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On Enhancing Event-to-Sink Data Delivery Throughput in Sensor Networks

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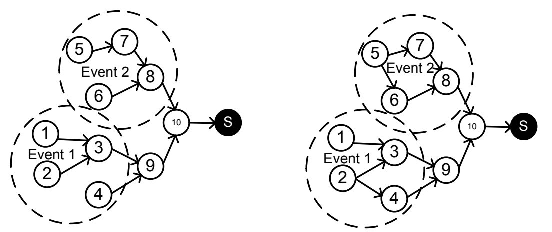
Abstract

The many-to-one multihop traffic pattern of Wireless Sensor Networks (WSN) puts a great challenge on enhancing the event-to-sink data delivery throughput. Because, in CSMA/CA driven medium access control protocols, contention of the shared medium raises both at the event detection area and near the sink, which in turn increases the packet collisions greatly. In this paper, we exploit the amount of traffic load a node carries to control its medium access frequency by assigning the minimum contention window (CW_{min}) value in a differentiated way. The proposed scheme is fully distributed. The performance of the proposed scheme is evaluated by ns-2 simulations and the results show that it can significantly decrease the packet losses due to collisions and buffer drops, which in turn helps to enhance event-to-sink throughput. It also outperforms the existing approaches.

1. Introduction

Recent years have witnessed a growing number of Wireless Sensor Network (WSN) deployments for environmental monitoring such as habitat monitoring, battle field surveillance, disaster relief, structural and earthquake monitoring, etc. While sensor nodes usually operate under light load, they may suddenly be activated by abrupt events such as enemy attack or earthquake detection[1]. In such cases, large volume of data may be generated by the surrounding nodes of the event, which is required to deliver to the sink within a short period demanding a high throughput end-to-end data delivery.

In this paper, we study the functions of medium access control (MAC) protocols in enhancing the end-to-end throughput of WSN. The MAC protocols proposed so far for WSN may be divided mainly into two groups: contention based and schedule based MAC protocols. The contention based protocols [5], [6], [7] use IEEE 802.11



(a) Single path routing (b) Multipath routing

Figure 1. An example network showing how data packets from two different events are routed from the event detection area(s) to the sink using single path and multipath forwarding. For (b), initially nodes 2 and 5 divide their traffic equally towards two routes.

DCF for medium access and a variety of periodic sleep-listen schedule to conserve energy. Since the typical traffic pattern of sensor network is many-to-one and convergent in nature[4], downstream nodes have to carry more traffic than their upstreams. Therefore, the long term MAC level fairness property of the above CSMA/CA driven protocols instigates bottleneck condition at downstream nodes. Hence, in presence of a bottleneck node, queue build-up and packet-drop happen which result in waste of the system resources utilized to deliver the packets halfway through the multihop network. For example, in Fig. 1 (a), nodes 3, 4 and 9 are in the same contention zone, only one of them can transmit at a given time; and the same is true for nodes 1, 2, 3 and 4. With CSMA/CA, the upstream sensors 1, 2, 3 and 4 collectively have more chance to send packets to node 9 than it can forward. The excessive packets received by node 9 will eventually cause *buffer overflow* and packets are dropped. Another type of congestion happens due to media contention, namely congestion due to *packet collision*. It is caused whenever a number of nodes contend the shared medium using the same contention parameter values,

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as used in the above protocol. Irrespective of the reason behind the congestion, it causes many folds of problems. When a packet is dropped/collided, the energy spent by upstream sensors on the packet is wasted. This wastage increases when the packets drop after traveling more number of hops. Finally and above all, the data loss due to congestion may abruptly decrease the throughput and jeopardize the mission of the application.

On the other hand, in schedule based MAC protocols [3][4][11], nodes exchange traffic and transmit schedule information in order to predetermine and reserve the time slots of their future transmissions. These protocols guarantee collision free transmission slots. However, for large-scale multihop wireless networks, schedule based protocols exhibit inherently higher delivery delays when compared to contention based approaches[3]. Therefore, in today's emerging sensor networks, there is a growing need for improved MAC protocol that can provide higher throughput, reduced latency and energy-efficiency.

