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Providing Reliable Data Transport for Dynamic Event Sensing in Wireless Sensor Networks

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Abstract— In this paper, we propose a Loss Tolerant Reliable (LTR) data transport mechanism for dynamic Event Sensing (LTRES) in WSNs. In LTRES, a reliable event sensing requirement at the transport layer is dynamically determined by the sink. A distributed source rate adaptation mechanism is designed, incorporating a loss rate based lightweight congestion control mechanism, to regulate the data traffic injected into the network so that the reliability requirement can be satisfied. An equation based fair rate control algorithm is used to improve the fairness among the LTRES flows sharing the congestion path. The performance evaluations show that LTRES can provide LTR data transport service for multiple events with short convergence time, low lost rate and high overall bandwidth utilization.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are important emerging technologies for providing observations on the physical world with low cost and high accuracy. Reliably collecting the data from the sensor nodes to convey the features of a surveillance area, especially the events of interest, to the sink is one of the most critical parts of WSN design. Typically, two kinds of reliable data transport requirements can be found in WSN applications - Loss Sensitive Reliable (LSR) data transport and Loss Tolerant Reliable (LTR) data transport. For LSR, each data packet is required to be successfully transmitted from the source to the destination. Every single packet loss enforces a packet retransmission. LSR is commonly required for critical packet delivery. Several transport mechanisms have been proposed to provide LSR data transport services over WSNs using hop-by-hop packet recovery [1] [2]. However, hop-by-hop packet recovery requires a large memory space on sensor nodes to guarantee successful retransmission and introduces significant control overhead in terms of power and processing. ART [3] improves the traditional LSR design by constructing a coverage set on the sensor network and enforcing end-to-end successful transmission of each event alarm packet from the coverage set to the sink. However, forming the coverage set introduces extra session initialization delay and the alarm-style event detection greatly narrows down its applications.

For LTR, the receiver defines application-specific reliable data transport requirements for the senders in terms of throughput, loss rate or end-to-end delay. Retransmission is not required for packet loss as long as the application-specific reliable data transport requirements are achieved at the receiver. Most event monitoring applications in WSN requires LTR data transport services because collecting sufficient data from the sensor nodes in a timely and energy efficient manner is much more important than guaranteeing the successful reception of each data packet. ESRT [4] is the first protocol that provides LTR transport services along with a congestion control mechanism. A centralized closed-loop control mechanism is used to periodically assign each sensor node with a common transmission rate so that a required event sensing fidelity can be achieved at the sink. The buffer occupancy of the intermediate nodes from an event area to the sink is monitored for congestion control. The main drawback of ESRT design lies in the centralized homogeneous rate assignment, which can deteriorate the overall bandwidth utilization and introduce additional energy consumption due to local congestion. There are some other loss tolerant data transport protocols proposed recently for WSN applications [5] [6]; However, none of them focuses on providing required event sensing reliability at transport layer.

In this paper, we propose a distributed data transport mechanism to provide LTR data transport for dynamic Event Sensing (LTRES) in WSNs. This mechanism can be applied to a continuous surveillance WSN with heterogeneous sensing fidelity requirements over different event areas. In LTRES, the sink defines the LTR data transport requirements in terms of required sensing fidelity over an event area. The sensor nodes accordingly adapt their source rates in a distributed manner to meet the LTR requirement based on dynamic network conditions. A loss rate based lightweight congestion control mechanism is used to maintain a low packet loss rate and help the sink determine the satisfiability of an LTR requirement. If an LTR requirement cannot be satisfied by the current network conditions, the sensor nodes can detect the available bandwidth to provide best-effort services using an equation based fair rate control algorithm.

II. DEFINITIONS

A. Network Model

We consider a homogeneous wireless sensor network with a sensor set $\{S = s_i | i = 1, 2, ..., N\}$ and a sink, where i is the globally unique ID of a sensor node. s_i generates data packets at a source rate r_i and forwards any bypass traffic. The sink receives the source packets from s_i at rate t_i, which is defined as the *per-node goodput*. We consider a common environmental surveillance application, where each sensor node is pre-configured with a common default source rate r_d. r_d can be derived based on prior knowledge of the sensing area and network conditions so that the WSN conducts the sensing with low power consumption and no congestion. Based on the sensing data collected by the sensor nodes, the sink can monitor the sensing field and identify one or more areas of interest, where special events are predicted or detected. We call the area of interest as *event area*, and the sensor nodes covering the event area as *Enode*s, forming an Enode set E. We assume that the sink is able to determine a required event sensing fidelity for an event area based on its computational capability and the dynamic event feature.

