DST: Delay Sensitive Transport in Wireless Sensor Networks

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***Abstract*—In this paper, the delay sensitive transport (DST) protocol is presented for wireless sensor networks (WSN). The objective of the DST protocol is to timely and reliably transport event features from the sensor field to the sink with minimum energy consumption. In this regard, the DST protocol simultaneously addresses congestion control and timely event transport reliability objectives in WSN. In addition to its efficient congestion detection and control algorithms, it incorporates the Time Critical Event First (TCEF) scheduling mechanism to meet the application-specific delay bounds at the sink node. Importantly, the algorithms of the DST protocol mainly run on resource rich sink node, with minimal functionality required at resource constrained sensor nodes. Performance evaluation via simulation experiments show that the DST protocol achieves high performance in terms of real-time communication requirements, reliable event detection, and energy consumption in WSN.**

I. INTRODUCTION

The recent advances in Micro Electro-Mechanical Systems (MEMS) and wireless communication technologies have enabled the realization of wireless sensor network (WSN) paradigm. In general, WSNs are comprised of large number of low-cost, low-power, multifunctional sensor nodes. Through short distance and multi-hop communications, these tiny sensor nodes collaboratively work towards achieving the application-specific objectives of the deployed WSN. In fact, the existing and potential applications of WSN span a very wide range including homeland security, environmental monitoring, biomedical research, human imaging and tracking, and military applications [2]. The practical realization of these currently designed and envisioned applications, however, directly depends on the efficient real-time and reliable communication capabilities of the deployed sensor network.

Recently, there has been considerable amount of research efforts which have yielded many promising communication protocols to address the challenges posed by the WSN paradigm [2]. The common feature of these research results is that they mainly address the energy-efficient and reliable data communication requirements of WSN. However, in addition to the energy-efficiency and communication reliability, there exist many proposed *WSN applications which have strict delay bounds and hence mandate timely transport of the event features from the field.*

Many of the potential WSN applications such as real-time target tracking, homeland security, process control, controlling the vehicle traffic in highways necessitate the reliable event transport to be achieved within a certain application-specific delay bound. For instance, the accuracy and effectiveness of military WSN applications such as border surveillance and intrusion detection are directly related to the timeliness of the reliable event detection at the sink, e.g., military decision center. Clearly, late detection of a certain event at the sink leads to the failure of the ultimate objectives of the deployed WSN for such applications. Therefore, the communication protocols, which only consider the energy-efficiency and transport reliability, are deemed to be incapable of addressing the needs of applications, which have certain delay bounds.

Consequently, to assure reliable and timely event detection in WSN, reliable event transport to the sink node within a certain delay bound must be effectively handled by an efficient transport protocol mechanism. Several transport protocols have been developed for sensor networks in recent years [2]. These protocols are mainly designed for congestion control and reliable data delivery from the sink to the sensor nodes [6],[13] and from the sensor nodes to the sink [1],[8],[12]. However, none of these protocols address the application-specific real-time delay bounds of the reliable event transport in WSN. Clearly, there is an urgent need for a new real-time and reliable data transport solution with efficient congestion detection and control mechanisms for WSN.

To address this need, in this paper, the Delay Sensitive Transport (DST) protocol is introduced for WSN. The DST protocol is a novel transport solution that seeks to achieve reliable and timely event detection with minimum energy consumption and no congestion. It enables the applications to perform right actions timely by exploiting both the correlation and the collaborative nature of sensor networks. To achieve this objective, based on event transport reliability and event-to-sink delay bound, *a delay-constrained event-to-sink reliability* notion is defined.

We emphasize that the DST protocol has been designed for use in typical WSN applications involving event detection and signal estimation/tracking within a certain delay bound, and not for guaranteed end-to-end data delivery services. Our work is motivated by the fact that the sink is only interested in timely and reliable detection of event features from the collective information provided by numerous sensor nodes and not in their individual reports, as illustrated in Fig. 1. The notion of delay-constrained event-to-sink reliability distinguishes the DST