In this paper, we design a generous MAC scheme that adapts to the application at hand and works in networks either with single path or multipath routing. It uses traffic-flow based information to determine the frequency of medium access of a node (which is determined by the minimum contention window, CW_{min}, of the node). Nodes calculate their aggregated traffic flow weights and thereby determine their CW_{min} values locally. The proposed scheme is fully localized and simple so that it can be run by nodes having limited processing, memory and power capabilities. The rest of the paper is organized as follows. Related works are discussed in Section 2 and Section 3 discusses the network model and assumptions. Section 4 presents the proposed scheme and its performance evaluation is carried out in Section 5. The paper concludes in Section 6.

2. Related Works

There exists a number of medium access control protocols for WSN aiming to adapt with its traffic behavior in order to reduce the packet drops and to increase the energy efficiency. Some of them are detailed as follows. Traffic-adaptive medium access protocol, TRAMA [3], tries to maximize the length of sleep periods by determining the presence or absence of traffic. It needs a neighbor protocol and a medium access schedule exchange protocol that has significant overhead of broadcasting schedule packets periodically. It also performs an adaptive election algorithm to reduce the number of unused time slots. The key problem of this protocol is that the overall signaling overhead of the above fairly complicated algorithms may create scalability problem and increase end-to-end packet delivery latency. It also suffers from computation and distribution of global network wide scheduling information and time synchronization.

The funneling-MAC [4] is a sink-oriented hybrid MAC protocol that uses both schedule-based TDMA and contention based CSMA/CA MAC schemes. Pure CSMA/CA operates network wide in addition to acting as a component of the funneling-MAC that operates in the high traffic region. This protocol mitigates the funneling effect by using local TDMA scheduling for the nodes closer to the sink that typically carry considerably more traffic than nodes further away from the sink. The switching between the CSMA/CA and TDMA modes are controlled by the beacon messages broadcasted from the sink on demand. This makes the protocol unscalable and incurs a lot of message overhead. Finally, unlike our proposed scheme, funneling-MAC handles congestion only at the region near the sink. It does not consider the congestion due to link contention at the event detection area.

Probably the most well-known and highly referenced MAC protocol for WSNs is S-MAC [5]. S-MAC is a contention based protocol that avoids overhearing and dynamically sets the duty-cycle based on adaptive listening. It uses in-line signaling for exchanging SYNC packets. The distributed maintenance of clock synchronization by exchanging SYNC packets and their periodic sleeps significantly reduces the throughput and increases the packet latency.

3. Network Model and Assumptions

We consider a sink-rooted tree-based network architecture, where identical sensors are randomly distributed over the terrain. The sink may be located anywhere of the terrain. Sensor nodes and the sink are static after the deployment. All nodes have the equal transmission range (R_{tx}) and sensing range (R_s). We also assume that all data packets have the same size and the buffer size of a node is counted as the maximum number of data packets that it can hold. The underlying routing protocol may use either single path or multipath forwarding [2][12]. In some recent research results, we observe that the multipath forwarding can achieve higher throughput, reduced end-to-end latency, higher security and spatial energy consumption. Therefore, in the following section, we develop a framework of traffic model for the multipath forwarding case, which can easily be tuned for single path also. Note that in case of multipath forwarding, the total traffic load of any node i may be distributed over a set of downstream nodes D_i, which are the next hop nodes on the routing paths from i to the sink. Similarly, if U_i represents i's set of upstream nodes, each node in U_i uses i as next hop node on its routing path. The load distribution policy of node i towards multiple paths (defined by D_i) depends on the specific multipath routing algorithm[1].

