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DETECTING AND EFFECTIVE ROUTING OF TIME CRITICAL EVENTS USING CONGESTION AND DELAY AWARE ROUTING IN WSNS

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Abstract - Reliability and timeliness are two essential requirements of successful detection of critical events n Wireless Sensor Networks (WSNs). The base station (BS) is particularly interested about reliable and timely collection of data sent by the nodes close to the ongoing event, and at that time, the data sent by other nodes have little importance. In this paper, we modify Congestion and Delay Aware Routing (CODAR) protocol that tries to route data to the multiple sinks in congestion and delay aware manners. In this case every sensor communicates with the closest sink. If congestion occurs, it also mitigates congestion by utilizing an accurate data-rate adjustment. Each node collects control information from neighbours and works in a distributed manner. Experimental results show that modified CODAR protocol is capable of avoiding and mitigating congestion effectively, and performs better than similar known techniques in terms of reliable and timely event detection.

Keywords*-event reliability; congestion; timeliness; wireless sensor network.*

I. INTRODUCTION

Wireless sensor networks (WSNs) [1] have attracted increasing attention recently with the growing development of Micro-Electro-Mechanical System (MEMS). A typical WSN consists of few tens to thousands of sensor nodes that are deployed in a field and work together for a specific task. These sensors are small in size and they get their power from built-in batteries. As WSNs are frequently deployed in inaccessible areas, it is difficult to replace these batteries after depletion. Therefore, existing research works have focused mostly on energy issue [2]. But reliability remains one of the vital issues in WSNs. If a WSN is set up to detect fire in a sensitive area then we would like to get data reliably and timely from those nodes that detect higher temperatures beyond a certain threshold. Here, data delivery success rate of these critical nodes is equally important as the energy efficiency. But reliable data delivery is inherently correlated to congestion. Congestion in the network causes packet drop which reduces the reliability of data transmission. We need an effective congestion control technique to achieve the required level of reliability. In case of event sensing WSNs, time critical reliability of transmitted data is of great importance. Some event (like, fire ignition) can be controlled with minimal effort if the event is detected early. Beside the congestion control, a delay aware routing of data is necessary in these phenomena to meet the time criticality so that early detection of events is possible. In this paper, we consider applications where sensor nodes are deployed in ad-hoc manners to detect critical events in the deployed area. All sensor nodes forward their data towards a single static base station (BS). We design a routing protocol that proactively avoids congestion and meets delay requirements of transmitted data by choosing lightly loaded and low delay incurring nodes during data forwarding towards the BS. All nodes broadcast periodic control data packets describing their congestion status and delay measurements so that the neighbouring nodes can utilize these data during route selection process. The performance of the proposed scheme is highly dependent on the successful delivery of these control packets. Special effort has been made to improve the success probability of these control packets. The proposed protocol also has a congestion mitigation technique. The MAC layer always sends feedback to network layer about its achievable data forwarding rate. If the application layer has a higher traffic generation rate, the protocol suggests the application layer to lower its rate. The network layer simply drops an appropriate fraction of packets received from other nodes if the incoming rate is higher than the data forwarding rate of MAC layer. In this paper, our primary objective is to improve the reliability and the timeliness of data transmitted by the critical nodes (i.e., nodes close to the current event) through congestion avoidance and mitigation. Our contribution is three-fold: we propose (i) a simple but highly effective method to ensure desirable node density in inaccessible areas, (ii) techniques by which every node can measure the end-to-end delay of its packets reaching the BS and can route data packets in a deadline-aware manner, and (iii) a MAC layer specific approach to ensure high success probability of control data sent by different nodes in the network which are utilized by neighbouring nodes to choose appropriate routes. The rest of the paper is organized as follows: section II provides a discussion on relevant existing works, section III thoroughly explains the design issues of the proposed protocol whereas its performance has been examined in section IV and finally section V presents conclusions on this research.