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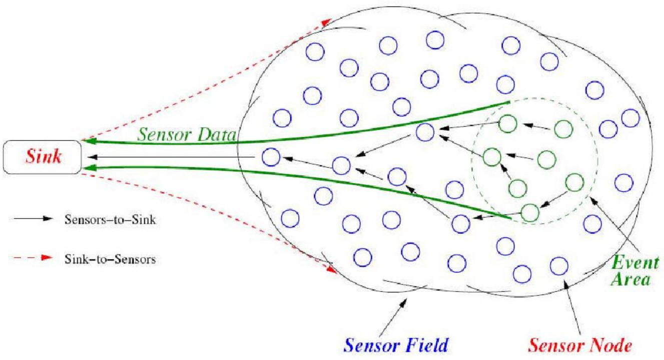


Fig. 1. Typical wireless sensor network architecture. The sink is only interested in collective information of sensor nodes within certain delay bound and not in their individual data.

protocol from other existing transport layer models that focus on end-to-end reliability. To the best of our knowledge, reliable transport in WSN has not been studied from this perspective before and this is the first research effort focusing on real-time and reliable event data transport with minimum energy consumption in WSN.

The remainder of the paper is organized as follows. In Section II, we describe the design principles and functionalities of the DST protocol in detail. In Section III, we explain combined congestion detection and control mechanism of the DST protocol. The detailed protocol operation of the DST is described in Section IV. Performance evaluation and simulation results are presented in Section V. Finally, the paper is concluded in Section VI.

II. DST PROTOCOL DESIGN

In the following sections, we first discuss the main design components of the DST protocol in detail and then we present a case study to gain more insight regarding the challenges of wireless sensor networks.

A. Reliable Event Transport Mechanism

In WSNs, sensors-to-sink transport does not require 100% reliability due to the correlation among the sensor readings [1],[11]. Hence, conventional end-to-end reliability definitions and solutions would only lead to over-utilization of scarce sensor resources. On the other hand, the absence of reliable transport mechanism altogether can seriously impair event detection. Thus, the sensors-to-sink transport paradigm requires a collective event-to-sink reliability notion rather than the traditional end-to-end reliability notion. The DST protocol also considers the new notion of *event-to-sink delay bound* (described in Section II-B) to meet the application deadlines for proper operation of the deployed network. Based on both event-to-sink reliability and event-to-sink delay bound notions, we introduce the following definitions:

- The *observed delay-constrained event reliability* (DR_i) is the number of received data packets within a certain delay bound at the sink in a decision interval i.
- The *desired delay-constrained event reliability* (DR^*) is the minimum number of data packets required for reliable event detection within a certain application-specific delay bound. This lower bound for the reliability level is determined by the application and based on the physical characteristics of the event signal being tracked.
- The *delay-constrained reliability indicator* (δ_i) is the ratio of the observed and desired delay-constrained event reliabilities, i.e., $\delta_i = DR_i/DR^*$.

Based on the packets generated by the sensor nodes in the event area, the event features are estimated and DR_i is observed at each decision interval i to determine the necessary action. If the observed delay-constrained event reliability is higher than the reliability bound, i.e., $DR_i > DR^*$, then the event is deemed to be reliably detected within a certain delay bound. Otherwise, appropriate action needs to be taken to assure the desired reliability level in the event-to-sink communication. For example, to increase the amount of information transported from the sensors to the sink, reporting frequency of the sensors can be increased properly while avoiding congestion in the network. Therefore, sensors-to-sink transport reliability problem in WSN is to *configure the reporting rate, f, of source nodes so as to achieve the required event detection reliability, DR^*, at the sink within the application-specific delay bound.*

B. Real-Time Event Transport Mechanism

To assure reliable and timely event detection, it is imperative that the event features are reliably transported to the sink node within a certain delay bound. We call this *event-to-sink delay bound*, Δ_{e2s}, which is specific to application requirements and must be met so that the application-specific objectives of the sensor network operation are achieved. The event-to-sink delay bound has two main components as outlined below:

1) **Event transport delay (Γ^{tran}):** It is mainly defined as the time between when the event occurs and when it is reliably transported to the sink node. Therefore, it involves the following delay components:
    a) *Buffering delay ($t_{b,i}$):* It is the time spent by a data packet in the routing queue of an intermediate forwarding sensor node i. It depends on the current network load and transmission rate of each sensor node.
    b) *Channel access delay ($t_{c,i}$):* It is the time spent by the sensor node i to capture the channel for transmission of the data packet generated by the detection of the event. It depends on the channel access scheme in use, node density and the current network load.
    c) *Transmission delay ($t_{t,i}$):* It is the time spent by the sensor node i to transmit the data packet over the wireless channel. It can be calculated using transmission rate and the length of the data packet.
    d) *Propagation delay ($t_{p,i}$):* It is the propagation latency of the data packet to reach the next hop over the wireless channel. It mainly depends on the distance and channel conditions between the sender and receiver.