[1]Possible load distribution policies could be as follows: (i) homogeneous distribution - the total traffic load of node *i* could be equally divided

amongst the available paths (ii) proportional distribution - loads could be distributed proportional to the minimum hop count of a path, free buffer space in the downstream node, maximum residual energy of the downstream node, successful packet delivery rate of a link/path etc.

4. Proposed Scheme

The use of an existing CSMA/CA based MAC in WSN may cause the source nodes to inject as many packets as possible into the network with no regard for whether the packets reach their final destination. The high amount of data packets transferred by source nodes overwhelms the capacity of downstream nodes, particularly the nodes near the sink. To diminish this problem, the MAC protocol for sensor network should be designed in such a way that the downstream nodes get more medium access than their upstreams. More explicitly, the frequency of medium access of different sensor nodes should be proportionate to the amount of data traffic carried by them. This motivation insisted us to design an aggregated traffic flow weight (F^{agg}) driven hierarchical MAC protocol that gives higher access to the downstream nodes than their upstreams. In what follows, we first present the formulation and computation procedure of F^{agg} values for all source and forwarder nodes in subsections 4.1 and 4.2, respectively, and then present how to determine CW_{min} values using F^{agg} in subsection 4.3.

4.1. Traffic Flow Weight Calculation

Since all the sensors have equal sensing range, the radius of an event detection area is equal to the sensing radius of a node. Therefore, when an event is occurred, a number of sensor nodes around the vicinity of the event detect it and generates data packets at a constant rate. Then they forward the sensed data packets toward the sink in a multihop fashion.

Definition 1 (Traffic flow): A traffic flow is defined as a stream of data packets from an upstream node i to a downstream node j, denoted by f_{ij}. Hence, f_{ij} may aggregate data packets from multiple flows.

Definition 2 (Aggregated traffic load): In case of multipath routing, each node divides its total traffic into multiple traffic flows and those flows pass through multiple downstream nodes. Therefore, the aggregated traffic load of an intermediary node i (L_i) is the total sum of the data packet rates (in packets per second, pps) of its all upstream traffics plus its own data packet generation rate (g_i), and is expressed as follows

$$L_i = \Big(\sum_{k \in U_i} r_{ki} \Big) + g_i \tag{1}$$

where, r_{ki} is the data packet transmission rate (in pps) of flow f_{ki}. Note that the aggregated traffic load of a *source only node* is simply its packet generation rate, g_i.

Definition 3 (Traffic flow weight): We define the traffic flow weight of a source node i as the ratio of its instantaneous data packet reporting rate (R_i) to its constant data packet generation rate (g_i), and is expressed as follows

$$F_i = \frac{R_i}{g_i} \ , \ g_i > 0 \tag{2}$$

where, $R_i \leq g_i$ and initially set as $R_i = g_i$ for all source nodes. While g_i represents the application-defined constant packet generation rate for a particular event type, R_i is a dynamically controllable variable and it's value is determined by an appropriate congestion control (CC) or rate control (RC) algorithm. In multipath data forwarding, a CC or RC algorithm may be activated whenever a certain path/link is congested. In the case, congestion may be reduced either by diverting the excessive amount of traffic from overloaded path to other alternative lightly loaded paths or by decreasing the reporting rate R_i (*i.e.*, R_i becomes less than g_i). The first option is not applicable whenever all other paths are adequately/highly loaded so that they are unable to carry additional traffic. Then the activation of second option becomes mandatory. However, in this paper, we take advantage of neither of the approaches in support of unbiased evaluation of the proposed scheme[2].

Definition 4 (Aggregated traffic flow weight): Since in multipath routing, each downstream node may receive multiple flows from its upstreams, the aggregated traffic flow weight of any intermediate node is defined as the total sum of the weighted fractions of all flows passing through it plus its own traffic flow weight. Therefore, node i's aggregated traffic flow weight is calculated as

$$F_i^{agg} = \Big(\sum_{k \in U_i} \frac{r_{ki} \times F_k^{agg}}{L_k} \Big) + F_i. \tag{3}$$

These aggregated traffic flow weights of different sensor nodes are a new way to look into the heart of medium access control for sensor network (see Section 4.3).