B. Transport Layer Reliability Definition for Dynamic Event Sensing

We define the LTR data transport requirements using event sensing fidelity under our network model.

Definition 1 *Observed Event Sensing Fidelity* (OEF_E): the observed goodput achieved at the sink originating from E, where $OEF_E = \sum_{S_i \in E} t_i$.

OEF_E serves as a simple but adequate event reliability measure at the transport level [4].

Definition 2 *Desired Event Sensing Fidelity* (DEF_E): the desired goodput achieved at the sink originating from E, according to the sensing fidelity requirement.

DEF_E is determined by the sink based on its computational capability and the event sensing accuracy requirement. Such a decision-making process is application-dependent, which is beyond the scope of this paper. Interested readers can refer to [7] for an analysis of this topic.

Definition 3 *Event Sensing Fidelity Level* (ESF_E): the ratio of observed event sensing fidelity at the sink to the desired event sensing fidelity, where $ESF_E = OEF_E/DEF_E$.

ESF_E reflects the quality of reliable data transport services provided for event sensing. If $ESF_E \geq 1$, the reliable event sensing can be guaranteed by the LTR transport service under the available network capacity. If more than one event is identified by the sink, $ESF_E \geq 1$ should be guaranteed for any event area simultaneously to provide LTR services for the WSN under the available network capacity. If a DEF is not achievable under the limited wireless channel capacity, a congestion control mechanism should be able to dynamically detect the sustainable ESF based on instantaneous network conditions for minimizing energy consumption. In effect, the event nodes should explore the upper bound of the network capacity to provide best-effort data transport service.

III. LTRES DESIGN

A. Case Study

In a wireless sensor network, the source rate r_i determines not only the sensing fidelity achieved at the sink, but also the amount of traffic injected into the sensor network [8]. Finding out the relationship among the source rates, the OEF_E and the network congestion level is critical to our design. A simple simulation scenario is constructed for this purpose using the wireless network simulator GloMoSim with the simulation parameter shown in Table I.

TABLE I
SIMULATION PARAMETERS

Sensing field dimensions	(100×200) m
Sink Location	$(0, 0)$
Number of sensor nodes	50
Sensor node radio range	60m
Packet length	128 bytes
Radio Bandwidth	250 kbps
MAC layer	IEEE 802.11

The sensing field is uniformly divided into 50 grids. Each sensor node is randomly positioned in a grid. All sensor nodes are pre-configured with $r_d = 1$ pkt/sec. Since sensor nodes are usually static in a surveillance WSN, a proactive routing protocol is selected at the network layer [6]. Two event areas covered by three and five Enodes are separately identified at different locations, where $E_1 = \{s_{36}, s_{37}, s_{46}\}$, $E_2 = \{s_{13}, s_{14}, s_{23}, s_{24}, s_{33}\}$. All the Enodes uniformly increase their source rates, with event source rate defined as $ESR_E = \sum_{s_i \in E} r_i$. From the simulation results (please see [9] for details), we make the following observations:

Observation 1: *Loss rate can be used as a simple and accurate indication of upstream congestion level of Enodes.*

In WSNs, packet loss is mainly due to two reasons: wireless link error and congestion [10]. When the source rate is low, the traffic load in the network is also low. Only the wireless link error affects the packet transmission; thus a steady low loss rate can be observed from each Enode. When the sensor node source rate is increased beyond a certain threshold value, the traffic load would exceed the network capacity. In this case, both the wireless link error and the network congestion affect the packet transmission; thus the loss rate dramatically increases at the event nodes that share the congestion bottleneck.

Observation 2: *The network status can be divided into three regions with increasing source rates at Enodes.*

In Region 1, OEF and ESR maintain an approximately linear relation with no network congestion. Steady low loss rates can be observed from all Enodes. In Region 2, higher OEF can be achieved by increasing ESR; however, the linear relation between OEF and ESR is broken with local network congestion. Dramatically increased loss rates can be observed at certain Enodes sharing a congestion bottleneck. In Region 3, OEF reaches the upper bound or even decreases with increasing ESR. High loss rates are observed at all Enodes because of full network congestion.