II. RELATED WORK

Most of the existing congestion-control schemes [3] in WSNs aim at mitigating congestion after its formation. Protocols presented in CODA [4], Siphon [5] and TARA [6] mitigate congestion rather than avoiding it. Packets are dropped due to congestion and thus reliability of data is reduced until congestion is mitigated. Congestion avoidance reduces such packet drops. RTMC [7] provides a reliable transport with memory consideration. A node defers transmission until it gets a node with free buffer space. Although, the authors claim to achieve congestion control, actually they avoid congestion without considering delay in data transfer. CAM [8] provides a routing protocol that tries to avoid as well as mitigate congestion to ensure successful event detection. The scheme assumes a high number of critical packets (packets sent by the nodes near an event) successfully reached the BS as the successful detection of an event. But it does not consider delay of these packets. In most cases, a critical packet reaching the BS has some significance if it reaches within a time threshold after its generation at the critical node. Moreover, the performance of the protocol relies on periodic control data broadcasted by nodes; but the scheme has no special technique to ensure successful delivery of these control data. Many recent works attempt to meet delay bound of data packets reaching the BS. The technique presented in [9], considers residual-time-aware routing where each sensor node is static and randomly duty cycled of other nodes. The scheme is applicable when only one node in the network acts as a data source. Moreover, end-to-end data delivery is not guaranteed. It cannot be used in event detection system where end-to-end data delivery from multiple critical nodes is essential. In [10], Heo *et al.* present a routing protocol where each node considers energy, delay and reliability of its neighbours to choose a suitable route. Nodes periodically broadcast beacon messages to exchange control data with neighbours. The performance of the protocol highly depends on successful transmission of these beacon messages. The protocol considers IEEE 802.11 DCF as its MAC protocol, but does not take any special measure for successful transmission of beacon messages which may be collided and the performance of the protocol might be seriously degraded. Munir *et al.* develop a mathematical model to minimize the delay in the network through the choice of suitable transmission scheduling and it is described in [11]. The model particularly fits where nodes' sampling processes are independent of their transmission schemes. The model does not fit well in an event sensing network where some nodes' sampling processes abruptly change in response to an event. Also the model is computationally expensive and therefore, can be applied to networks with few nodes which is not the case for most of event sensing WSNs. Reference [12] provides an energy aware real-time routing protocol. To choose a suitable route, every node uses energy level and hop-count of its each neighbour. Hop-count of a node means the total number of intermediate nodes involved to transmit a data packet form this node to BS. The protocol uses hop-count of a node as a measurement of delay of that node, which is not correct. Due to congestion around a particular event, each link will have a different delay associated with it. Hop-counts of neighbours are obtained only once during network setup, but energy levels of neighbours are obtained periodically through control messages sent by neighbours. Like works presented in [8, 10], this protocol does not take any special measure to improve success probability of control messages. All schemes in [9 - 12] treat all data with equal importance. But we are considering event detection in WSNs where few nodes close to the ongoing event produce very important data with a high generation rate. Our aim is to route data in congestion and delay aware manners so that the highest amount of important data can reach the BS timely which is essential for successful event detection.

III. CONGESTION AND DELAY AWARE ROUTING

Congestion and Delay Aware Routing (CODAR) protocol which tries to improve end-to-end data success rate of nodes near to an event and also tries to reduce the latency of these time critical data. It considers a static WSN with a single BS where nodes generate monitoring or regular data with a low generation rate. When some nodes sense a critical event, they generate critical data with a high generation rate. To detect the event successfully, the BS needs to receive a high number of critical data packets. Moreover, each critical data packet must reach the BS within certain time after its generation. Delay of regular data arriving at the BS is not detrimental. Critical data generating nodes are called critical nodes and other nodes are called regular nodes. When the event is no longer sensible, the critical nodes become regular nodes.

