Adaptive QoS Routing for Significant Events in Wireless Sensor Networks

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***Abstract*— Wireless sensor networks (WSN) can report large volumes of slowly varying routine data, while important or significant events can be relatively rare. An important challenge is then to offer the significant or unusual data an adequate routing policy that will allow it to rapidly reach the sink nodes, despite the large volume of routine packets in the network. In this paper we introduce *Randomized Re-Routing (RRR)*, to detect the unusual events in a distributed manner, and dynamically transfer routine data packets to secondary paths in the network, while offering a fast track path with better QoS for the packets carrying unusual data. In this paper we describe the RRR algorithm and evaluate it with extensive simulations.**

I. Introduction

Wireless sensor networks [1], [2] must forward significant data promptly and efficiently from the different sensors where the data originates to one or more sinks in the network at which data is collected and where it may also be interpreted. In such networks: (1) routine measurements and sensing take place constantly resulting in a steady volume of data being transmitted towards the sink(s), and (2) unusual events of particular interest will occur unexpectedly, and the information related to such events will require fast transmission to the sink(s). While routine data are essential for reporting on the conditions that the WSN is monitoring, unusual events are more critical and need a faster or "better QoS" treatment by the network, such as short delay, very low loss, possibly high bandwidth, better security, etc.. Thus we propose an adaptive technique which we call **Randomized Re-Routing** (RRR) for addressing these needs of WSNs based on the following steps:

- During network operation, the network nodes observe the traffic they are conveying and each of them learns the different traffic flows that it may be carrying. In the simplest case, this may just imply that a node maintains the running average value of a measurement which is contained in packets belonging to each of the connections (source-to-destination) that it is conveying. Thus nodes can be classified as a "normal" packet if the packet's contents are very similar to those of the running average for the same connection; the node then inserts a ZERO bit header in that packet.
- A node which generates or conveys a packet whose content differs significantly from the running average value will classify that packet as being "unusual" and insert a ONE bit in its header.
- Each node also monitors the rate at which it receives "unusual" packets, and if this rate does not exceed a threshold θ_U, then the node forwards all packets it receives along their preferred (e.g. shortest or best QoS) path towards their destinations. Obviously the preferred path may be determined by criteria such as the minimum delay, greatest security, lowest power consumption, smallest loss etc.
- If a node (source or transit) senses that the rate at which it forwards unusual packets exceeds the threshold θ_U, then it will forward all ONE-bit packets along the best QoS path to their destination, while all ZERO-bit carrying packets will be directed along a randomized route which spreads the lower priority traffic across the network away from the high priority paths, reserving the better paths to the high priority traffic.

In the sequel we will present this algorithm and provide an evaluation of its effectiveness using simulations.

A. Related Work

Several real-time communication protocols have been studied for sensor networks. He et al. [3] propose SPEED, a protocol which combines feedback control and non-deterministic quality of service (QoS) aware geographic forwarding. Lu et al. [4] describe a packet scheduling policy, called Velocity Monotonic Scheduling, which inherently accounts for both time and distance constraints. Felemban et al. [5] propose Multi-path and Multi-Speed Routing Protocol (MMSPEED) for probabilistic QoS guarantee in WSNs. Multiple QoS levels are provided in the timeliness domain by using different delivery speeds, while various requirements are supported by probabilistic multipath forwarding in the reliability domain; our approach has some similarity to this work. Huang et al. [6] consider a spatiotemporal multicast protocol, called "mobicast", which provides reliable and just-in-time message delivery to mobile delivery zones. Some routing protocols with congestion awareness have also been proposed for ad hoc networks [7][8].

In our work we focus on the quality of service in forwarding routine data and unusual events in WSNs, and consider how to manage routing so that network capacity within the WSN is created so as to offer uncongested paths to traffic emanating

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from unexpected events, in addition to routing the routine parts of the traffic.