2) **Event processing delay (Γ^{proc}):** This is the processing delay experienced at the sink, when the desired features of event are estimated using the data packets received from the sensor field. This may include a certain decision interval [1] during which the sink waits to receive adequate samples from the sensors.

Let Δ_{e2s} be the event-to-sink delay bound for the data packet generated by the detection of event. Then, for a reliable and timely event detection, it is necessary that

$$\Delta_{e2s} \geq \Gamma^{tran} + \Gamma^{proc} \qquad (1)$$

is satisfied. Here, Γ^{tran} is clearly a function of $t_{b,i}$, $t_{c,i}$, $t_{t,i}$, $t_{p,i}$, and $\hat{N}$, where $\hat{N}$ is the average hop count from the source nodes to the sink node. Note that Γ^{tran} is directly affected by the current network load and the congestion level in the network. In addition, the network load depends on the event reporting frequency, f, which is used by the sensor nodes to send their readings of the event. Hence, the main delay component that depends on the congestion control and thus, can be controlled to a certain extent is the event transport delay, i.e., Γ^{tran}. More specifically, the buffering delay, i.e., $t_{b,i}$, directly depends on the transport rate of the event and the queue management and service discipline employed at each sensor node i. In addition, for the events occurring at further distances to the sink node, the average number of hops that event data packets traverse, $\hat{N}$, increases. Thus, it is more difficult to provide event-to-sink delay bound for further event packets compared to closer ones. Considering that the per-hop propagation delay, $t_{p,i}$, does not vary[1], then the buffering delay, $t_{b,i}$, must be controlled, i.e., decreased, in order to compensate the increase in the event transport delay so that the event-to-sink delay bound is met.

TABLE I

NS-2 SIMULATION PARAMETERS

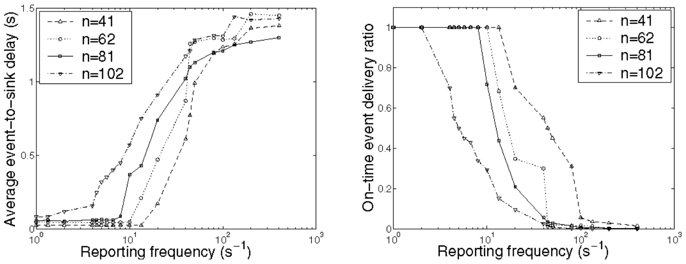
Area of sensor field	200x200 m^2
Number of sensor nodes	200
Radio range of a sensor node	20 m
Packet length	30 bytes
Buffer length	65 packets
Transmit Power	0.660 W
Receive Power	0.395 W
Idle Power	0.035 W
Decision interval (τ)	1 s

To accomplish this objective, the DST protocol introduces *Time Critical Event First* (TCEF) scheduling policy. In fact, TCEF policy applies the general principles of Earliest Deadline First service discipline on each sensor node, which is shown to be the optimal scheduling policy when real-time deadlines of the system are considered [3],[7]. However, we also integrate some novel mechanisms so as to fit it to unique challenges of sensor networks. For example, to update the remaining time to deadline without a globally synchronized clock in the network, we measure the elapsed time at each sensor and piggyback the elapsed time to the event packet so that the following sensor can determine the remaining time to deadline without a globally synchronized clock. Then, by using these elapsed time measurements and service index assignments of TCEF policy, the event packets are given high priority at the sensor nodes, as their remaining time to deadline decreases. This way, time critical sensor data obtain high priority along the path from the event area to the sink node and is served first, which is crucial to meet the application deadlines. The details of elapsed time measurement and service index assignment mechanisms of TCEF scheduling is omitted due to the lack of space.

TABLE II

RANDOMLY SELECTED EVENT CENTERS USED IN THE SIMULATIONS

Number of source nodes	**Event center** (X_{ev}, Y_{ev})	**Event radius**
41	(75.2, 72.3)	$30m$
62	(52.1, 149.3)	$30m$
81	(59.2, 68.1)	$40m$
102	(90.6, 119.1)	$40m$



(a) (b)

Fig. 2. The effect of varying reporting frequency of source nodes on (a) average event-to-sink delay and (b) on-time event delivery ratio. The number of source nodes is denoted by n.