B. Basic LTRES Design

Based on the above observations, a distributed LTR data transport mechanism, LTRES, is designed to achieve dynamic ESF requirements with congestion control. In LTRES, the sink dynamically identifies the event area by Enode set E and determines the desired event sensing fidelity DSF_E based on the sensing accuracy requirement. The sink then measures OSF_E and derives ESF_E as the current quality of LTR service provided for the event sensing and sends it to E covering the event area. Based on this ESF_E notification for the entire event area and the local network congestion level, each Enode adapts its source rate in a distributed manner so that enough event goodput can be delivered to the sink with $ESF_E \geq 1$. From Observation 2, we know that a higher ESF_E always requires a higher source rate. In order to provide LTR data transport service with minimum energy consumption and delivery latency, we set $ESF_E = 1$ as the reliable event sensing objective with the least possible number of packet transmissions.

1) Sink-end Congestion Control: Many WSN transport protocols use a buffer occupancy monitoring technique to accomplish congestion detection and avoidance. ESRT uses a closed-loop congestion control mechanism by monitoring the buffer occupancy of the intermediate nodes from the event area to the sink. Obviously, this is unfair to those sensor nodes not sharing the congested bottleneck but are located within the event area. CODA [10] also uses a buffer occupancy monitoring technique with back-pressure. However, back-pressure introduces extra communication overhead and makes the goodput and protocol convergence time hard to be estimated. Following Observation 1, LTRES uses a loss rate based lightweight ACK mechanism to provide congestion control. In our network model, proactive routing is supposed to be used at the network layer so that the data flows originating from E have static route. Therefore, a static end-to-end wireless path model can be used to derive the probability of packet loss due to wireless congestion and wireless link error [11] as shown below:

$$Pr(L) = 1 - [1 - Pr(W)][1 - Pr(C)] \tag{1}$$

where $Pr(L)$ is the probability of packet loss during transmission; $Pr(W)$ is the probability of packet loss due to wireless link error; $Pr(C)$ is the probability of packet loss due to congestion. Since the WSN starts from no network congestion with every sensor node transmitting at r_d, according to (1), $Pr(L) = Pr(W)$. Therefore, the sink can estimate the path $Pr(W)$ using a weighted moving average of the instantaneous packet loss rates as

$$avgPr(W) = (1 - w_q) * avgPr(L) + w_q * instPr(L) \tag{2}$$

where w_q reflects the channel diversity. A larger w_q value can be used in a highly dynamic wireless channel and vice versa. The sink periodically observes the loss rate at each Enode using the formula:

$$instPr(L) = (t_i - r_i)/r_i \tag{3}$$

If a steady low loss rate is observed, the upstream routing path for this Enode is deemed to have no congestion or low congestion level; thus $avgPr(W)$ is updated according to (2). If a dramatically increased loss rate is observed compared with $avgPr(W)$, the upstream routing path for this Enode is deemed to be congested. As a result, a congestion notification is sent to the congested event node to trigger the congestion avoidance operation.

2) Node-end Distributed Source Rate Adaptation: Whenever an event area is identified, the ESF_E is evaluated by the sink and sent to E as an event sensing reliability measure at the transport level. Based on this event sensing reliability measure, the Enodes periodically conduct the distributed source rate adaptation with network congestion level awareness.

Based on Observation 2, the source rate adaptation operates in three stages. In $Stage\ One$, each Enode periodically performs multiplicative increase (MI) operation on source rate adaptation to approach $ESF_E = 1$ in an aggressive manner before any local congestion is detected. Since ESR is linear to OEF without network congestion, if each Enode satisfies $r_i = \frac{r_{j,0}}{ESF_E}$, the source rate adaptation on each Enode can be stopped at the first stage with $ESF_E = 1$. The $Stage\ One$ operation satisfies the LTR requirement with fast convergence time and low control overhead.

If any local congestion is detected by the sink before the end of the first stage, the Enodes start to operate at $Stage\ Two$. This implies that the MI operation at certain Enodes leads to local congestion. Although the sink may still achieve similar or even higher ESF level under congestion because of higher ESR, more energy is consumed due to the high packet loss rate. In order to provide energy efficient source rate control, in $Stage\ Two$, the congested Enodes start the available bandwidth detection process using steady-state throughput estimation, which will be discussed in detail in next subsection. The congested Enodes finish the $Stage\ Two$ operation with upstream congestion avoidance and maximized bandwidth utilization. These nodes then become inactive Enodes, and stop any source rate adaptation operations. The sink derives the new ESF_E for the rest of the Enodes. These nodes then restart the operation from $Stage\ One$.