Some congestion control algorithms have also been proposed for wireless sensor networks. Wan et al. [9] proposed an energy efficient congestion control scheme for sensor networks called CODA (COngestion Detection and Avoidance), which includes receiver-based congestion detection, open-loop hop-by-hop backpressure, and closed-loop multi-source regulation. Hull et al. [10] have examined three techniques to mitigate congestion in WSN, which includes hop-by-hop flow control, rate limiting source traffic, and prioritized medium access control (MAC). Ee et al. [11] propose a distributed algorithm for congestion control and fairness in many-to-one routing, which measures the average transmission rate, then divides and assigns the average to downstream nodes equally. Woo et al. [12] consider an adaptive rate control mechanism for energy efficiency and fair bandwidth allocation in WSN, while Yi et al. [13] develop a congestion control algorithm with MAC constraints to provide proportionally-fair resource allocation among users in wireless multi-hop networks. Finally, Kang et al. [14] study a Topology-Aware Resource Adaptation (TARA) strategy to alleviate congestion in sensor networks, which increases capacity by enabling more active sensors during congestion. It also considers the effects of the type of congestion, the traffic pattern, and network topology. Some recent work also studies the effect of time-outs on the travel delays in wireless sensor networks [15].

Most of the existing work provides congestion control and avoidance in wireless WSNs by backpressure by limiting the transmission rate, or by checking the congestion states of neighboring nodes. These mechanisms require feedback from sensor nodes which result in extra overhead in the network. Moreover, these approaches often do not focus on the quality of service offered to data having different levels of importance. The RRR approach we propose is quite simple and easy to implement in a distributed manner since all decisions are locally taken by the nodes, and it requires no feedback messages from the congested nodes.

B. Sensor Network Congestion with Unusual Events

Sensor nodes forward packets containing their measurements or observations towards one or more sink nodes. This may happen at regular intervals or only when certain significant events occur. Since the sensor nodes have limited wireless range, multi-hop communications are generally required to forward the data to the sinks. In such a network, sensors perform sensing constantly which results in a steady volume of data being transmitted towards the sinks. When unusual events of particular interest occur unexpectedly, large amounts of data may be generated causing a sudden increase of network traffic or even a congestion as shown in Figure 1. Since the data from unusual events may be significantly slowed down or event lost due to the large and steady volume of routine data, a number of approaches have been proposed to reduce network congestion [9], [11], [10]. However, some of these mechanisms introduce extra overhead from the feedback messages and reduce the transmission rate from the source nodes. Thus we propose a lightweight and adaptive technique which fully utilizes the network capacity by diverting the routine data away from the preferred path to reduce the traffic and leave the best paths to traffic from the unusual events.

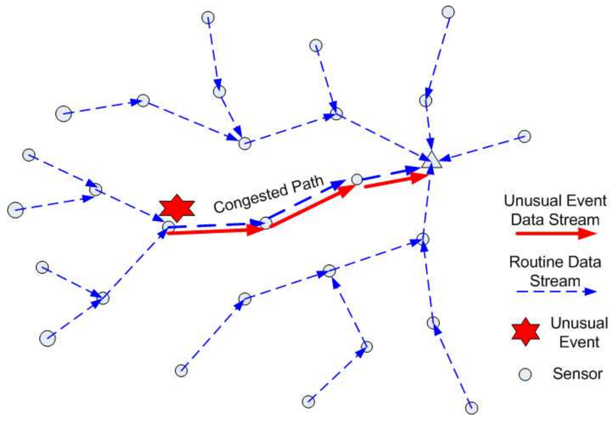

Fig. 1. Congestion caused by unusual events.

In another paper [16] we will show how RRR can be evaluated using a diffusion model for delays in wireless sensor networks [17], [18], based on diffusion approximations developed in [19], [20], [21], [22]. For lack of space, this theoretical approach will not be discussed here.

II. The Randomized Routing Algorithm

Random Re-Routing (RRR) is an adaptive randomized routing algorithm to reduce network congestion and provides QoS by detecting the occurrence of unusual events and providing differentiated QoS for different data streams. It observes the sensor measurements and distinguishes packets of routine data and unusual events. Afterward, packets from unusual events are routed along the preferred path, while the routine data are randomly shunted to slower secondary path.