Note that although TCEF policy makes it possible to meet deadlines in the normal operating conditions of the network, in case of severe network congestion, it may become insufficient to provide delay-constrained event reliability. Hence, in addition to TCEF scheduling, the DST protocol considers the event-to-sink delay bounds and congestion conditions in its reporting rate update policies to assure timely and reliable event transport (see Section IV). In the following, we present a case study to gain more insight regarding the communication challenges of sensor network.

C. Case Study

To investigate the relationship between the event-to-sink delay and the event reporting rate, we develop an evaluation environment using ns-2 [9]. The parameters used in our case study are listed in Table I. Event centers (X_{ev}, Y_{ev}) were randomly chosen and all sensor nodes within the event radius behave as sources for that event. In this case study, the sink node receiving the data is placed in the middle of the lower side of the deployment

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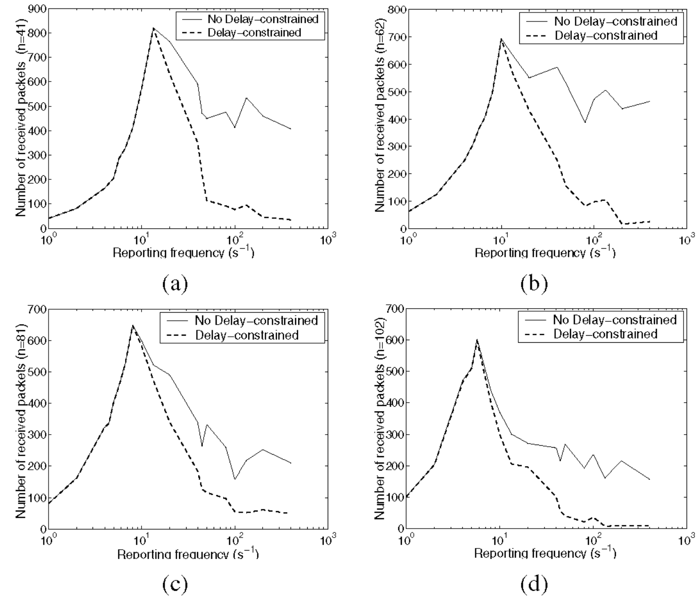
[1] While the channel access delay can also be controlled to a certain extent via priority-based QoS-aware MAC protocols [2], we do not assume the presence of such MAC protocol.



(a) (b)

(c) (d)

Fig. 3. The number of received packets at the sink in a decision interval, when the number of sources, (a)$n = 41$, (b)$n = 62$, (c)$n = 81$, (d)$n = 102$.

area. To communicate source data to the sink node, we employed a simple CSMA/CA based MAC protocol and Dynamic Source Routing (DSR) [5]. For each simulation, we run 10 experiments and take the average of the measured values.

First, we investigate the impact of event reporting frequency on average event-to-sink delay and *on-time event delivery ratio*. Here, on-time event delivery ratio represents the fraction of data packets received within event-to-sink delay bound (which we refer to reliable packets) over all data packets received in a decision interval. The results of our study are shown in Fig. 2 for different number of source nodes, i.e, $n = 41, 62, 81, 102$. Note that each of these curves was obtained by varying the event reporting frequency, f, for a randomly chosen event center (X_{ev}, Y_{ev}) and corresponding number of sources, n. These values are tabulated in Table II.

As shown in Fig. 2(a) and 2(b), it is observed that as the event reporting frequency, f, increases, average event-to-sink delay remains constant and on-time event delivery is ensured, until a certain $f = f_{max}$ at which network congestion is experienced. After this point, the average event-to-sink delay starts to increase and on-time event delivery cannot be provided. This is obvious because the increased network load due to higher reporting frequency leads to increase in the buffer occupancy and network channel contention. Moreover, as the number of sources increases, on-time event delivery ratio cannot be provided even at lower reporting frequencies.