4.2. Distributed Computation of F^{agg} values

We consider that each node k, while transmitting a data packet to its downstream node i, includes r_{ki}, L_k and F_k^{agg} in the header of every packet. Note that a simple distributed algorithm can compute the aggregated traffic flow weights of all nodes iteratively and it works as follows. Initially, sensor i sets $r_{ki} = 0$, $F_k^{agg} = 0$ and $L_k = 0$, $\forall k \in U_i$, and $r_{ij} = 0$, $\forall j \in D_i$. When source nodes start to transfer data packets, their downstream nodes learn the amount of

[2]In our simulation, we assign $R_i = g_i$ and keep unchanged during the whole simulation period. Obviously, the consideration of R_i opens the door of designing an optimal traffic engineering algorithm for multipath data forwarding in WSN, which we leave as our future work.

incoming traffics, upstream's aggregated traffic loads and aggregated traffic flow weights (as they are embedded into the packet headers). A downstream node i then periodically computes L_i and F_i^{agg} using Eq. 1 and Eq. 3, respectively, as shown in Algorithm 1.

Note that these computations are performed only when the value of at least one parameter of the current packet differs from that of previous one. It is obvious that L_i and F_i^{agg} values become stable whenever node i receives at least one packet from all of its upstreams. After that, in the next iteration i's downstream nodes (j) will compute their L_j and F_j^{agg} values in the same way. This process repeats until the aggregated traffic flow weights of all nodes are calculated. Therefore, the upstream nodes would stabilize the values before their downstreams and the maximum number of iterations required before all variables become stabilized is bounded by the length of the longest routing path. More specifically, a particular intermediary node will require at most h iterations to stabilize its variables, where h denotes its hop distance from the furthest source node for which it is carrying traffic. Therefore, in our proposed scheme, the frequency of these computations is driven by the event occurrence frequency, which is typically very minimum. Also note that, the aggregated traffic flow weights of each node along the routing path(s) are updated without transferring any additional control packets, incurs only a little overhead of few bytes in the packet header.

Algorithm 1: *At each node i*

Initialization
  for all upstream node $k \in U_i$
    $r_{ki} = 0, F_k^{agg} = 0$ and $L_k = 0$;
  for all downstream node $j \in D_i$
    $r_{ij} = 0$;

loop
  wait (until i receives data packet from any $k \in U_i$)
  if(any of r_{ki}, F_k^{agg} and L_k has new value)
    compute F_i^{agg} and L_i using Eq. 1 and Eq. 3
    respectively.
  endif
forever

The Fig. 2 plots the aggregated traffic flow weight values of 5 individual nodes of Fig. 1(b) over the simulation time, for 8pps traffic load during 0.01sec. to 10.01 sec. Values of the graphs depict that the F^{agg} values of upstream nodes get stabilized earlier than their downstreams, which is obvious. Also, F^{agg} value of the nearest node (i.e. node 10) of the sink is stabilized at last. Note that the duration of unstable region is so small (0.13 seconds) that it can't significantly affect the performance of the proposed protocol.

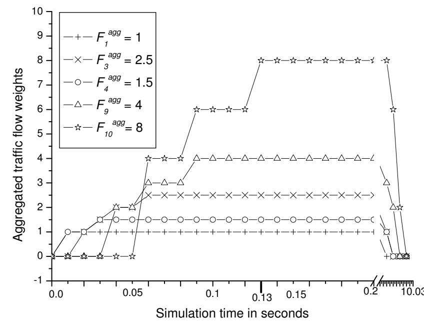


Figure 2. F^{agg} values of nodes over the simulation time.