A. Detecting the occurrence of unusual events

Sensors detect the occurrence of unusual events and differentiate the packets by observing a significant change on the content of traffic that they are conveying. Packets are associated with a ZERO-bit and ONE-bit in the headers as shown in Algorithm 1.

During network operation, the network nodes observe the traffic they are conveying and each of them learns the different traffic flows that it may be carrying. Each sensor node i keeps a running average $M(t)$ over a short time window T of the value of the measurement $m(t)$ that it is sending. If the measurement at time t is very similar to the *average* evaluated over time $[t-T,t[$, i.e. $|M(t)-M(t+T)| \leq \varepsilon$, then the packet sent out at time t is marked with a ZERO-bit indicating a routine data packet.

If the measurement is significantly different from the previous average, i.e. $|M(t)-M(t+T)| > \varepsilon$, then the packet is marked as an unusual event and given a ONE-bit in its header.

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This simple mechanism allows for an on-line classification of each successive packet from a given source. However it can also be used by intermediate nodes if they themselves wish to decide whether a packet is a routine or unusual event packet, as long as they are able to distinguish between the source-destination pairs contained in the packets as well as keeping track of content values.

Algorithm 1 Detecting the occurrence of unusual events

for Each time interval T **do**
  Each node monitors the current sensor measurement $m(t)$
  Updates $M(t) = a \cdot m(t) + (1-a) \cdot M(t-T)$
  if $|M(t) - M(t-T)| \leq \varepsilon$ **then**
    Marks packets as $ZERO - bit$
  else
    Marks packets as $ONE - bit$
  end if
end for

B. *Routing for differentiated quality of service*

Sensors change their routing strategies adaptively according to the traffic level in the network. When the traffic level is low, the preferred path will be shared for forwarding both ONE-bit and ZERO-bit packets. However, the preferred path will be reserved for forwarding the ONE-bit packets and only the secondary paths will be used for the ZERO-bit packets if the network traffic is heavy. The adaptive technique is shown in Algorithm 2.

Each node i also observes the level of arriving traffic τ_t from unusual events. If this rate τ_t does not exceed a threshold θ_U, then the node forwards all packets it receives along their preferred (e.g. shortest or best QoS) path towards their destinations. Obviously the preferred path may be determined by criteria such as the minimum delay, greatest security, lowest power consumption, smallest loss, etc..

However, if $\tau_t \geq \theta_U$, then ZERO-bit packets and ONE-bit packets, whether they arrive from some other node for forwarding, or are generated internally, will be routed differently. More specifically, each node i ranks its neighboring nodes $i_1, ..i_H$ so that i_1 is located closest to the sink in number of hops, and i_H is the one which is farthest away. Then, node i forwards ONE-bit packets to neighbors $i_1, ..., i_K$, and forwards all ZERO-bit packets to the remaining neighbors $i_{K+1}, ..., i_H$.

Note that in general we will select one of these output nodes at random among the given set, and also we may choose not to use some of the nodes at the tail end of the ranking, because they may lead to excessively long paths.

Figure 2 shows how RRR allocates the shortest (or preferred) path for the conveying the unusual event data, while dispersing the routine data away from the preferred path.

III. SIMULATIONS

We have conducted extensive simulations using the *ns-2* tool [23] to evaluate the RRR algorithm. The simulation parameters that we have chosen are summarized in Table I, and have been selected so as to be compatible with other studies of WSNs [3], [5], [24].