To further elaborate the relationship between observed delay-constrained event reliability, DR_i, and the event reporting frequency, f, we have observed the number of packets received at the sink node in a decision interval, τ. As shown in Fig. 3, until a certain $f = f_{max}$, observed delay-constrained event reliability and no delay-constrained event reliability[2] coincides, beyond which delay-constrained event reliability significantly deviates from no delay-constrained event reliability. Furthermore, the observed delay-constrained event reliability, DR_i, shows a linear increase (note the log scale) with source reporting rate, f, until a certain $f = f_{max}$, beyond which the observed delay-constrained event reliability drops. This is because the network is unable to handle the increased injection of data packets and packets are dropped because of network congestion and contention. Note that such an initial increase and a subsequent decrease in observed delay-constrained event reliability is observed regardless of the number of source nodes, n. It is also important to note that f_{max} decreases with increasing n, i.e., network congestion occurs at lower reporting frequencies with greater number of source nodes.

In summary, with increasing reporting frequency, f, a general trend of an initial increase and a subsequent decrease (due to network congestion) in delay-constrained event reliability is observed in our preliminary studies, as shown in Fig. 3. Furthermore, when the application specific event-to-sink delay bound is considered, the observed delay-constrained event reliability decreases significantly with the network congestion. These observations confirm the urgent need for a delay-constrained event-to-sink reliable transport solution with an efficient congestion detection and control mechanism in WSN. In the following section, combined congestion detection mechanism of the DST protocol is described in detail.

III. CONGESTION DETECTION AND CONTROL

In WSNs, because of the memory limitations of the sensor nodes and limited capacity of shared wireless medium, congestion might be experienced in the network. Congestion leads to both waste of communication and energy resources of the sensor nodes and also hampers the event detection reliability because of packet losses [1],[10]. Hence, it is mandatory to address the congestion in the sensor field to achieve reliable event detection and minimize energy consumption.

However, the conventional sender-based congestion detection methods for end-to-end congestion control purposes cannot be applied here. The reason lies in the notion of delay-constrained event reliability rather than end-to-end reliability. Only the sink node, and not any of the sensor nodes, can determine the delay-constrained reliability indicator $\delta_i = DR_i/DR^*$, and act accordingly. In addition, for efficient congestion detection in WSNs, the sensor nodes should be aware of the network channel condition around them, since the communication medium is shared and might be congested with the network traffic among other sensor nodes in the neighborhood [4]. Therefore, because of shared communication medium nature of WSNs, the sensor nodes can experience congestion even if their buffer occupancy is small.

In this regard, the DST protocol uses a *combined congestion detection* mechanism based on both average node delay calculation and local buffer level monitoring of the sensor nodes to

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[2] No delay-constrained event reliability represents the number of event packets received at the sink node irrespective of their packet delay.

accurately detect congestion in the network. Note that average node delay at the sensor node gives an idea about the contention around the sensor node, i.e., how busy the surrounding vicinity of the sensor node. To compute the average node delay at the sensor i, the sensor takes exponential weighted moving average of the elapsed time measurements (see Section II-B).

In combined congestion detection mechanism of the DST protocol, any sensor node whose buffer overflows due to excessive incoming packets or average node delay is above a certain delay threshold value is said to be congested and it informs the congestion situation to the sink node.[3] More specifically, the sink node is notified by the upcoming congestion condition in the network by utilizing the *Congestion Notification* (CN) bit in the header of the event packet transmitted from sensors to the sink node. Therefore, if the sink node receives event packets whose CN bit is marked, it infers that congestion is experienced in the last decision interval. In conjunction with the delay-constrained reliability indicator, δ_i, the sink can determine the current network condition and adjust the reporting frequency of the sensors.

IV. REPORTING FREQUENCY UPDATE POLICIES

In the previous sections, based on delay-constrained event reliability and event-to-sink delay bound notions, we had defined a new delay-constrained reliability indicator $\delta_i = DR_i/DR^*$, i.e., the ratio of observed and desired delay-constrained event reliabilities. To determine proper event reporting frequency update policies, we also define T_i, which is the amount of time needed to provide delay-constrained event reliability for a decision interval i. In conjunction with the congestion notification information (CN bit) and the values of f_i, δ_i and T_i, the sink node calculates the updated reporting frequency, f_{i+1}, to be broadcast to source nodes in each decision interval. This updating process is repeated until the optimal operating point is found, i.e., adequate reliability and no congestion condition is obtained. In the following sections, we describe the details of the reporting frequency update policies.