A. Congestion Avoidance

All nodes have the same fixed transmission power as scheduled MAC (like TDMA) protocols may prolong the latency of event notification at the BS, we consider contention based MAC protocols. Like CAM [8], a utility function f is defined in (1). When any node B forwards a packet, it chooses the highest f-valued node among its neighbours.

$$f(k) = \alpha \times \frac{D_k}{D} + (1-\alpha) \times RSR_k$$

where Dk is the distance of the next node k towards the BS from node B, D is the maximum distance that can be covered by the transmission power of each node, $RSRk$ is the relative success rate of node k defined as the ratio of the number of packets transmitted from MAC layer to the number of packets forwarded from network layer to MAC layer over a small period, and $0 < \alpha < 1$. To calculate f for each neighbour k, node B needs the values of Dk and $RSRk$. CODAR assumes that each node knows its location. Each node k can broadcast its locationand RSR value using control packets after receiving a fixed number of packets from other nodes or after a fixed interval whichever is earlier. Using own and k's locations, B can calculate Dk. The last term in f helps to reduce congestion formation by choosing lightly congested nodes. In CAM [8], it is analytically shown that the distance parameter in (1) ensures high end-to-end data success rate at the BS. But this is true when nodes are deployed with uniform node density. Having uniform node density in inaccessible fields is challenging. We proposed a novel approach in section III-C for ensuring uniform node density in inaccessible areas.

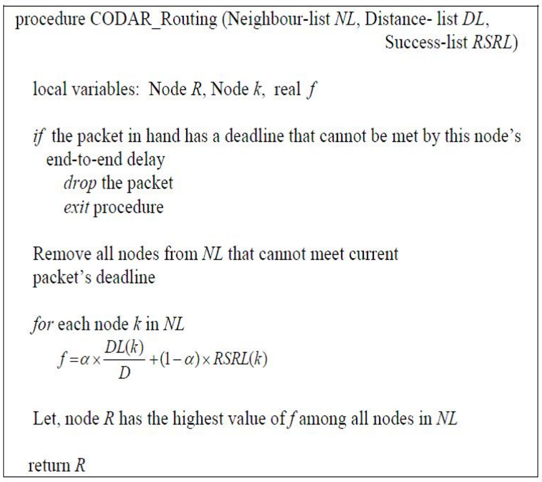
B. End-to-end Delivery Delay Management

Each node has measurements of end-to-end delays of its data packets. A node can easily determine the delay of a packet 358 (queuing delay plus medium access delay) inside it. As sensor nodes are densely deployed and the communication range is very small, propagation delay can be ignored. MAC layer records the current time TC when a packet arrives from higher layer. Subsequently, the packet is transmitted and MAC layer receives acknowledgement form receiving node for this packet at time TA. Now, total delay of this packet inside this node is TA - TC – TACK – TP, where TACK is time duration of acknowledgement packet and TP is the processing time, i.e., the interval between the receipt of the packet at the receiving node and transmission of acknowledgement. Of course, TP is dependent on the particular MAC protocol in use. The nodes having direct communication to the BS get their end-to-end delays in this way. With other information, they periodically broadcast delay data using the control packets (section III-A). After receiving these control packets, other nodes can calculate their end-to-end delays by adding their own delays to their neighbours' end-to-end delays. By continuing this process, finally all nodes get their end-to-end delays. Each critical data packet has a header field that indicates its deadline by which it should reach the BS. The deadline field is set by the source node and its presence indicates that the packet is critical. All intermediate nodes check this field before forwarding the packet. If an intermediate node has end-to-end delay that cannot meet packet's deadline then the node simply drops the packet to reduce unnecessary futile packets. The routing part of CODAR is described in ALGORITHM I. It is possible that each node can estimate its end-to-end delay in case of particular MAC and routing protocols under a specified node density, and it will eliminate the necessity of measuring and broadcasting of practical delay values. But the problem with this estimation is that it is only an *average value* not an *instantaneous* measurement. When a critical event occurs, the nodes need to ensure instantaneous (not average) timeliness of critical packets. On the contrary, in case of practical instantaneous delay measurement, the performance of each node will highly depend on the successful receipt of delay measurements of its neighbours. In sub-section F, we developed a technique to ensure high success probability of control messages carrying the delay measurements.

