QoS based Event Delivery for Disaster Monitoring Applications

Poonam Yadav, Julie A. McCann
Department of Computing
Imperial College London
(pooyadav,jamm)@doc.ic.ac.uk

***Abstract*—As Wireless Sensor Networks (WSN) become more technically mature, we are observing more deployment that is widespread. Disaster Monitoring and Recovery is one area receiving recent attention in the field. Here, due to hostile terrains or dangerous settings, standard manual or wired detections are not feasible. *In situ* WSN have the potential to analyze conditions and make predictions regarding dangerous situations potentially saving lives. However, this situation brings many challenges for the WSN in terms of event detection and the subsequent relaying of that event notification to the devices/systems/people that require it. The latter is the focus of this paper. Given the general unreliability of WSNs, there is a demand for Quality of Service driven mechanisms that can ensure that event data is delivered reliably and timely as required by the application. To this end, we present a novel Priority-Based Random Re-routing protocol (PB-RRR). We evaluate our protocol using both an analytical model and a 34-node proof-of-concept sensor deployment. We introduce five QoS levels that progressively improve high priority message throughput from best-effort to reliable event message delivery. We evaluate how congestion, proportions of priority event nodes/messages, and decision threshold affects message delay for each QoS level.**

I. Introduction

In disaster monitoring applications there are two critical tasks that need to be performed. The first one is the identification of the disaster event and the second is the reliable and timely delivery of the event information to the sink or base-station for further action. There is a move for event identification to be done locally at the individual sensor node or a group of sensor nodes may derive it collaboratively. Either way, the most typical and simplest method used in event detection and identification is the comparison of an event signature. Where a given disaster is predictable, all events and their signatures can be predefined. There are different ways to define events, which might be based on single sensor data or a combination of multi-sensor data. Once an event, often critical, is identified either locally or over a region of sensor nodes, this information would have to be delivered reliably to the base-station and as fast as possible for timely decision-making. In sensor-actuator networks, the base-station could automatically enable actuators to manage the situation, for example. There has been relatively much more related work concerning event detection in WSN; however prioritizing event message communication to either guarantee message delivery or provide a best effort delivery performance has received less attention. The Quality of Service (QoS) demands of a WSN for delivery of 'event data' come from application requirements. Some examples are packet delivery ratio, network energy optimization, fastest transmission of information to base station and reliability of transmitted information etc.

978-1-4244-5875-2/09/$26.00 ©2009 IEEE

In this paper, we introduce the concept of and algorithm for, PB-RRR (Priority Based Random Re-Routing) for critical event data delivery in disaster monitoring applications. This paper is organized as follows.

In section II, we present our PB-RRR algorithm and II-A describes network terminology. We analytically analyze the different modes of PB-RRR in section II-B. The experimental setups and results are described in section III. The related work is presented in section IV.

II. Priority Based Random Re-Routing

Priority Based Random Re-Routing (PB-RRR) is a distributed and adaptive routing algorithm which can detect the occurrence of unusual events and provide better QoS for packets that carry information about these unusual events.

The main steps of the PB-RRR algorithms are given below:

while *Node i ensures QoS to event traffic* **do**
  if *Event traffic* $\geq$ *Threshold* θ **then**
    Send event traffic towards best node i-1 towards sink and send routine traffic towards the secondary nodes towards sink;
  else
    Send all traffic(event + routine traffic) to best node i-1 towards sink
  end
end

Algorithm 1: Priority Based Random Re-Routing in Wireless Sensor Networks

We introduce our various QoS modes namely ModeB (Best Path for all traffic without any QoS preference), ModeD, ModeD+, ModeR and ModeR+ in Section II-A.

A. Network Overview and Terminology

We are assuming 'n' sensor nodes, $X = (x_1, x_2..x_n)$, x_i is individual sensor node where $i \in [1, n]$, are distributed independently and arbitrarily on a two dimensional deployment area A. We assume a radio link model where each mode has a certain transmission range r_{x_i} and uses omnidirectional antennas. For convenience we use symmetric links where each node degree is represented as $d(x_i)$ whereas the average degree per node is $d(x_{Avg})$. The number of event nodes in network is $N_E = n * P_e$, where the probability of any source node as event generating node is P_e. The total number of source nodes is $N_P = n * (1 - P_e)$. The packet rate for periodic data (PD) is λ_{PD} per sensor node; the packet rate for event data (ED) is λ_{ED} per sensor node, and the probability of N_P node to be a forwarder node in the multihop network for forwarding high priority packets is P_f. The total number of forwarder nodes $N_F = n * (1 - P_e) * P_f$ and the average number of hops each packet takes to reach sink is h_{Avg}, when all packets choose the best path; with average numbers of re-transmissions (ζ_{Avg}) per sensor node.