A. Early Reliability and No Congestion Condition

In this condition, the required reliability level specific to application is reached before the event-to-sink delay bound, i.e., $T_i \leq \Delta_{e2s}$. Also, no congestion is observed at the sink, i.e., $CN = 0$. However, the observed delay-constrained event reliability, DR_i, is larger than desired delay-constrained event reliability, DR^*. This is because source nodes transmit event data more frequently than required. The most important consequence of this condition is excessive energy consumption of the sensors. Therefore, the reporting frequency should be decreased cautiously to conserve energy. This reduction should be performed cautiously so that the delay-constrained event-to-sink reliability is always maintained. Thus, the sink decreases the reporting frequency in a controlled manner. Intuitively, we try to find a balance between saving energy and maintaining reliability. Hence, the updated reporting frequency can be expressed as follows:

$$f_{i+1} = f_i \frac{T_i}{\Delta_{e2s}} \tag{2}$$

B. Early Reliability and Congestion Condition

In this condition, the required reliability level specific to application is reached before the event-to-sink delay bound, i.e., $T_i < \Delta_{e2s}$. Also, congestion is observed at the sink, i.e., $CN = 1$. However, the observed delay-constrained event reliability, DR_i, is larger than desired delay-constrained event reliability, DR^*. In this situation, the DST protocol decreases reporting frequency in order to avoid congestion and save the limited energy of sensors. This reduction should be in a controlled manner so that the delay-constrained event-to-sink reliability is always maintained. However, the reporting frequency can be decreased more aggressively than the case of early reliability and no congestion. This is because in this case, we are further from optimal operating point. Here, we try to avoid congestion as soon as possible. Hence, the updated reporting frequency can be expressed as follows:

$$f_{i+1} = min(f_i \frac{T_i}{\Delta_{e2s}}, f_i^{(T_i/\Delta_{e2s})}) \tag{3}$$

C. Low Reliability and No Congestion Condition

In this condition, the required reliability level specific to application is not reached before the event-to-sink delay bound, i.e., $T_i > \Delta_{e2s}$. Also, no congestion is observed at the sink, i.e., $CN = 0$, and the observed delay-constrained event reliability, DR_i, is lower than desired delay-constrained event reliability, DR^*. This can be caused by i) packet loss due to wireless link errors, ii) failure of intermediate relaying nodes, iii) inadequate data packets transmitted by source nodes. Packet loss due to wireless link errors might be observed in WSN due to energy inefficiency of powerful error correction and retransmission techniques. However, regardless of the packet error rate, the total number of packets lost due to link errors is expected to scale proportionally with the reporting frequency, f. Here, we make the assumption that the net effect of channel conditions on packet loss does not deviate appreciably in successive decision intervals. This is reasonable with static sensor nodes, slowly time-varying [1] and spatially separated channels for communication from event-to-sink in WSN applications. Furthermore, when intermediate nodes fail, packets that need to be routed through these nodes are dropped. This can cause a reduction in reliability even if enough number of data packets is transmitted by source nodes. However, fault-tolerant routing/re-routing in WSN is provided by several existing routing algorithms [2]. DST protocol can work with any of these routing schemes. Therefore, to achieve required event reliability, we need to increase the data reporting frequencies of source nodes. Here, we exploit the fact that the DR vs. f relationship in the absence of congestion, i.e., for $f < f_{max}$, is linear (see Section II-C). In this regard, we use the multiplicative increase strategy to calculate updated reporting frequency, which is expressed as follows:

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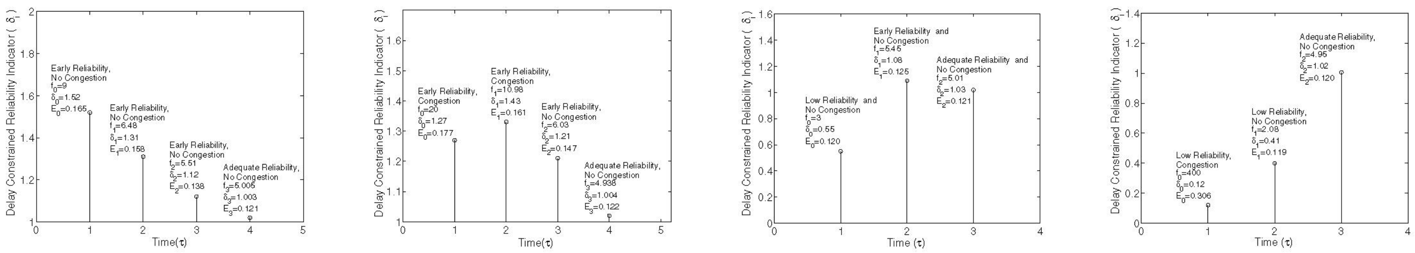
[3] To avoid reacting to transient network behavior and to increase the accuracy of congestion detection, the DST protocol detects congestion, if the node delay measurements exceed a delay threshold more than a certain number of successive times.



