Data-driven MAC for Efficient Transmission of Spatially Correlated Data in WSNs

Nahdia Tabassum and Guojun Lu

Faculty of Information Technology, Monash University, Australia,
{Nahdia.Tabassum,Guojun.Lu}@monash.edu

Abstract. In Wireless Sensor Networks (WSNs), nodes closer to an event are able to detect the event earlier and more accurately, thus contain more important information. Also, tiny nodes are usually scarce of energy and a major portion of their energy is used through communication. Therefore saving the energy by allowing only a limited number of communications is desirable in designing protocols for WSNs. We propose a data-driven Medium Access Control (MAC) protocol which allows only the more useful information to enter into the medium by using a modified contention mechanism and also suppressing other spatially-correlated data that are of less importance. Simulation results show that the proposed MAC outperforms the existing ones in terms of event reporting delay and packet delivery ratio for urgent data.

Key words: medium access control; data-driven; energy-efficiency; delay; sensor networks.

1 Introduction

Wireless Sensor Networks (WSNs) is a fascinating area with endless possibilities. It is envisioned as one of the most dominating futuristic technologies and promised to bring remote monitoring into the reality. In future almost every aspects of our life is going to be touched by this technology including home safety, wildlife habitat, industrial, medical, child care, aged care, bushfire, and military battle field monitoring [2, 8].

In a typical WSN, nodes are deployed in a target field to monitor an event and can measure the usual physical phenomena like temperature, humidity, light, sound, gaseous concentration, radiation, nitrate level in the water etc. [6]. Collected information from the field is then transmitted back to the Base Station (BS) for further processing. But these battery-operated tiny sensor nodes are severely energy constraint because once they are deployed in a target field, it is impractical or often impossible to replace batteries in hundreds or thousands of nodes. Since communication is the most costly part in sensor network operation, the number of data transmission should be reduced to a possible minimum. Hence careful design of MAC protocol is required to allow only limited and meaningful information to enter into the medium.

Now the problem is to determine which data are to give priority in transmission and which one to suppress. In the case of an event monitoring system, occurrence of the particular physical event produce spatially correlated data around the event. In nature, many physical phenomena follow the diffusion laws. As a result, nodes have better information in the proximity of the phenomenon. For example, the values of the temperature are higher in the vicinity of a heat source and decrease with the distance to the source. Moreover, authors in [11] proved that if a sensor node is located far from the source, it is likely to observe more distorted version of the event. Therefore, the closer a node to the event source the more reliable and useful the information it holds. Now if we limit the number of data transmissions, we should allow only the most urgent/useful information to enter into the medium. Hence we emphasize the fact that in event monitoring application of WSNs, MAC protocol should allow the transmission based on the data characteristics and not by any random choice.

In this paper, we design a data-urgency based medium access technique. In this context our MAC protocol is data-driven, as we utilize node's data urgency levels and initiate data transmission accordingly. Neighboring nodes with less urgent data have to wait longer and if they overhear any transmission of more urgent data, they ultimately suppress their own data. Due to fewer transmission attempts, probability of collision is decreased to a significant amount which leads to a fewer retransmissions resulting in overall less energy consumption and lower delay in data delivery.

The rest of the paper is organized as follows: We discuss the related work in Section 2. The proposed data-driven MAC is discussed in details in Section 3. An environment model is presented in Section 4. The performances of our protocol are compared in Section 5. Finally, we present a brief conclusion in Section 6.

2 Related Work

Energy-efficient MAC protocols for WSNs have made contributions in mainly two parts. Firstly, the channel access mechanism is explored (i.e. the contention problem). Correlation-based Collaborative Medium Access Control (CC-MAC) [11], SIFT [7] etc. fall into this category where they demonstrated how restriction can be put on the number of data entering the medium in order to save energy in transmission. By limiting the number of data transmission within the network, they achieve higher energy efficiency and lower delay in data delivery. Secondly, researchers adopt the classic CSMA/CA based contention mechanism to access the media and made contribution in how nodes periodically follow sleep-wake cycles to save energy. Well known protocols like S-MAC [12], T-MAC [5] etc. fall into this category where they demonstrated how node-to-node data transfer can be made while following a periodic sleep-wake cycles. In this paper we focus on the contention part of the MAC protocol and propose a data-driven MAC utilizing the node's information level.