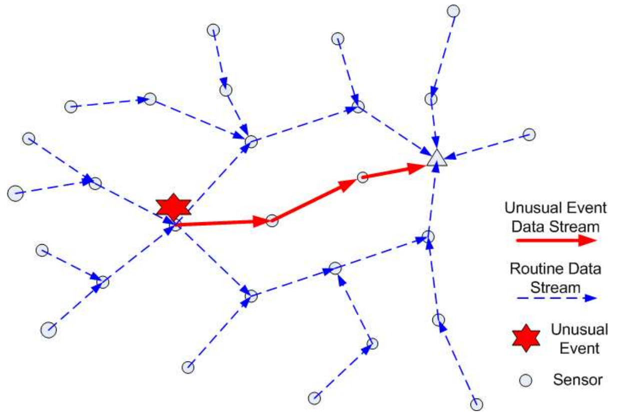

Fig. 2. Random Re-Routing for routine data and unusual events

Algorithm 2 Routing for differentiated quality of service

for Each time interval T **do**
  Each node monitors the incoming packet rate τ_t
  if $\tau_t < \theta_U$ **then**
    Forwards packets to the neighbor on the preferred path
  else
    Ranks the best H neighbors in $nList$ to get $i_1, ..., i_H$
    if ONE-bit packets **then**
      Forwards packets to neighbors $i_1, ..., i_K$
    else
      Forwards packets to neighbors $i_{K+1}, ..., i_H$
    end if
  end if
end for

The simulations we have conducted focus on a WSN which collects and reports routine data to the sink constantly. Any of the sensors has a probability p to be the source of routine data and generates data independently of the other nodes; note that this independence assumption may be unreasonable when correlated events are being reported across a sensory field. Under normal conditions the sensors they report routine data to the sink at a low data rate. Unusual events are assumed to occur infrequently, and in the simulations we have included four nodes which simulate the sources of such events which generate a high traffic rate. We have also introduced a probability of packet loss at each node given by the parameter f.

The network considered has a total of 100 nodes with a single sink. The node positions are all uniformly distributed at random within a 200m x 200m square (m=metres). The communication range is 40 meters, and the sink is located at the center of the square. The "routine" data packet rate is 1 pkt/s for each of the nodes, while the "unusual" event traffic rate is 5 pkt/s at 4 nodes in the network.

A. *Delay caused by routine data*

We evaluate how the routine data affect the transmission delay in a network using RRR with f=0. There are four unusual events at (50, 50), (50, 150), (150, 50), and (150, 150), together with a varying number of routine data sources

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TABLE I

SIMULATION PARAMETERS

Network area	200m*200m or 400m*400m
Number of sensor	100 or 400
Sensor distribution	Uniform random
Location of Sink	Center of area
Radio range	40m
MAC layer	IEEE 802.11
Unusual event sources	4
Routine data sources probability	p
Failure rate	f
Time-out constant ξ	$1/r$
Delay for retransmission M	0.02s
Data rate of unusual events	λ_U
Data rate of routine data	λ_R

which is defined by a p.

Figure 3 shows that the travel delay of unusual events (ONE-bit packets) is much shorter than that of routine data (ZERO-bit packets). The delay of four reference points at (30, 100), (170, 100), (100, 30), and (100, 170) are shown for comparison. They are located with equal distance to the sink as the unusual events. As p increases, the travel delays of both ZERO-bit and ONE-bit packets increase. This is because the network becomes more congested with the additional traffic introduced by the increased number of routine data sources. Similar trends can also be found in Figure 4, which shows the results of same experiment with reference routine data sources at (30, 30), (30, 170), (170, 30), and (170, 170).