C. Ensuring Uniform Node-density

Although planned deployments of nodes in accessible environments are possible, inaccessible areas often require aerial dropping of sensor nodes in which case uniform node density achievement is a challenging task. One novel solution is first to deploy nodes with a high density. Each node then finds its position through localization techniques [13, 14] and sends its location to the BS. After getting all nodes' locations, the BS will select the necessary nodes to be active to cover the maximum possible sensing area and will instruct other nodes to remain inactive. The network will now operate only with active nodes ensuring coverage while achieving approximately uniform node-density. Still this process may leave some void spots creating connectivity problem. Deployment with high density of nodes will solve the connectivity problem, but it cannot eliminate it totally. There will be some spots where node-density would be insufficient causing connectivity disruption of some parts of the network to the BS. To solve this problem we can deploy nodes with communication range higher than their sensing range.

ALGORITHM I. CONGESTION AND DELAY AWARE ROUTING



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procedure CODAR_Routing (Neighbour-list NL, Distance- list DL,
                                          Success-list RSRL)

  local variables:  Node R, Node k,  real f

  if the packet in hand has a deadline that cannot be met by this node's
     end-to-end delay
        drop the packet
        exit procedure

  Remove all nodes from NL that cannot meet current
  packet's deadline

  for each node k in NL
       $f = \alpha \times \frac{DL(k)}{D} + (1-\alpha) \times RSRL(k)$