IEEE 802.11 DCF standard [1]: Though IEEE 802.11 DCF is not a protocol for WSNs; its contention mechanism is also the basic contention mechanism for many WSN MACs (e.g. S-MAC, T-MAC etc.). Therefore we discuss details about the IEEE 802.11 DCF contention mechanism. IEEE 802.11 DCF is a random access mechanism that combines the good features of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with Medium Access with Collision Avoidance Wireless (MACAW) [4] to lower the probability of packet collision. In CSMA, whenever a node intends to send data, it checks the status of the medium to find whether the medium is being currently used by any other neighboring nodes and this checking is called carrier sensing. After detecting the channel as being idle for a minimum duration called DCF Inter Frame Space (DIFS), sender performs a random backoff procedure. The duration of this random backoff time is determined as a multiple of a slot time. If the channel remains idle, the backoff time counter is decremented by one for each idle time slot. If the channel becomes busy, backoff counter is frozen until the medium becomes idle again. Once the backoff counter reaches 'zero', the device is allowed to access the medium and transmits. Each device maintains a so-called Contention Window (CW), from which sender chooses a random backoff time before transmission. Backoff Time (BT) in IEEE DCF is calculated as below:

$$BT = Random\,(0, CW_i) \times aSlotTime \tag{1}$$

Here, CW is the contention window. After each successful transmission, the contention window is reset to CW_{min}, otherwise CW_i is calculated as $CW_i = 2^{k+i-1}$, where i is the number of attempts (including the current one) that have been made to transmit the current packet, and k is a constant defining the minimum contention window CW_{min}. And $aSlotTime$ is the slot time determined by physical layer characteristics.

We can see from (1) that backoff time is a random integer value that corresponds to a slot-number. This slot-number is taken randomly from a uniform distribution. In shared wireless medium, access to the channel depends on the picked slot-number. For example, if two nodes want to access the medium at the same time, and both sense the medium is idle for DIFS amount of time, then both of them take a random backoff time (measured in slot-numbers) before actually transmit into the medium. The node which chooses lower slot-number gets access into the medium first. The node with higher slot-number waits for the other node to finish before transmits itself. But choice of the slot-number does not depend on the node itself and is completely random in nature.

CC-MAC: M.C. Vuran, and I. F. Akyldiz proposed CC-MAC for event-driven WSN applications. They were first to explore spatial correlation in designing MAC protocol for WSNs. To avoid spatial redundancy in transmitted information, CC-MAC proposes to choose only a few representative nodes to transmit data from the target field. One representative node is selected from a correlation region of the area determined by the correlation radius (r_{corr}). Authors claim that only one node is sufficient to transmit from a correlation region in order to achieve desired performance at the sink. To find the representative nodes, all sensor nodes with event information contend for the medium using random access mechanism similar to that of the IEEE 802.11 standard where some sensor nodes can access the channel while others have to backoff. After the initial contention phase, node that captures the medium first becomes the representative node of the area determined by the r_{corr}. Other nodes within the correlation region suppress their data upon overhearing the transmission of the representative node. Neighbors of the correlation region can sleep and only participate in forwarding the packets thus saving energy.

In CC-MAC, though spatial redundancy in data transmission is eliminated, but there is no control on representative node selection. Representative nodes are selected as a result of the random contention protocol, and due to the random characteristics of CSMA-based MAC protocol, there is no means to ensure that nodes with the more urgent data get prior chance in transmission.

SIFT: Jamieson et al. described SIFT as a non-persistent CSMA wireless MAC protocol. But instead of taking a random number from uniform distribution (as used in $[12, 5, 1]$), they propose to take a random number from geometric distribution to determine the transmission-slot. The non-uniform, truncated increasing geometric distribution is given in (2).

$$p_r = \frac{(1-\alpha)\,\alpha^{CW}}{1-\alpha^{CW}} \times \alpha^{-r} \quad \text{for } r = 1, 2, \cdots CW \tag{2}$$

Here $0 < \alpha < 1$ is a parameter and is defined by $\alpha = N_{max}^{-\frac{1}{CW-1}}$, where N_{max} is the maximum number of nodes that can be supported by the protocol.