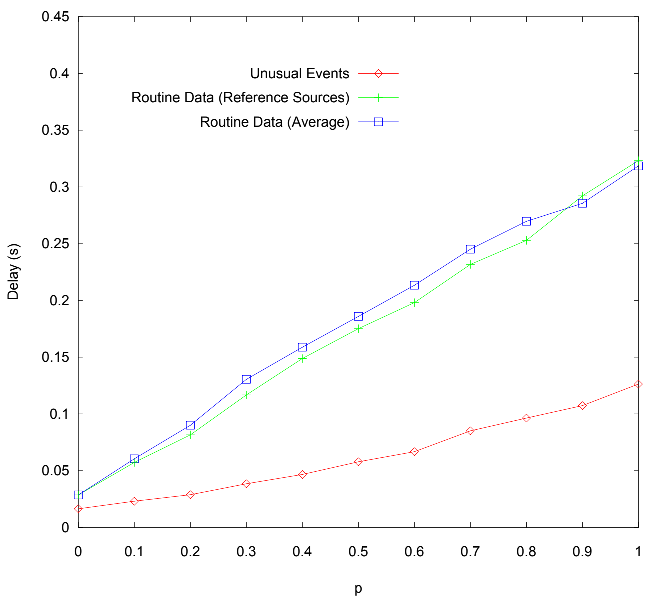

Fig. 3. Travel delay versus p with f=0, λ_U=5pkt/s, λ_R=1pkt/s, reference routine data sources at (30, 100), (170, 100), (100, 30), and (100, 170).

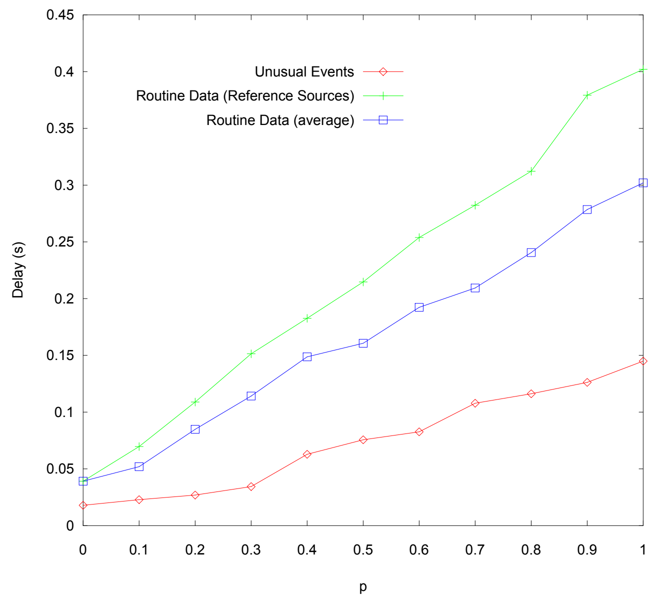

Fig. 4. Travel delay versus p with f=0, λ_U=5pkt/s, λ_R=1pkt/s, reference routine data sources at (30, 30), (30, 170), (170, 30), (170, 170).

B. Transient behavior

We study the transient behavior of the network in response to the sudden increase of network traffic caused by unusual events. We consider a larger network with 400 nodes deployed in a $400m \times 400m$ area with the sink at the center (200, 200) and focus on event detection and transient behavior. We set $p = 0.1$, $f = 0$, λ_R=1pkt/s and λ_U=5pkt/s.

Traffic starts at 0s with no events, followed by four events to occur at 40s. The sources of unusual events are located at $(100, 100), (100, 300), (300, 100), (300, 300)$, while the reference sources of routine data are located at $(60, 200), (200, 60), (200, 340), (340, 200)$ for comparison. All of these source nodes are at roughly equal distances to the sink. Each sensor keeps checking the arrival rate of the ONE-bit packets τ_t. If $\tau_t > \theta_U$, then RRR will be applied.

Figure 5 shows the travel delay of packets with θ_U=3pkt/s. The event data are received from 45s and the delay of event packets become steady at 50s. It indicates that the sensors can detect the event and start RRR quickly. There are more fluctuations on the line of Routine Data (Reference Sources) than Unusual Events as paths are selected with more randomness for the Routine Data.

Figure 6 shows similar results with θ_U=4.5pkt/s. The results indicate that the travel delay of event data stabilizes more slowly when θ_U is large.