  Let, node R has the highest value of f among all nodes in NL

 return R
```

This solution is also helpful in case of planned deployment where both ranges might be equal. If nodes have higher communication range then active nodes remain connected to BS after energy depletion of some intermediate nodes. Of course, the network will lose some sensing coverage. Empirical study can determine the required ratio of communication range to sensing range for different sizes of sensing fields. CODAR desires uniform node density and this technique is a part of network setup phase only. It may be noted that uniform node density is desirable but not mandatory in the operation of CODAR.

D. Congestion Mitigation

Network layer calculates *RSR* with the feedback from MAC layer and sends the value of *RSR* to the application layer. If the value of *RSR* is less than 1, the application layer reduces its data generation rate to *RSR* factor of the current rate. If the application layer has a lower data generation rate than its targeted rate and the value of *RSR* is 1 (which is the maximum possible value), then it increases its data generation rate by a small factor (10% of current rate). In this way, the application layer always maintains its targeted data generation rate when there is no congestion. For packets coming from other nodes, network layer simply forwards *RSR* factor of the packets to MAC layer and drops the remaining ones. While dropping packets coming from other nodes, the network layer tries to forward as many critical packets (packets sent by nodes close to the event) as possible so that the BS can get the maximum number of critical packets to be able to detect the event reliably and timely. If the network layer finds a deadline field in a packet then it understands that it is a critical packet.

E. MAC Layer Queue Management

The aim of CODAR is to deliver high amount of critical data within specified delays. When a critical data packet comes from network layer to MAC layer, the packet is inserted in the transmission queue according to its deadline with the packet having earliest deadline at the front. Each regular data packet is appended at the rear of the same queue. This technique will reduce the average delay of critical packets although it will increase the delay of regular packets at the same time. Each control packet (that includes location, delay and *RSR* information of a node) is placed exactly at the front of the queue.

F. Improving the Success Probability of Control Data

The performance of CODAR highly relies on successful receipt of control packets broadcast by different nodes. Techniques to improve the success probability of these control packets are specific to a particular MAC layer protocol. Our proposition is so far valid for any contention-based MAC protocol. But this subsection is only devoted to a widely used MAC protocol, IEEE 802.11 DCF. For other MAC protocols, similar techniques might be available. We have a very simple but highly effective technique to improve the success probability of control packets. When a node decides to broadcast a control packet, it first broadcast it using the protocol described in IEEE 802.11 DCF. After completing its transmission, the same node waits for Short Inter-Frame Space (SIFS) time and then immediately retransmits the same control packet. We can consider two neighbouring nodes *S* and *R* who have collision domains called *CS* and *CR* respectively (Fig. 1). In CODAR, nodes periodically broadcast control packets, but independently of one another. Therefore, there is a little chance that node *S* and any other node in *CS* (including *R*) will broadcast control packets at the same time. If *S* and *R* transmit control packets at the same time, then they both will retransmit packets after SIFS time and in this case, none's control packet will succeed. But there is a high probability that only node *S* in *CS* sends a control packet at a time. This first control packet may easily collide with other node's data packet. After collision, other than *S*, all nodes wait for Distributed Inter-Frame Space (DIFS) time before transmitting any data. As *S* retransmits control packet after SIFS time (SIFS < DIFS), all other nodes in *CS* can sense that transmission and they all wait until *S* finishes its transmission. So control packet of *S* will not be destroyed by other nodes' data inside *CS*. But not all neighbours of *S* will successfully receive that control packet. Node *T* is in *CR* but not in *CS*. *T* cannot sense *S*'s transmission. Therefore, it can transmit both times when *S* broadcast the control packet resulting in garbled receipt of *R* about *S*'s control packet. But this probability is low and our simple technique will significantly improve success probability of the control packets.