By using this geometric distribution, nodes have higher probability to pick up the later transmission-slots. Only a few nodes choose lower transmission-slots and get access to the medium first. Sift also allows only R number of event reports to transmit toward the BS through message suppression. Applying the geometrically increasing distribution, SIFT can reduce the collision while there is a sudden increase in traffic load, but there is no control on which node can access the channel first. Nodes near the event with urgent data may not get opportunity to access the medium, because, with the geometrically increasing distribution, it is not possible to determine which node is finally winning the shared medium. In this paper, we propose a data-driven MAC to improve the above schemes. The details are discussed in Section 3.

3 Data-driven MAC

In event detection applications of WSNs, users are interested in getting the event-source information quickly and reliably. MAC protocols designed for such event-driven applications should give higher priority to the critical data (e.g. high temperature/gaseous concentration reading) than normal data (i.e. low temperature readings) in accessing the medium. By critical data we mean that readings that are highly indicative to the occurrence of an event under observation. For example, temperature reading that indicates an ignition nearby for bushfire monitor application or higher gaseous concentration that indicates a leakage nearby for an industrial leakage monitor application. By allowing only meaningful and urgent information to enter into the media, MAC protocol can reduce redundant transmissions and energy consumption while reducing data delay.

While CC-MAC chooses a random number from uniform distribution and SIFT chooses a random number from geometric distribution in order to deter-

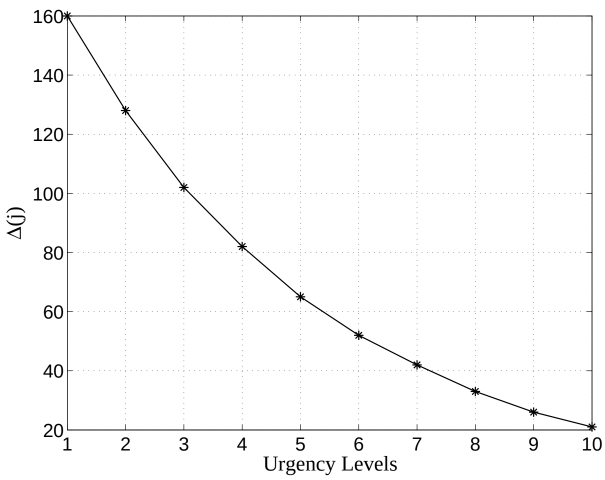

Fig. 1. Relationship between urgency levels and $\Delta(j)$.

mine the index of the transmission-slot, we propose to directly calculate the slot-number within the CW based on the urgency of the data. The main disadvantage of CC-MAC and SIFT's contention mechanism is, due to the inherent randomness in choosing the index of transmission-slot, a node with some urgent information may not have any opportunity in accessing the medium.

Instead of using any probability distribution to choose the slot-number from we propose the following equation to choose the index of the transmission-slot.

$$BT = \begin{cases} Random(0, \Delta(j)) \times aSlotTime & \text{when } j = j_{max} \\ Random((\Delta(j+1)+1), \Delta(j)) \times aSlotTime & \text{otherwise} \end{cases} \tag{3}$$

Here, $\Delta(j)$ is given by the following equation:

$$\Delta(j) = \left\lfloor \frac{(1-\alpha)^j}{\alpha \times [1-(1-\alpha)^{j_{max}}]} \times \beta \right\rfloor \quad \text{where } 0 < \alpha < 1 \tag{4}$$

Here, j represents different urgency levels namely, $1, 2, \cdots, j_{max}$. The values of j are chosen based on the sensor's measurement about the event's effect. Mapping of j's to the data readings are discussed in details in subsection 4.2.

