and arrival rates of packets for the nodes, the conditions on the fairness have been almost exclusively derived. 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. We have also quantitatively shown the energy allocation to different nodes based on the analysis and show that nodes at different locations have different energy requirements to maximize the network lifetime.

7 Conclusions

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 analyzed the nonuniform traffic flow behavior for different nodes in the network, and we showed that nodes with appropriate media access and packet forwarding strategies can enjoy equal throughputs. We have shown that throughput and delay can be improved significantly with our design. We also derived the energy distribution policy and showed that nodes in different locations require different amounts of energy in order to maximize the overall network lifetime. 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.

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