4.3. Differentiated CW_{min} Value Assignments

In order to give different levels of medium access to the nodes we can control the contention process so that the nodes can access the wireless medium with different probabilities. The contention process of nodes can be controlled by allowing them to use different contention parameters. We can control the value of CW_{min} used by individual nodes to give them different opportunities to access the shared medium. Since the number of medium access of a node is approximately inversely proportional to its CW_{min} value [10], we can easily control each node's share of the medium access in a distributed manner using F^{agg} values. More specifically, higher the aggregated traffic flow weight of a node, lower its CW_{min} value is. To implement this notion, our proposed medium access control scheme gives proportional medium access to the nodes by assigning CW_{min} value of any node i as follows

$$CW_{min}[i] = \left\lceil \frac{(W_0 - 1) \times C}{F_i^{agg}} \right\rceil \quad (4)$$

where, W_0 is usually chosen as a power of 2, and C is a system parameter corresponding to the number source nodes within an event radius. When an event is detected, each source node broadcasts an special notification message (that includes its ID and detected event ID) to all of its two hop neighbor nodes (by re-broadcasting from one hope neighbors) and thus each node can calculate the number of source nodes C for the event. Therefore, the value of C linearly varies with the node density of the network. The motivation of taking C value into account for the determination of CW_{min} is described below. When an event is detected, the amount of traffic produced by the sensing nodes increases with the value of C, which in turn increases the contention of the shared medium and thus, the collisions become more frequent. This problem can be reduced by Eq. 4 which assigns higher CW_{min} values to sensing nodes taking C into consideration. In other words, the value of C helps the source only nodes to choose more appropriate CW_{min} value that minimizes the collisions. For all other intermediary nodes, working as forwarders of the event traffic, the use of the same C value is justified in order to build a hierarchical medium access ordering among the nodes.

Choosing the appropriate value of W_0 is a critical concern since very higher value of it decreases the medium utilization and thereby the network throughput. Conversely, very lower value of it might greatly increase the medium contention as well as packet losses due to collision. By empirical evaluations and analyzing the extensive simulation results, we found that setting $W_0 = 2^4 = 16$ produces the best results for our deployment. Also note that W_0 is a tunable parameter depending on the node density of a network and is propagated from the sink node. Its value may be higher for low density deployment and vice-versa; and this is required for better adjustment of CW_{min} value using Eq. 4 since C's value decreases as node density decreases. For instance, in our example network scenario (Fig. 1), $C = 4$ and we set $W_0 = 2^5 = 32$. Table 1 shows the aggregated traffic flow weights and CW_{min} values of nodes 1-10, calculated using Eq. 4.

Notice that the calculation of F^{agg} and the assignment of CW_{min} values as of Eq. 4 tells that the nodes near the sink carry more traffic than the distant nodes and therefore their CW_{min} values are much smaller. It means that the medium access ordering is done on a per-hop basis so that any one hop node will have precedence over any two hop nodes. Therefore, the following condition holds true: $p(h_1) \geq p(h_2) \geq ... \geq p(h_s)$, $1 \leq k \leq s$, where $p(h_k)$ denotes the probability of medium access of nodes h_k hops away from the sink. The equality condition appears when two nodes have the same aggregated traffic flow weights.

Table 1. F^{agg} and CW_{min} values of individual nodes of Fig. 1 ($R_i = g_i$, for all nodes).

Single path Routing			Multipath Routing	
Node ID	F^{agg}	CW_{min}	F^{agg}	CW_{min}
1	1	124	1	124
2	1	124	1	124
3	3	42	2.5	50
4	1	124	1.5	83
5	1	124	1	124
6	1	124	1.5	83
7	2	62	1.5	83
8	4	31	4	31
9	4	31	4	31
10	8	16	8	16

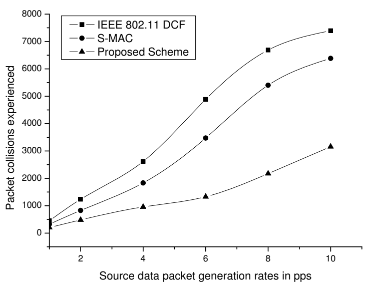
5. Performance Evaluation

We compare IEEE 802.11 DCF and S-MAC[5] with the proposed scheme. In addition to packet collisions, buffer drops and packet delivery ratio, we show the comparisons in terms of the following performance metrics.