The α is a skewness parameter and β is a scale factor. The values of these two parameters are used to adjust the size of CW. The bigger the value of α, the smaller the $\Delta(j)$ s resulting in smaller CW size and vice versa. We have seen from experiments that if the CW is too small, it creates more collisions and at the same time if the CW is too big, it can introduce unnecessary delay. Based on our observation we have taken $\alpha = 0.2$ and $\beta = 45$ and, Fig. 1 and Table 1 show the CW boundaries for different priority levels from (3) and (4), for these values of α and β.

Equation (4) ensures that node with urgent information have shortest waiting time as shown in Table 1. But considering the fact that more than one node may possess the same urgency level, we retain a small random part in our algorithm in order to alleviate the probability of nodes with same urgency levels colliding with each other.

Table 1. Urgency levels and corresponding CW boundaries

Urgency Levels	**CW boundaries** (Lower - Upper)	**Urgency Levels**	**CW boundaries** (Lower - Upper)
10 (highest)	0 - 21	5	53 - 65
9	22 - 26	4	66 - 82
8	27 - 33	3	83 - 102
7	34 - 42	2	103 - 128
6	43 - 52	1 (lowest)	129 - 160

Now, we further explain our algorithm by taking a particular scenario with different urgency levels, i.e. $j = 1, 2, \cdots, 10$ (highest-urgency-level). At first, nodes while sensing events determine their own urgency level on the basis of sensor's measurement about the event's effect (i.e. sensed-data). After deciding on the urgency level, nodes calculate the appropriate backoff time using (3). For example, if it has the highest urgency level (i.e. j_{max}), it takes a random number within the first CW (i.e. within 0 and 21) and gets chance to transmit first. Neighboring nodes suppress their own data if they overhear transmission of higher urgency data packet. If there is no data in the highest urgency level, then the nodes with second highest urgency level send their data and so on.

In order to reduce the number packets to enter into medium, we introduce a threshold in the urgency level as X_{th}. Nodes having data above X_{th} are allowed to transmit. Threshold is setup in a way that only the nodes with useful-data can access the medium. For example, no data should be transmitted when the temperature is in normal range. The urgency level is embedded in the data packets so that intermediate nodes can also access the medium appropriately based on the urgency levels of route-through packets.

4 Environment Model

In this section, we explain how urgency levels used in our proposed scheme are determined.

4.1 Modeling the Environment

Event's Effect. We used the similar environment model used in [6] to populate data in various sensor nodes around the event source. Authors in [6] argues that every physical event produces a fingerprint in the environment in terms of the event's effect; e.g., fire increases temperature, chemical spilling increases contamination, and gas leakage increases gaseous concentration. Moreover, most of the physical phenomena follow diffusion property [3] with distance, d and time t, and can be modeled as a function of distance and time, $f(d,t)$. Now, considering sensors reading at particular time instance, say t_1, diffusion can be expressed as a function of distance only, i.e., $f(d) \propto 1/d^a$, where d is the distance from the point having maximum effect of the event, $f(d)$ is the magnitude of the event's effect at d and a is the diffusion parameter depending on the type of effect; e.g., for light $a = 2$, heat $a = 1$.

Environmental Noise. A sensor readings may include noise due to surrounding condition, such a humidity, prolonged heat exposure, obstacles etc. The amount of noise included in sensor readings is less where the distance between the event source and sensor is less [11]. The noise level gradually increases with distance from the source. Including this noise, sensor's reading can be modeled as follows,

$$f(d_i) = f^*(d_i) \pm f_{env}(f^*(d_i)) \tag{5}$$

Here, $f_{env}(f^*(d_i)) \propto (f_{max} - f^*(d_i))$, d_i = distance of the location from peak information point (i.e., the event), $f(d_i)$ = gradient information of the location with environmental noise, f_{max} = peak information, $f^*(d_i) = f_(max)/d^a$ = gradient information of the location without environmental noise. In the simulation, $a = 0.8$ is taken [6]. The proportional constant is considered 0.03 as in [6] to model the environmental for our protocol, i.e., 3% environmental noise is considered.