If there is no active Enode, all Enodes stop the source rate adaptation and enter $Stage\ Three$. In $Stage\ Three$, the Enodes provide best-effort service without network congestion.

C. Improving the Fairness Among LTRES Data Flows

Compared with a centralized rate assignment mechanism, such as the one used in ESRT, a distributed source rate control considers the local network conditions at different Enodes so that the overall network bandwidth utility is improved; however, the distributed algorithm may lead to unfair bandwidth utilization at Enodes sharing the congestion bottleneck. One possible solution for fairness control among LTRES data flows is using AIMD (Additive Increase Multiplicative Decrease) source rate adaptation, which inherently results in a fair bandwidth assignment among the Enodes sharing the congestion bottleneck. Nevertheless, AIMD source rate adaptation cannot guarantee a limited convergence time by achieving the required ESF level. Moreover, it may cause a jittered event goodput at the sink.

In order to achieve a fair rate control with steady event goodput, in our design, each Enode calculates the steady-state throughput that could be achieved by assuming that the AIMD operation is used in $Stage\ Two$ source rate adaptation using a congestion-free throughput model for wireless channel [11].

Assume that each Enode periodically increases its source rate additively and decreases its source rate in half if any congestion is detected at the sink. An LTRES flow originating from an Enode starting at $t = 0$ transmits $X(t)$ packets and achieves $T(t) = X(t)/t$ throughput in t time period. The steady-state throughput T for this flow can be derived as $T = \lim_{t\to\infty} \frac{\overline{X(t)}}{t}$. We call the time period between any two congestions as *congestion free duration* D_k, which can be divided into N_k *Source Rate adaptation Periods* (SCP).

Assume the total number of packets transmitted in D_k is X_k, the steady-state throughput can be also be represented as $T = \frac{\overline{X}}{\overline{D}}$. If we present the source rate at the end of D_k as R_k, then $R_{k+1} = \frac{R_k}{2} + N_k$. Hence, the expectation of i.i.d. random variable R can be expressed as $\overline{R} = 2\overline{N}$. On the other hand, $X_k = \frac{1}{2}(R_{k+1} + \frac{R_k}{2} - 1)N_k$. For mutually independent random variables, N_k and R_k, the expectation of X_i can be expressed as $\overline{X} = \frac{1}{2}(3\overline{N} - 1)\overline{N}$. In a congestion-free duration, we assume n_k packets are transmitted before the congestion is detected at the sink. Since the congestion requires one SCP to be detected and notified to the Enode, W_k more packets are sent after the packet loss due to congestion. Hence, $X_k = n_k + W_K$. Accordingly, $\overline{X} = \overline{n} + \overline{W}$. Based on above deduction, we obtain the steady-state throughput as

$$T = \frac{1}{4 \cdot SCP}(3 + \sqrt{25 + 24\overline{n}}) \tag{4}$$

Since n_k gives the number of packets transmitted until a congestion occurs, it is geometrically distributed with the unconditional probability of packet loss due to congestion $Pr(C)$. According to (1), $\overline{n} = 1 - Pr(W)\,\Pr(L) - Pr(W)$.

The Enodes operating in $Stage\ Two$ use T as the fair source rate to achieve better overall bandwidth utilization without congestion.

D. LTRES Operation

1) Session Initialization Phase: The LTRES operation starts with no event area and no congestion in the WSN. For all sensor nodes, $r_i = r_d$. Whenever an event area is identified by the sink, the sink determines the Enode set E and DEF_E for the event area. It initializes the *Active Enode Set* $E^A = E$, *Inactive Enode Set* $E^{IA} = \emptyset$, *Standard Loss Rate* $avgP_i(W,0) = l_{i,0}$ and ESF_{E^A} following Definition 3. The sink starts the service session by sending Session Initialization Packet (SIP) to E. SIP contains the sequence number, timestamp, ESF_{E^A} and the E^A ID group.