(a) (b) (c) (d)

Fig. 4. The DST protocol trace, when (a) early reliability and no congestion, (b) early reliability and congestion, (c) low reliability and no congestion, (d) low reliability and congestion, is observed.

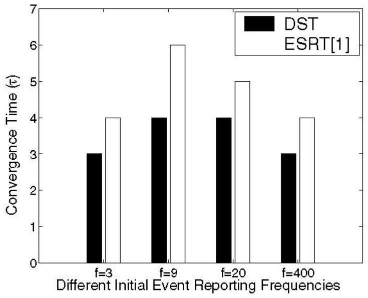


Fig. 5. The comparison of DST and ESRT[1] in terms of convergence times.

$$f_{i+1} = f_i \frac{DR^*}{DR_i} \tag{4}$$

D. Low Reliability and Congestion Condition

In this condition, the required reliability level specific to application is not reached before the event-to-sink delay bound, i.e., $T_i > \Delta_{e2s}$. Also, congestion is observed at the sink, i.e., $CN = 1$, and the observed delay-constrained event reliability, DR_i, is lower than desired delay-constrained event reliability, DR^*. This situation is the worst possible case, since desired delay-constrained event reliability is not reached, network congestion is observed and thus, restricted energy of sensors is wasted. Hence, the DST protocol aggressively reduces reporting frequency to reach optimal reporting frequency as soon as possible. Therefore, to assure sufficient decrease in the reporting frequency, the reporting frequency is exponentially decreased and the updated frequency can be expressed as follows:

$$f_{i+1} = f_i^{(DR_i/DR^*/k)} \tag{5}$$

where k denotes the number of successive decision intervals for which the network has remained in the same situation including the current decision interval, i.e., $k \geq 1$. Here, the purpose is to decrease reporting frequency with greater aggression, if a network condition transition is not detected.

E. Adequate Reliability and No Congestion Condition

In this condition, the network is within β tolerance of the optimal operating point, i.e., $f < f_{max}$ and $1 - \beta \leq \delta_i \leq 1 + \beta$. Hence, the reporting frequency of source nodes is left constant for the next decision interval:

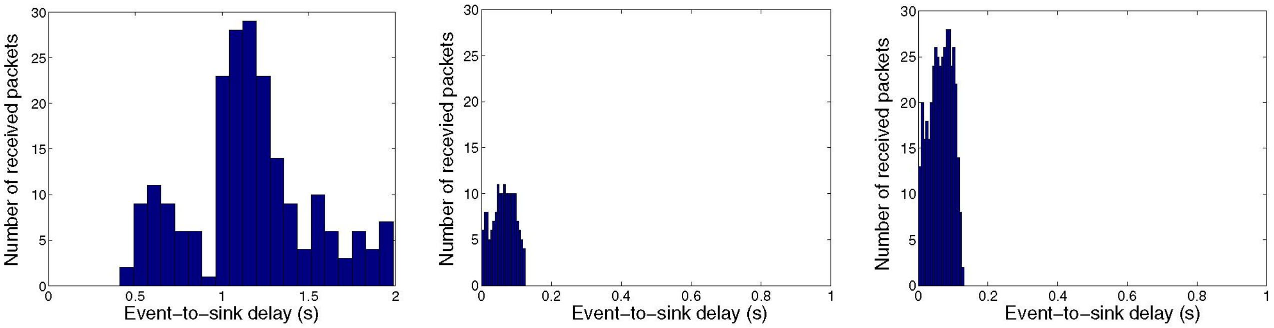
$$f_{i+1} = f_i \tag{6}$$

Here, our aim is to operate as close to $\delta_i = 1$ as possible, while utilizing minimum network resources and meeting event-to-sink delay bounds. For practical purposes, we define a tolerance level, β, for optimal operating point. If at the end of decision interval i, the delay-constrained reliability indicator δ_i is within [1-β,1+β] and if no congestion is detected in the network, then the network is in (Adequate reliability, No congestion) condition. In this condition, the event is deemed to be reliably and timely detected at the sink node and the reporting frequency remains unchanged. Note that greater proximity to the optimal operating point can be achieved with small β. However, smaller the β, greater the convergence time needed to reach corresponding (Adequate reliability, No congestion) condition.