4.2 Mapping of Sensor data to the urgency levels.

Mapping of sensed data to the urgency levels depends entirely on the target application of WSN and the nature of the physical phenomena under observation. Based on the target application, sensor readings can be varied widely including but not limited to temperature, humidity, seismic vibration, motion, acceleration etc. For example, in bushfire detection application nodes sense the ambient temperature among other possible sensing parameters and hence the ambient temperature reading can be affected by various factors like distance, obstacles, wind direction etc. As shown in Table 2, higher urgency levels are given to the higher temperature readings while the lower end (e.g. urgency levels 1, 2, and 3) actually refers to non-threat situation because these temperatures fall within the normal range. Urgency level 4 can be assumed as the upper threshold and temperatures above the threshold need reporting. For real applications, these urgency levels and upper/lower threshold can be easily further fine-tuned to suit the desired accuracy level.

5 Performance Analysis

We use $ns-2$ [9] simulator for analyzing the performance of the proposed data-driven MAC protocol. Comparisons will be made with (1) IEEE 802.11 standard and (2) SIFT which is one of the recent protocols to manage spatially correlated data. Though IEEE 802.11 standard is not suitable for WSN but its

Table 2. Mapping of temperatures with urgency levels

Ambient Temp. ($^\circ C$)	Urgency Level	Ambient Temp. ($^\circ C$)	Urgency Level
80 and above	10	50 - 59	5
75 - 79	9	40 - 49	4
70 - 74	8	30 - 39	3
65 - 69	7	20 - 29	2
60 - 64	6	0 - 19	1

contention mechanism is used as the basic access mechanism by many renowned WSN-MACs (i.e. S-MAC, T-MAC etc.) and in this paper we are focusing on the contention part to allow urgent data to reach the destination quickly. The performance of the data-driven MAC protocol has been studied in the following two scenarios: (1) a single node in the network has data of maximum-urgency and (2) multiple nodes have data of maximum-urgency. We are going to measure the following performance metrics for data-driven MAC, SIFT and IEEE 802.11 standard:

- Event reporting delay: The total delay experienced by data packets. The lower the reporting delays for the important data, the better.
- Packet delivery ratio: The ratio of the number of data packets actually delivered to the destinations versus the number of data packets supposed to be received. This number presents the effectiveness of a protocol.

These measurements indicate how quickly and reliably the urgent data are sent to the sink. They also indirectly indicate the energy consumption: lower delay means lower number of collision and lower number of retransmission resulting in lower energy consumption.

In the subsection 5.1, we discuss simulation topology and parameters. We compare the performance of the proposed MAC in subsection 5.2. In the subsection 5.3, the impact of parameter on the performances of our protocol is analysed.

5.1 Simulation Topology and Parameters

We arrange 100 nodes in a 10 by 10 grid as shown in Fig. 2. Nodes are separated by five meter from each other and the sink is located at the upper-right corner (x = 50 meter, y = 50 meter). As in [5], a radio range chosen for all nodes so that non-edge nodes all have 8 neighbors. As well, two-ray ground reflection model is used for signal propagation. The sensor nodes are modeled according to the $ns-2$ wireless node module [9]. In routing layer, we have used Ad hoc On-Demand Distance Vector (AODV) routing protocol [10] for all MACs. Data traverse a multi-hop route from source to the sink.

Event-Based Traffic: Constant-bit-rate (CBR) or TCP flows do not suffice to evaluate protocols for sensor networks, because they capture neither the burstiness inherent in the network, nor some underlying physical process that the network should be sensing [7]. We therefore propose two event-based workloads to evaluate our design. In the first, a single node is having maximum-urgency:

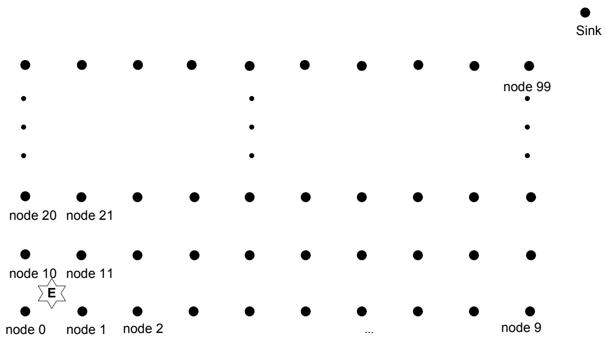

Fig. 2. 100-node network with sink situated at the right-top corner.