IV. PERFORMANCE EVALUATION

To evaluate the performance of CODAR, we compared it with similar protocol CAM [8]. CAM provides high success rate of critical data in the presence of regular data through congestion avoidance and mitigation. But CAM considers critical data as delay insensitive which is not true in case of critical events. CODAR ensures high success rate of delay sensitive critical data.

A. Simulation Environment

We have run simulations using OPNET [15] modeler software. We placed 196 sensor nodes in an area of 345 metre × 345 metre with uniform node distribution. One BS is placed at location (345, 172). Desired node density is achieved by applying the technique described in section III-C. All nodes have a fixed transmission power. We considered ideal environment (i.e., no obstacle) and also considered energy expenditure only during transmission (as energy loss during reception is low). We employed 1 Mbps IEEE 802.11 DCF MAC protocol. An event occurs at location (50, 50). All nodes within 40-metre radius of this location generate critical data with a high generation rate. The remaining nodes generate regular data with a low generation rate. In CODAR, we set α =0.50.

B. *Simulation Results*

We conducted three different types of experiments. In first type of experiments, transmission range of each node and the critical data generation rate are kept fixed whereas the regular data generation rate is varied. Data generation rate is denoted by *pps* (packets per second). Transmission range of nodes and the regular data generation rate remain constant while the critical data generation rate is varied in second type of experiments.

In third type of experiments, both data generation rates are constant and transmission range of nodes is varied. In each experiment, packet success rates and average packet delays of both regular and critical data, and the maximum node energy consumption are measured. As we are interested in reliable and timely event detection and we have limited space here, we showed packet success rate and average packet delay of critical data, and maximum node energy spent in the network under different conditions. Lifetime of the network is limited by the maximum energy used by any node in the network. Fig. 2(a) shows average packet success rate of critical data at BS from all critical nodes under different generation rates of regular data where data generation rate of each critical node is 15 pps and transmission range of all nodes is 80 metres. Fig. 2(b) shows average delay of critical data at BS and Fig. 2(c)shows maximum node energy spent in the network under same conditions. With the increase in regular data generation rate, the congestion status of all nodes deteriorates which causes higher number of packet drops and eventually reduces the average success rate of critical data at the BS as shown in Fig. 2(a). The average delay of critical data at the BS is also increased in Fig. 2(b) because worse congestion condition causes higher number of transmission & attempts for packets at each node. In both Fig. 2(a) and 2(b), from each node to the BS, and it drops a particular data packet when the current node cannot meet the deadline of that packet. In this way, CODAR reduces congestion caused by unfruitful data transmission.

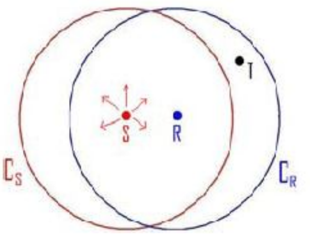
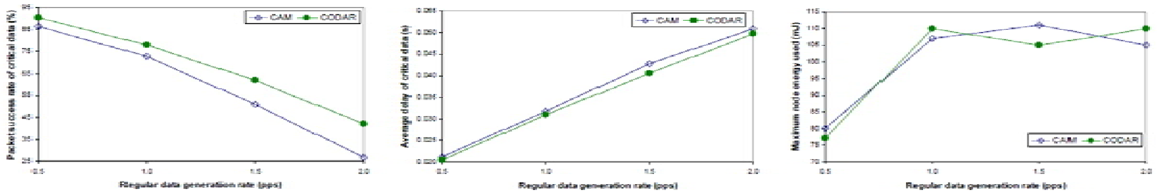


Figure 1. Node S broadcasts a control packet

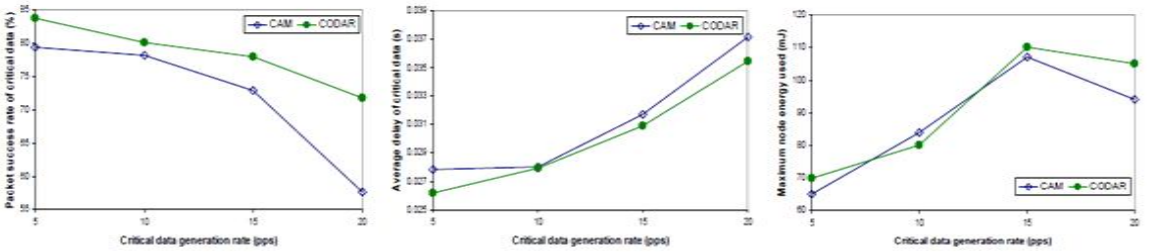
As a result, CODAR has lower congestion than CAM and consequently it has 4.5% to 56.43% higher packet success rate and also a lower packet delay of critical data than those of CAM. Maximum node energy spent by any node in the network as shown in Fig. 2(c) increases by increased congestion in the network caused by higher generation rate of regular data. In Fig. 2(c), maximum node energies used in both CAM and CODAR are comparable. Fig. 3(a)-3(c) show same three parameters as in Fig. 2(a)-2(c) under different data generation rates of critical nodes while data generation rate of each regular node is 1 pps and transmission range of all nodes is 80 metres. As congestion in the network is increased by increased generation rate of critical data, the average success rate of critical data at the BS decreases and the average delay of critical data at the BS increases as shown in Fig. 3(a) and Fig. 3(b) respectively.