In our analytical evaluation of PB-RRR, we examine the transmission and receive overheads for each sensor node to evaluate the performance and the possibility of congestion. The whole deployment area A is dynamically partitioned into two virtual regions; namely the Decision Dominated Area (DDA) that carries mostly event data and the Non-Decision Dominated Area (NDDA) that carries mostly non-event data as shown in Figure 1-b; where sensor nodes x_1 to x_{10} are part of the DDA and rest of nodes are part of the NDDA. The DDA consists of nodes that are on the fastest route to the sink and therefore make the decisions regarding how they route their messages. The NDDA nodes just route messages in the standard multihop manner. Some modes of PB-RRR affect the DDA size and may extend it. We call this the Extended Decision Dominated Area (EDDA).

We assume that an application using the PB-RRR protocol selects one of five modes that are dependent on the nature of, and reliability requirements that occur when an event arises. When event data (ED) has high priority and periodic data (PD) has low priority, each source and forwarder node prioritizes the transmission of ED flows over PD flows with the probability, ρ and the decision parameter in the DDA is based on the reception rate of ED at each sensor node with respect to the decision threshold θ for forwarding PD to the Random (lower-priority) Routes. In each mode, we explicitly study the Decision Dominated area (DDA) and the Non Decision Dominated area (NDDA) as shown in Figure 1-b; where sensor nodes x_1 to x_{10} are part of DDA and rest of nodes are part of NDDA.

We assume that when a node generates an event, it wishes to propagate that event data and will not be sending non-event data at the same time. Therefore the total traffic rate λ_{total} in network when we assume $N_E \cup N_P = n$, $N_E \cap N_P = \Phi$, $N_E \cap N_F = \Phi$, $N_P \cap N_F = N_F$, $N_P \cup N_F = N_P$:

$$\lambda_{total} = \lambda_{PD} * n + (\lambda_{ED} - \lambda_{PD}) * n * P_e \quad (1)$$

$$\lambda_{N_E} = \lambda_{ED} * n * P_e \quad (2)$$

$$\lambda_{N_P} = \lambda_{PD} * n * (1 - P_e) \quad (3)$$

Here λ_{total} is total number of messages generated over the whole network per unit time whereas λ_{N_E} and λ_{N_P} are the total number of messages generated by all event nodes and all non-event nodes per unit time. Further, the total Transmission rate Tx_{total} where all packets routed to best path:

$$Tx_{total} = \lambda_{total} * h_{Avg} * (\zeta_{Avg} + 1) \quad (4)$$

$$Tx_E = \lambda_{N_E} * h_{Avg} * (\zeta_{Avg} + 1) \quad (5)$$

$$Tx_P = \lambda_{N_P} * h_{Avg} * (\zeta_{Avg} + 1) \quad (6)$$

The total received and snooped (overhearing) rate Rx_{total} in network when all packets routed to best path thus:

$$Rx_{total} = \lambda_{total} * h_{Avg} + \lambda_{total} * h_{Avg} * (\zeta_{Avg} + 1) * d(x_{Avg}) \quad (7)$$

We now introduce our various QoS modes namely ModeB, ModeD, ModeD+, ModeR, and ModeR+, which gradually increase a bias towards deliveries of the priority packets at the cost of low-priority packets.

ModeB: In the Basic Mode of Priority Based Random re-routing, $\Omega(LC) < \theta \leq \infty$ (LC is the link capacity of the network [1]), so here all data is routed through the best path and no data is routed using a random route; i.e. all nodes are effectively in the DDA(See figure 1-a).
The total transmissions in DDA are thus:

$$Tx_{DDR} = (\lambda_{ED} * P_e + (1 - P_e) * p_f * \lambda_{PD}) * n * h_{Avg} * (\zeta_{Avg} + 1) \quad (8)$$

$$Rx_{DDR} = (\lambda_{ED} * P_e + (1 - P_e) * p_f * \lambda_{PD}) * n * h_{Avg} \quad (9)$$

$$Rx_{DDR}(Overheard) = Rx_{DDR} * d(x_{Avg}) * (\zeta_{Avg} + 1) \quad (10)$$

Total transmissions in NDDA are therefore:

$$Tx_{ND} = \lambda_{PD} * (1 - P_e)(1 - P_f) * n * h_{Avg} * (\zeta_{Avg} + 1) \quad (11)$$

ModeD: This is the Decision mode of Priority Based Random re-routing whereby the shortest path from the event to the sink form the DDA and the priority packets will be routed therein. Here, $0 \leq \theta < \Omega(LC)$. We set decision threshold $\theta = 0$ to indicate that all the low-priority PD flow is re-routed using the random path by all N_F nodes in the DDA. Therefore the NDDA essentially forwards all the low-priority packets. Nodes 1 through 10 compose the DDA for mode D in Figure 1-b.