C. Effect of time-out ξ

The same network with 400 nodes which includes packet losses with $f = 0.1$ is tested here. The source nodes incorporate a time-out mechanism to retransmit the packet if it does not receive an acknowledgement from the receiver by a certain time while a packet within the network will be destroyed if it

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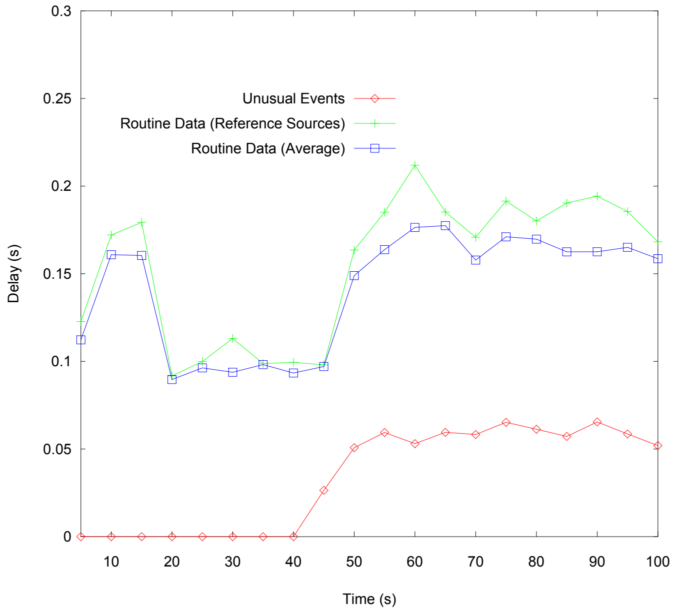

Fig. 5. Transient behavior with f=0, λ_U=5pkt/s, λ_R=1pkt/s, θ_U=3pkt/s.

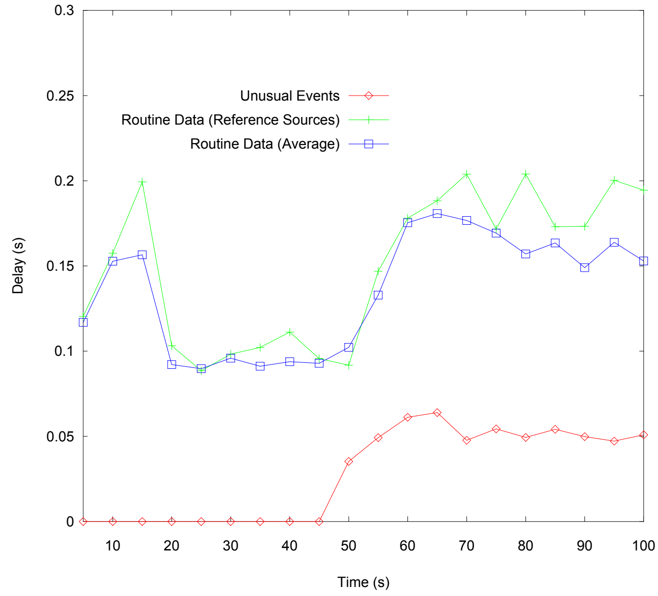

Fig. 6. Transient behavior with f=0, λ_U=5pkt/s, λ_R=1pkt/s, θ_U=4.5pkt/s.

has travelled for more than that time. After the time-out ξ, the source node retransmits the packet after an additional delay M.

Figure 7 shows the travel delay $E[T]$ of packets with $p = 0.2$, $M = 0.02s$, λ_U=5pkt/s, and λ_R=1pkt/s. When the time-out value is small, $E[T]$ is extremely high. There is an optimal value of $E[T]$ in the curve. When the time-out value is greater than the optimal value, $E[T]$ increases again. The travel delay for ONE-bit packets is clearly shorter than that of the routine data packets.

Similarly, Figure 8 illustrates the results of the same experiment with $p = 0.4$ and the travel delay here is greater than that in Figure 7.

IV. Conclusions

In this paper we have proposed an adaptive Randomized Re-Routing (RRR) algorithm that is designed to react to congestion caused by unusual events in WSNs so as to provide better quality of service to the packets carrying the novel or unusual data. It also achieves overall good performance by distributing the secondary or routine data across a wider area of the network thus reducing congestion in the network. We have designed a scheme to detect the occurrence of unusual events by observing a significant change on the content of packets being conveyed and an adaptive randomized routing technique to provide differentiated quality of service to routine data and unusual events. We have evaluated the RRR algorithm using extensive simulation results, demonstrate that RRR can achieve significant QoS improvements for unusual events, while offering acceptable QoS levels to routine data.