2) Stage One (Guaranteed LTR service with congestion control): Upon receiving the SIP, each active Enode starts the source rate adaptation in $Stage\ One$ and piggybacks the SIP sequence number in upstream data packets as an implicit acknowledgement SIP_ACK. Meanwhile, each active Enode $e_i^A \in E^A$ adapts its source rate as follows:

$$r_{i,K+1} = min(2 \times r_{i,K}, \frac{r_{i,0}}{ESF_E}) \tag{5}$$

Upon receiving the SIP_ACK from e_i^A, the sink estimates the instantaneous packet loss rate $l_{i,K+1} = instPr_i(L)$ every $2 \times RTT$ period using (3). If $l_{i,K+1} - avgP_i(W,K) \le \varepsilon$, the sink updates $avgP_i(W,K+1)$ using (2) and sends the Good News Packet (GNP) to e_i^A. If $l_{i,K+1} - avgP_i(W,K) > \varepsilon$, the sink sends the Bad News Packet (BNP) with timestamp, $avgP_i(W,K)$ and $l_{i,K+1}$ to e_i^A. ε is the tolerable variation of loss rate without congestion, which can be derived empirically based on application-specific congestion tolerance level.

Upon receiving the GNP, e_i^A repeats the MI operation following (5). Whenever e_i^A reaches $r_{j,K+1} = \frac{r_{j,0}}{ESF_E}$, it stops the source rate adaptation and sets $ESF\_SUCC\ bit = 1$ in the transport header.

Upon receiving the $ESF\_SUCC\ bit = 1$ from e_i^A, the sink stops sending GNP or BNP to this Enode. If all Enodes have $ESF\_SUCC\ bit$ set to '1', LTRES stops at $Stage\ One$.

3) Stage Two (Available bandwidth detection with fair rate control): Upon receiving BNP, all e_i^A start $Stage\ Two$ operation. In this stage, e_i^A adapts the source rate following (4) using the congestion level information contained in BNP. $P(W) = avgP_i(W,K)$. $P(L) = l_{i,K+1}$. $SCP = 2 \times RTT$. It then sets $r_j = T$ and sets $DET\_SUCC\ bit = 1$ in transport header. The sink places all the Enodes with $DET\_SUCC\ bit = 1$ into E^{IA}. All active Enodes finish their source rate adaptations. The sink then sets $E^A = E - E^{IA}$. If $E^A \neq \emptyset$, the sink updates ESF_E as follows:

$$ESF_{E^A} = \frac{\sum_{s_i \in E^A} t_{i,0}}{DEF_E - \sum_{s_i \in E^{IA}} t_i} \tag{6}$$

The sink generates and sends the new SIP with new ESF_{E^A} to E^A. Upon receiving the new SIP, an active Enode e_i^A starts the source rate adaptation from $Stage\ One$.

4) Stage Three (Best-Effort Service): If $E^A = \emptyset$, all Enodes finish the available bandwidth detection. The best-effort service is provided.

5) Session Finalization Phase: Whenever the event area is deemed uninteresting by the sink, the sink sends the Session Close Packet (SCP) to E. All critical nodes set $r_j = r_d$. The LTRES operation finishes.

E. Protocol Operation Correctness and Convergence

Lemma 1: If LTRES finishes at $Stage\ One$, the LTR service is guaranteed with $ESF_E = 1$.

Lemma 2: LTRES operation converges within $2 \times N \times (log\frac{r_{j,0}}{ESF_E} + 1) \times RTT$ unit time.

The proof of Lemma 1 and Lemma 2 is given in [9].

IV. PERFORMANCE EVALUATION

In order to study the performance of the LTRES protocol, we once again construct a simulation environment, using the same simulation parameters, as shown in Table I. The sensor network topology remains the same as in the case study. We conduct a simulation with three different application scenarios to compare the performance of LTRES and ESRT in operation convergence time and bandwidth utilization. In Scenario I, the sink identifies an event covered by $E1 = \{s_{37}, s_{38}, s_{47}, s_{48}\}$ with desired event sensing fidelity requirement $DEF_{E1} = 10$ pkt/s. In Scenario II, the sink identifies another event covered by $E2 = \{s_{13}, s_{14}, s_{23}, s_{24}, s_{33}, s_{34}\}$ with desired event sensing fidelity requirement $DEF_{E2} = 30$ pkt/s. In Scenario III, the sink derives a new event sensing fidelity requirements for $E2$ as $DEF_{E2} = 40$ pkt/s. According to the network conditions, we set $r_D = 1$ pkt/s, $\varepsilon = 0.05$,