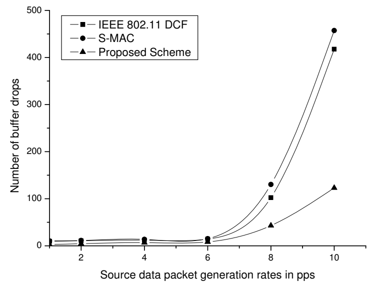
- *End-to-End Throughput*: We measure the end-to-end effective data throughput in KBps for different traffic loads. The results do not count any control packets. Only data packets received at the sink are counted for the throughput calculation. The higher the value is, better the protocol performance is.
- *End-to-end packet delay*: Delay of a single packet is measured as the time difference between when the packet is received at sink from its generation time at the source node. Delays experienced by individual data packets are averaged over the total number of individual packets received by the sink. The lower the value is, better the performance is.
- *Energy cost per packet*: The total amount of energy dissipated by all nodes of the network is averaged first. Then this per node average energy dissipation is divided by the total number of received packets to calculate the average energy cost per packet.

The simulation environment parameters are listed in Table 2. Other than the default values in 802.11 MAC layer implementation in ns-2.30[13], we have done the following changes: the MAC header size is increased to 184 bits (additional 24 bits for inserting r_{ij}, L_i and F_i^{agg} fields in each packet) and the value of CW_{min} of each node is determined online according to the proposed scheme. We establish p number of alternate braided paths (where, $1 \leq p \leq 3$) from each node to the sink using [14]. We consider that paths do not change/fail during data traffic and each upstream node distributes its aggregated traffic load equally towards all of its downstream nodes. We execute simulation runs for four randomly chosen event traffics for varying data packet generation rates. The data points in each graphs of following figures are average of 5 simulation runs.

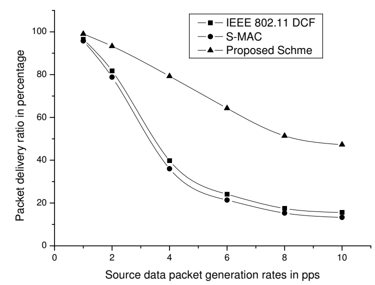
As shown in Fig. 3(a), packet collisions in the network increases with the data packet generation rates in all protocols. However, the proposed scheme experiences much less collisions as compared to IEEE 802.11 DCF and S-MAC protocols and this is because of using differentiated CW_{min} values governed by traffic flow weights of source and forwarder nodes. It enables more controlled access of the medium by the competing nodes. Similarly, packet drops due to buffer overflow is very minimum in the pro-



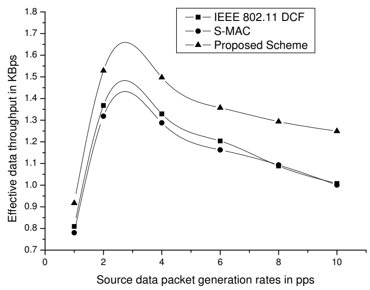
(a) Total packet collisions experienced



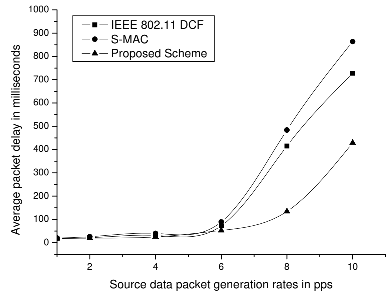
(b) Packet drops due to buffer overflow



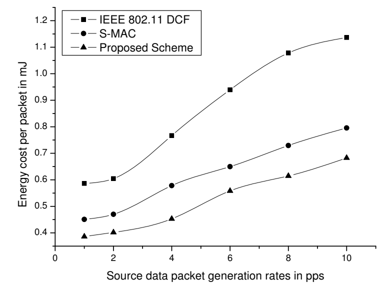
(c) Packet delivery ratio



(d) Effective data delivery throughput



(e) End-to-end packet delay



(f) Energy cost per received packet

Figure 3. Performance comparisons among three different MAC protocols.