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References

[1] K. Romer and F. Mattern, "The design space of wireless sensor networks," *IEEE Wireless Communicationss*, vol. 11, no. 6, pp. 54–61, Dec. 2004.

[2] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *WSNA '02: Proc. of the 1st ACM international workshop on Wireless sensor networks and applications*. New York, NY, USA: ACM, 2002, pp. 88–97.

[3] T. He, J. Stankovic, C. Lu, and T. Abdelzaher, "SPEED: a real-time routing protocol for sensor networks," in *Proc. of IEEE ICDCS*, Providence, RI, U.S., May 2003, pp. 46–55.

[4] C. Lu, B. M. Blum, T. F. Abdelzaher, J. A. Stankovic, and T. He, "RAP: a real-time communication architecture for large-scale wireless sensor networks," in *Proc. of IEEE RTAS*, San Jose, CA, U.S., Sep 2002.

[5] E. Felemban, C.-G. Lee, and E. Ekici, "MMSPEED: multipath multi-speed protocol for QoS guarantee of reliability and timeliness in wireless sensor networks," *IEEE Trans. on Mobile Computing*, vol. 5, no. 6, pp. 738–754, Jun 2006.

[6] M. Caccamo, L. Y. Zhang, L. Sha, and G. Buttazzo, "An implicit prioritized access protocol for wireless sensor networks," in *Proc. of IEEE RTSS*, Austin, TX, U.S., Dec 2002, pp. 39–48.

[7] D. Tran and H. Raghavendra, "Routing with congestion awareness and adaptivity in mobile ad hoc networks," in *Proc. of IEEE WCNC*, Mar 2005.

[8] W. H. Lee, J. M. Chang, and Y. Hasan, "Dynamic memory measuring tool for C++ programs," in *Proc. of the 3rd IEEE Symposium on Application-Specific Systems and Software Engineering Technology (ASSET 2000)*, Richardson, TX, 2000.

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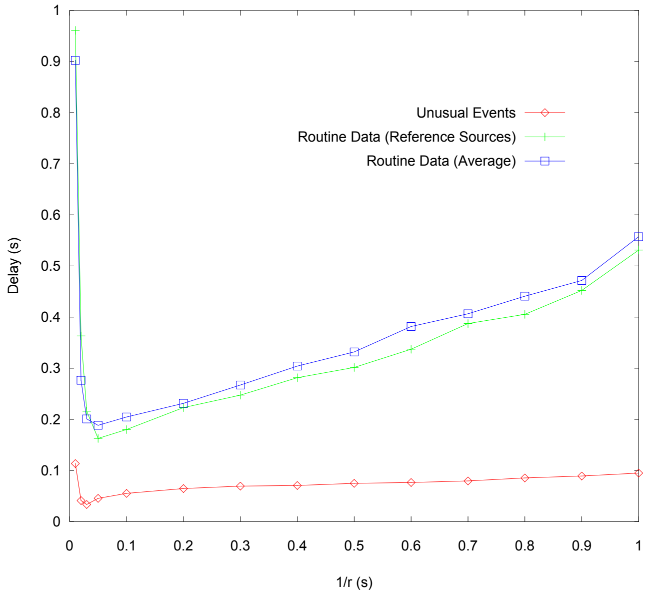

Fig. 7. Travel delay versus time-out with f=0.1, p=0.2, M=0.02s, λ_U=5pkt/s, λ_R=1pkt/s.