Due to the congestion reduction through the dropping of unreachable packets in CODAR, it has a lower packet delay and 2.5% to 24.5% higher success rate of critical data delivery at the BS than those found in CAM. Fig. 3(c) shows that maximum node energies used in CAM and CODAR are comparable in this case also. Fig. 4(a)-4(c) show same parameters under different transmission ranges of nodes while data generation rates of regular and critical nodes are kept fixed at 1 pps and 15 pps respectively. When the transmission range of nodes is increased, the number of nodes in collision domain of each transmitting node is also increased. This causes lower success probability and higher delay of transmission in each hop. But due to higher transmission range, the total number of hops for each data packet to reach the BS is reduced which tends to increase overall success rate and reduce total delay at the BS. Energy required to transmit a packet increases with increased transmission range of the node.



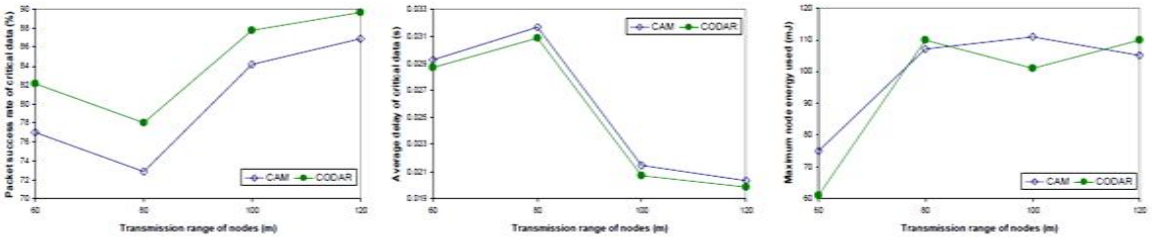
(a) (b) (c)

Figure 2: (a) Packet success rate of critical data, (b) average delay of critical data, (c) maximum node energy used, under different generation rates of regular data (critical data generation rate = 15 pps and transmission range of nodes = 80m)



(a) (b) (c)

Figure 3: (a) Packet success rate of critical data, (b) average delay of critical data, (c) maximum node energy used, under different generation rates of critical data (regular data generation rate = 1 pps and transmission range of nodes = 80m)



(a) (b) (c)

Figure 4: (a) Packet success rate of critical data, (b) average delay of critical data, (c) maximum node energy used, under different transmission ranges of nodes (critical data generation rate = 15 pps, regular data generation rate = 1 pps)

Therefore, the maximum node energy spent by any node should increase as it is found in Fig.4(c), and also the performances of CODAR and CAM is again comparable here. CODAR has a lower packet delay and 3.2% to 7.1% higher success rate of critical data at the BS than those found in CAM. But there are abnormal behaviours in Fig. 4(a) and Fig. 4(b) when transmission range changes from 60 metres to 80 metres. Regular data generation rate is 1 pps which is low compared to critical data generation rate of 15 pps. As a result, when the collision domain of a node includes more number of regular nodes, the success probability of its transmission is affected by a little. But when the collision domain of a node includes more number of critical nodes, the success probability is highly reduced. In our experiment, all critical nodes reside in a region having a diameter of 80 metres. When transmission range increased from 60 metres to 80 meters, the collision domain of each critical node contains a large number of critical nodes which reduces success probability and also increases transmission delay of each critical node significantly. Therefore, performances deteriorate in Fig. 4(a) and Fig. 4(b) when transmission range increases from 60 metres to 80 metres. But when transmission range increases above 80 metres, collision domain of each critical node adds more number of regular nodes only, which does not affect performance significantly. Moreover, due to a lower number of transmissions required to transmit a packet from a critical node to the BS as a result of higher transmission range, end-to-end success probability and end-to-end delay of critical data at the BS is increased and reduced respectively. Therefore, higher transmission range above 80 metres gradually increases end-to-end success probability and reduces end-to-end delay of critical data at the BS. In all experiments, CODAR achieves more number of critical data packets at the BS within lower average packet delay than that achievable in CAM. This achievement of CODAR yields more reliable and timely detection of critical events.

V. CONCLUSION

Congestion and Delay Aware Routing (CODAR) protocol presented in this paper has the potential to reduce congestion by avoiding congested nodes during route selection process and also by dropping of futile data packets. It provides high success rate by accurately adjusting data rate of a node during congestion mitigation. In achieving its successs, CODAR utilizes congestion parameters into routing decision and at the same time, it works in a distributed manner as it needs control data only from neighbouring nodes. It also endeavours to provide better success rate of control packets which increases its reliability. Simulation results show that CODAR provides significantly high success rate and low average packet delay ofcritical data which eventually results in reliable and timely event detection. Future study will focus on analysing the effect of adaptive value of the weighting factor α in the utility function *f*. As individual nodes are located at different parts of the network, different values of α for different nodes might accurately sense the node’s congestion level and which in turn might help better congestion management.

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