Table 2. Simulation parameters.

Parameter	Value
Area of deployment	200m×200m
Num. of sensor nodes	200
Sink	1 at location [200, 100]
Node distribution	Random
Trans. radius, R_{tx}	40m
Sensing radius, R_s	20m
Initial node energy	5 Joule
Channel bandwidth	512Kbps
Buffer size	20 Packets
Payload size	64 Bytes
PHY, MAC headers	192 and 184 bits, respectively.
RTS, CTS, ACK pkts.	160, 112 and 112 bits, respectively.
Transmit power	$8.5872e^{-4}$ Watt
Rcv. signal threshold	$3.66152e^{-10}$ Watt
Propagation model	TwoRayGround
Simulation time	60 seconds

posed scheme as compared to other protocols, as shown in Fig. 3(b). Since in S-MAC and IEEE 802.11 DCF both the source and forwarder nodes get almost equal number of accesses to the medium, the forwarder nodes receive more packets than they can transfer to the next hop nodes over the time. Hence, buffer of the forwarder nodes is overflowed and significant number of packet drops occur. On the other hand, in the proposed scheme, the use of traffic flow weight controlled CW_{min} values enables the forwarder nodes to get more medium accesses than their upstream nodes and thereby less buffer drops are observed.

Packets may also be dropped due to collisions. When the repeated collisions of a packet crosses the maximum retry limit, the incumbent node drops the packet. Therefore, we observe reduced packet delivery ratio in IEEE 802.11 DCF and S-MAC protocols at higher packet generation rates. However, as the proposed scheme experiences very less packet collisions and buffer drops, it can maintain much higher packet delivery ratio even at increased packet generation rates. Fig. 3(c) depicts the above results.

A significant improvement achieved by the proposed scheme is that it can greatly increase the end-to-end effective data delivery throughput measured by the sink node. Fig. 3(d) shows that the IEEE 802.11 DCF and S-MAC offer much less throughput than the proposed scheme. This is due to decreased packet drops and delays at the intermediary nodes of the network. We also find that up to 6pps, the average end-to-end packet delay experienced in different protocols does not vary noticeably, as shown in Fig. 3(e). But, further increase in packet generation rate raises the delay significantly because of increased collisions. The use of differentiated CW_{min} value in the proposed scheme enables it to experience less collisions and ensure traffic volume driven medium access, which in turn decrease the queuing delays of packets in the intermediary hops.

Finally, in Fig. 3(f), we plot the energy cost per packet observed in different protocols. The proposed scheme and S-MAC can conserve much energy as compared to the IEEE 802.11 DCF. The energy conservation in S-MAC came from its dynamic sleep/listen schedule and that in the proposed scheme stems from the fact that it can greatly decrease the packet collisions and drops. Since we have divided the per node average energy consumption by the total number of received packets at the sink to measure the energy cost per packet, its value in the proposed scheme becomes less due to the higher value of the denominator.

6. Conclusions

In this paper, a differentiated medium access control scheme, governed by traffic flow weights of nodes, is proposed for Wireless Sensor Networks. The proposed scheme achieves higher data delivery throughput, reduced end-to-end packet delay, higher packet delivery ratio and so on. It is fully distributed and energy efficient.

In future, we would like to extend the proposed scheme for cluster-based heterogeneous sensor networks, where the different events may have different importance and require to maintain individual quality of service levels.

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