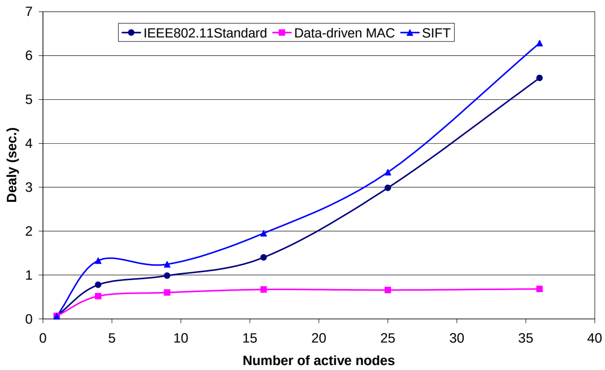

Fig. 3. Average reporting delay with respect to increasing number of active nodes.

a fire event (E) is simulated with $f_{max} = 200°C$ at $x = 3$, $y = 3$ as shown in Fig. 2. Any surrounding node calculates its urgency level based on the temperature data it has which is in turn dependent on the distance from the event source and the noise factor as discussed in Section 4. Nearby nodes have higher urgency levels than the far-away nodes. With this setup; we observed, only node 11 which is closest the event have maximum-urgency level. This can resemble to the early stage of forest fire which is just ignited. In the second, multiple nodes have maximum-urgency: we have simulated the fire with higher temperature (i.e. $f_{max} = 370°C$) and found that up to nine surrounding nodes may have maximum-urgency level. This situation can resemble to the situation when fire is reasonably spread over.

In the simulation, every node sensing the event calculates its urgency level, and then determines its backoff time using (3). After that, nodes start trying sending data (if their data is above the threshold). Neighboring nodes, upon overhearing any ongoing transmission, compare the data with their own. If the over-hearer has less important data, it suppress its data, otherwise it compete for the medium. Whenever, a node has data to send and takes transmission

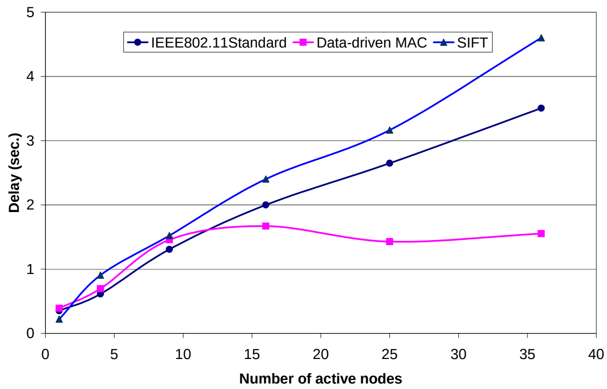

Fig. 4. First reporting delay for multiple source having maximum urgency.

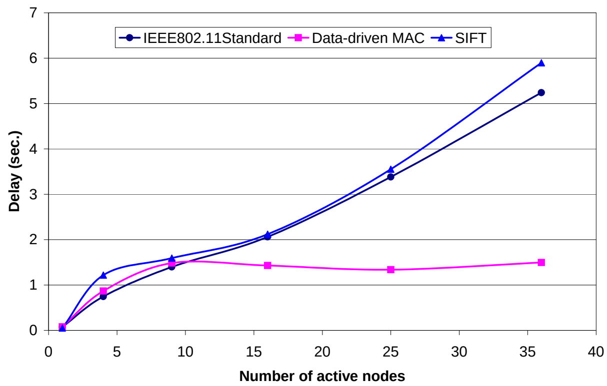

Fig. 5. Average reporting delay for multiple source having maximum urgency.

attempt, we call it in active mode and otherwise it is in the flat mode. In the flat mode, nodes do not have their own data but they take parts in forwarding other's data towards the sink. To create the worst case scenario to test protocol performance, data generation is engineered in such a way that all active nodes start to send data at the same time. For the observation purpose, at first node 11 is put into active mode and all others are taking part in forwarding. Then, the four surrounding nodes (i.e. nodes 0, 1, 10, and 11) are put into active mode. In this way 9, 16, 25 and 36 surrounding nodes are put into active modes to observe the performance under heavy traffic.