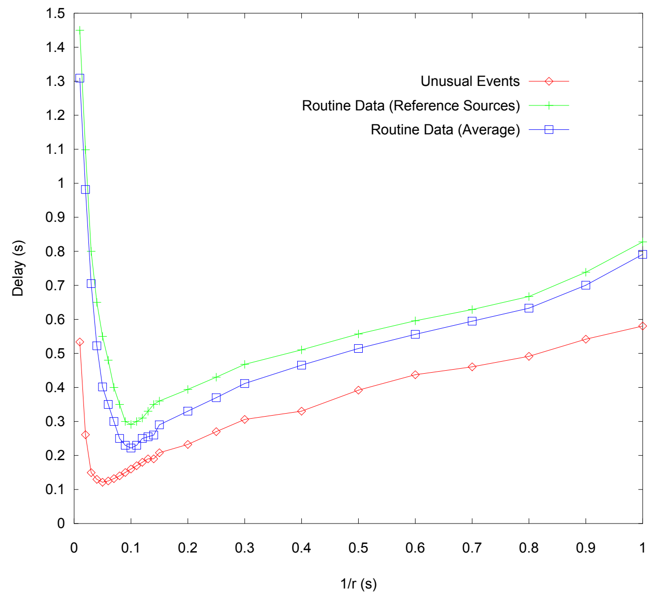

Fig. 8. Travel delay versus time-out with f=0.1, p=0.4, M=0.02s, λ_U=5pkt/s, λ_R=1pkt/s.

[9] C.-Y. Wan, S. B. Eisenman, and A. T. Campbell, “CODA: congestion detection and avoidance in sensor networks,” in *Proc. of ACM SenSys*, Los Angeles, California, U.S., Nov 2003, pp. 266–279.

[10] B. Hull, K. Jamieson, and H. Balakrishnan, “Mitigating congestion in wireless sensor networks,” in *Proc. of ACM SenSys*, Baltimore, Maryland, U.S., Nov 2004, pp. 134–147.

[11] C. T. Ee and R. Bajcsy, “Congestion control and fairness for many-to-one routing in sensor networks,” in *Proc. of ACM SenSys*, Baltimore, Maryland, U.S., Nov 2004.

[12] A. Woo and D. E. Culler, “A transmission control scheme for media access in sensor networks,” in *Proc. of ACM Mobicom*, 2001, pp. 221–235.

[13] Y. Yi and S. Shakkottai, “Hop-by-hop congestion control over a wireless multi-hop network,” in *Proc. of Infocom*, Hong Kong, Mar 2004.

[14] J. Kang, Y. Zhang, and B. Nath, “TARA: Topology-aware resource adaptation to alleviate congestion in sensor networks,” *Trans. on Parallel and Distributed Systems*, vol. 18, no. 7, pp. 919–931, July 2007.

[15] E. Gelenbe, A. Filippoupolitis, and I. Eid, “Energy and time trade-offs in duplicate packet transmission,” in *Proc. of SPECTS 2007*, July 2007.

[16] E. Gelenbe and E. C.-H. Ngai, “Random re-routing for differentiated QoS in sensor networks,” in *Proc. of BCS International Academic Conference*, 2008.

[17] E. Gelenbe, “Travel delay in a large wireless ad hoc network,” in *Proc. of 2nd Workshop on Spatial Stochastic Modeling of Wireless Networks*, Boston, April 2006.

[18] ——, “A diffusion model for packet travel time in a random mult-hop medium,” *ACM Trans. on Sensor Networks*, vol. 2, no. 3, June 2007.

[19] ——, “On approximate computer system models,” *Journal ACM*, vol. 22, no. 2, pp. 261–269, Apr 1975.

[20] E. Gelenbe and G. Pujolle, “An approximation to the behaviour of a single queue in a network,” *Acta Informatica*, vol. 7, pp. 123–136, 1976.

[21] C. Adams, E. Gelenbe, and J. Vicard, “An experimentally validated model of the paging drum,” *Acta Informatica*, vol. 11, pp. 103–117, 1979.

[22] E. Gelenbe and I. Mitrani, “Analysis and synthesis of computer systems,” *Academic Press (London and New York)*, 1980.

[23] K. Fall and K. Varadhan, *The ns manual*, Dec 2003, http://www.isi.edu/nsnam/ns.

[24] E. C.-H. Ngai, Y. Zhou, M. R. Lyu, and J. Liu, “Reliable reporting of delay-sensitive events in wireless sensor-actuator networks,” in *Proc. of IEEE MASS*, Vancouver, Canada, Oct 2006.

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