V. PERFORMANCE EVALUATION

To evaluate the performance of the DST protocol for WSN, we once again developed an evaluation environment using ns-2 [9]. For all our simulations presented here, the number of sources, event-to-sink delay bound and tolerance level were selected as $n = 81$, $\Delta_{e2s} = 1s$ and $\beta = 5\%$, respectively. The event radius was fixed at $40m$. We run 10 experiments for each simulation configuration. Each data point on the graphs is averaged over 10 simulation runs. The main performance metrics that we employ to measure the performance of the DST protocol are the convergence time to (adequate reliability, no congestion) condition from any other initial network conditions and average energy consumption per packet (E_i) for each decision interval.

The DST protocol convergence results are shown in Fig. 4 for different initial network conditions. As shown in the Fig. 4, it is observed that the DST protocol converges to (Adequate reliability, No congestion) condition starting from any of the other initial network conditions discussed in Section IV. The performance of our reporting frequency update policies for event-to-sink transport can also be seen from the trace values listed in Fig. 4. In this context, DST is self-configuring and can perform efficiently under random, dynamic topology frequently encountered in WSN applications. In addition to convergence time, the average energy consumed per packet during event-to-sink transport, i.e., E_i, is also observed. As shown in the



(a) (b) (c)

Fig. 6. Packet delay distributions in (a) (Low reliability, Congestion), (b) (Low reliability, No congestion), (c) (Adequate reliability, No congestion), conditions.

Fig. 4, E_i decreases as the (No congestion, Adequate reliability) condition is approached. This shows that energy consumption of the sensor nodes is also decreased while providing reliability constraints and delay bounds. Due to limited energy resources of the sensors, this result is also important for the proper operation of WSN.

To further investigate the DST protocol's convergence results, we have compared DST with ESRT [1] protocol in terms of convergence time to (Adequate reliability, No congestion) condition. The reason why we compare DST with ESRT is that both of them is based on event-to-sink reliability notion unlike the other transport layer protocols addressing conventional end-to-end reliability in WSNs. As shown in Fig. 5, the convergence time of DST is much smaller than that of ESRT for different initial network conditions. This is because ESRT does not consider application specific delay bounds in its protocol operations.

To elaborate the relationship between the event-to-sink delay notion and the DST protocol operation, in Fig. 6, we have also observed the delay distributions of the event packets received at the sink, when there is a transition from (Low reliability, Congestion) condition to (Adequate reliability, No congestion) condition. As seen in Fig. 6, when the (Adequate reliability, No congestion) condition is approached, the delay of the event data packets also decreases. This is because the DST protocol takes event-to-sink delay bounds into account, while adjusting reporting rate of sensor nodes and avoiding network congestion.

VI. CONCLUSION

The notion of delay-constrained event-to-sink reliability is necessary for timely and reliable transport of event features in WSN. This is due to the fact that the sink is only interested in timely collective information of a number of source nodes and not in individual sensor reports. Based on such a delay-constrained collective reliability notion, the Delay Sensitive Transport (DST) protocol for WSN is presented in this paper.

The DST protocol is a novel transport solution that seeks to achieve reliable and timely event detection with minimum possible energy consumption and no congestion. It enables the applications to perform right actions timely by exploiting both the correlation and the collaborative nature of sensor networks. To the best of our knowledge, reliable and timely event transport in WSN has not been studied from delay-constrained event-to-sink reliability perspective before.

In addition, the DST protocol has been tailored to meet the unique requirements of WSN. Its combined congestion detection and control mechanism serves the dual purpose of achieving reliability and conserving energy. Moreover, it considers event-to-sink delay bounds, while dynamically adjusting reporting frequency of the source nodes and avoiding network congestion. Performance evaluation via simulation experiments show that the DST protocol achieves high performance in terms of reliable event detection, communication latency and energy consumption. Future work includes extending the DST protocol to address multiple concurrent events and the implementation of the developed protocol in a physical testbed.

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