5.2 Simulation Results

Event reporting delay. This delay is calculated by subtracting (simulation) time when the maximum-urgency data are generated at a node from the time when that is received at the sink. We ran the simulation for 100 times with random seeds and calculated average delay.

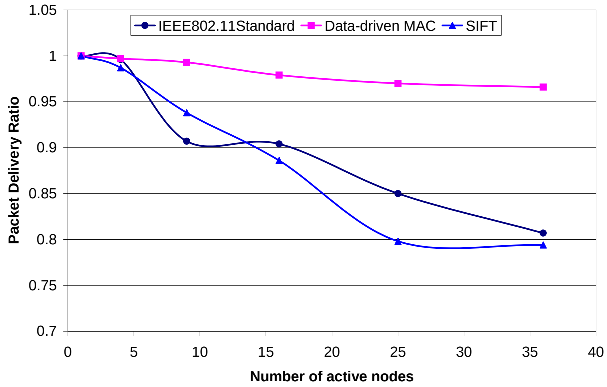

Fig. 6. Packet delivery ratio with increasing traffic.

a) Average reporting delay is given in Fig. 3 for single node having maximum-urgency scenario. The reporting delay increases with increasing number of active nodes in SIFT and IEEE 802.11. This is expected because with increasing number of contenders, probability of collision would also increase and results in higher network delay. In data-driven MAC, however the delay remains almost constant despite the increasing number of active nodes. This is because, in the single node having maximum-urgency scenario, other surrounding nodes have bigger backoff time and even far-off nodes have such low priority they eventually suppress their data allowing the maximum-urgency data to traverse quickly.

b) Average reporting delay (single report is required at the sink) for multiple nodes having maximum-urgency scenario is shown in Fig. 4. From Fig. 4, we see that all three protocols are perfoming closely until nine actives nodes. This is because, up to this point all the active nodes have maximum-urgency level and they are competing with each other. So the delays increase almost linearly with the number of active nodes. But after that when more nodes are active (i.e. in the case of 16, 25, and 36), they all compete with each other on both cases of SIFT and IEEE802.11, causing increased delay. For the data-driven MAC, the number of real competition remains almost same beyond nine active nodes (i.e. for the scenario of 16, 25 and 36 active nodes). So the reported delay remains low and almost constant.

c) Average reporting delay (multiple reports are required at the sink) for multiple nodes having maximum-urgency scenario is shown in Fig. 5. We have calculated the average delay for the three protocols when more than one reports are required at the sink to ensure the event reliability. In this case 10 reports are sent from each source. In this scenario, we also find that data-driven MAC outperforms the others.

The above discussion proved the proposed data-driven MAC protocol can deliver the urgent data more quickly.

Packet delivery ratio. This is a measure of reliability in data delivery. For the measurement of packet delivery ratio of maximum-urgency packets, ten packets are sent from each source in every run. Temperature is set up in such a way that up to four nodes may have maximum-urgency levels at any time. Simulation is repeated 100 times with different random seeds. So the ratio is calculated from the total number of packets received at the sink out of the total number packets sent from the nodes with maximum-urgency level. We see from the Fig. 6, the delivery ratio is higher in the proposed MAC than the IEEE802.11 and SIFT, and proposed protocol performs better with increasing number of contenders.

This shows that the proposed protocol is more reliable to send urgent data.

6 Conclusion

In this paper, we propose the data-driven MAC which exploits information level exists in sensor's reading in taking transmission decision. Medium access is favored to the higher-urgency level nodes which have more accurate and reliable event information. Energy efficiency is preserved by suppressing the redundant transmission from any neighboring node that has less urgent and noisier version of event information. Simulation results show that the event reporting delay is lower in our protocol than SIFT and the traditional IEEE 802.11 standard. Also the reliability factor (e.g. higher packet delivery ratio) is much higher in our proposed contention scheme than the IEEE802.11 standard and SIFT. Therefore, we can conclude that, our proposed data-driven MAC is more suitable for the event detection application of WSNs.

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