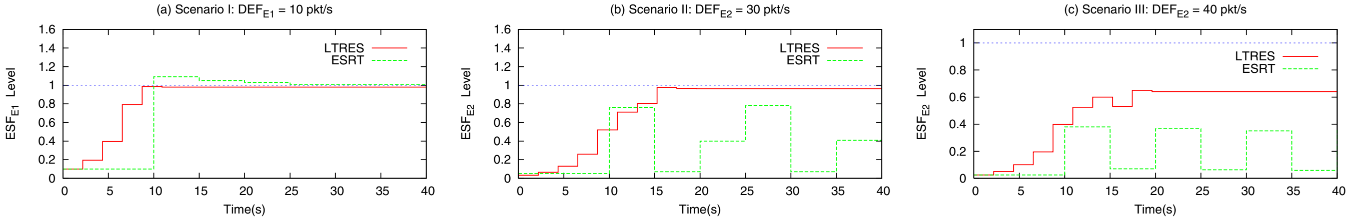

Fig. 1. ESF level trace for LTRES and ESRT protocol with dynamic event sensing fidelity requirements.

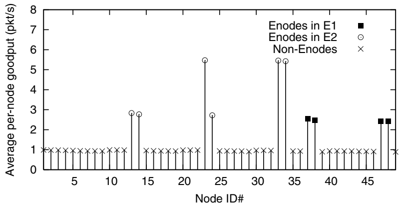

Fig. 2. Average per-node goodput distribution after LTRES operation for application Scenario III.

$w_q = 0.5$ as the default protocol parameters for LTRES and $Decision\_Interval = 5s$ for ESRT [4].

Fig. 1 shows the different ESF levels achieved by LTRES and ESRT for these scenarios. From Scenario I, as shown in Fig. 1(a), we can find out that LTRES provides LTR service with only $Stage\ One$ operation because of the low DEF requirement. Compared with ESRT, LTRES converges faster in achieving a sustainable DEF level. For Scenario II, a new event with a higher DEF is detected by the sink, which requires higher overall bandwidth utilization. As shown in Fig. 1(b), LTRES is able to achieve $ESF_E = 1$ using both $Stage\ One$ and $Stage\ Two$ operation. However, for ESRT, since it uses a centralized source rate control mechanism, which cannot deal with the dynamic network conditions at different Enodes, the local congestion is detected to trigger the source rate decrease with only a portion of the Enodes obtaining full bandwidth utilization. As a result, ESRT cannot provide the LTR service for $E2$ as shown in simulation results. Since ESRT does not provide any mechanism to determine the unsustainable DEF, it also fails to converge in Scenario II. For Scenario III, a higher DEF is determined by the sink for $E2$. As shown in Fig. 1(c), both LTRES and ESRT cannot provide the LTR service because this DEF is unsustainable by current network capacity. LTRES finishes at Stage Three, providing best-effort service for $E2$ with approximately $ESF_E = 0.64$; however, ESRT fails to converge, because it cannot determine the sustainable DEF and control the Enodes to detect the available bandwidth.

Fig. 2 shows the average goodput distribution observed at the sink after LTRES operation in application Scenario III. From the previous analysis, we know that LTRES provides LTR service to $E1$ with only $Stage\ One$ operation. Since each Enode starts from the same r_d and performs the same MI operation, the fairness is guaranteed among the data flows originating from $E1$. For $E2$, the Enodes are divided into two groups $\{s_{13}, s_{14}, s_{23}\}$ and $\{s_{24}, s_{33}, s_{34}\}$, which share the different congestion bottlenecks. From Fig. 2, we find out that the sink gets similar goodputs from the Enodes within the same group. Therefore, we conclude that both $Stage\ One$ and $Stage\ Two$ operations result in a fair bandwidth allocation for LTRES flows sharing the congestion bottleneck.

V. CONCLUSIONS

In this paper, we propose LTRES, a distributed source rate control mechanism, to provide LTR transport services for upstream data transmission in WSNs. LTRES can be applied to a continuous surveillance wireless sensor network with several event areas. Compared with earlier LSR data transport protocols, LTRES addresses fast and reliable event sensing with congestion control. Compared with an existing LTR data transport protocol ESRT, LTRES provides both reliable data transport for sustainable LTR requirements and best-effort data transport services for unsustainable LTR requirements. It has faster convergence time, lower packet loss rate and better bandwidth utilization, especially for a high DEF level. LTRES also provides fair rate control for the distributed source rate adaptation.

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