The total transmissions in DDA are thus:

$$Tx_{DDR} = (\lambda_{ED} * P_e * h_{Avg} + \lambda_{PD} * P_f * (1 - P_e)) * n * (\zeta_{Avg} + 1) \quad (12)$$

$$Rx_{DDR} = (\lambda_{ED} * P_e * h_{Avg} + \lambda_{PD} * P_f * (1 - P_e)) * n \quad (13)$$

$$Rx_{DDR}(Overheard) = Rx_{DDR} * d(x_{Avg}) * (\zeta_{Avg} + 1) \quad (14)$$

Total remaining transmissions in the NDDA is represented by:

$$Tx_{ND} = \lambda_{PD} * (1 - P_e) * n * (\zeta_{Avg} + 1)(h_{Avg} + P_f * \delta_{Avg}) \quad (15)$$

ModeD+: This is the extended Decision mode of Priority Based Random re-routing designed to try and reduce the low-priority packets competing on the high-priority routes. When event data (ED) has a high priority and periodic data (PD) has a low priority, each source and forwarder node of ED (sensor nodes in the DDA) declares itself as a Decision node, *'D'* and broadcasts itself as being Not Accessible(NA) to PD flows, as

[1] Measurement of Link Capacity is not part of this research, more details can be found at [5], [3]

indicated by the diamonds barrier in figure 1-c.
Therefore each neighbouring node of *'D'* forwards PD over Random routes with probability, ρ where $0 \leq \rho \leq 1$, this essentially creates an extended decision dominated area (EDDA) which is indicated by sensor nodes x_a, x_b, x_c and x_d as shown in figure 1-c. We assume $\theta = 0$ for all forwarder nodes in the DDA and $\rho > 0$ for the EDDA nodes, which effectively forces PD away from the best path as shown in figure 1-c.
The total transmissions in the DDA now become:

$$Tx_D = (\lambda_{ED}*P_e*h_{Avg}+(\lambda_{PD}*P_f(1-P_e)/h_{Avg})n*(\zeta_{Avg}+1) \quad (16)$$

$$Rx_D = (\lambda_{ED}*P_e*h_{Avg}+(\lambda_{PD}*P_f*(1-P_e)/h_{Avg})*n \quad (17)$$

$$Rx_D(Overheard) = Rx_D * d(x_{Avg}) * (\zeta_{Avg} + 1) \quad (18)$$

With the total transmissions in NDDA being thus:

$$Tx_{ND} = \lambda_{PD}*(1-P_e)*n*(\zeta_{Avg}+1)(h_{Avg}+P_f*\delta_{Avg}) \quad (19)$$

ModeR: This is the reserved mode for ED flows. When ED has is of high priority and the PD remains low priority, each source and forwarder node of ED declares itself as a decision node, *'D'* and, like the previous mode, broadcasts itself as being Not Accessible (NA) for PD flows. Each neighbouring node surrounding *'D'* then forwards PD over Random routes with probability, ρ = 0, which means all sensor nodes in the DDA and EDDA drop PD forwarding altogether. This again creates a DDA and EDDA one which is a highly reserved area where there will be no PD flowing as shown also in figure 1-d. The basic assumption here is that the priority messages must be delivered in a timely manner and that the low-priority massages (PD) are now of no real value to the application and can be almost discarded. The total transmissions in DDA are described thus:

$$Tx_D = \lambda_{ED} * P_e * h_{Avg} * n * (\zeta_{Avg} + 1) \quad (20)$$

$$Rx_D = \lambda_{ED} * P_e * h_{Avg} * n \quad (21)$$

$$Rx_D(Overheard) = Rx_D * d(x_{Avg}) * (\zeta_{Avg} + 1) \quad (22)$$

The total transmissions in NDDA are now:

$$Tx_{ND} = \lambda_{PD} * (1 - P_e)(1 - P_f) * n * h_{Avg} * (\zeta_{Avg} + 1) \quad (23)$$

ModeR+: This mode combines both the concepts of reservation as in the previous mode with high reliability through redundancy for ED flows. Again, when event data (ED) has high priority and periodic data (PD) has low priority, each source and forwarder node of ED, declares itself as decision node,*'D'* and broadcasts itself as Not Accessible (NA) for PD flows. Each of the neighbouring nodes of *'D'* forwards low-priority PD over Random routes with a probability, $0 \leq \rho \leq 1$ and also forwards ED flows over random route with probability, $0 \leq \rho_e \leq 1$ as on secondary paths. That is, all high-priority ED flows are not only routed through the fastest route that has been reserved, but a copy has been forwarded to the NDDA to increase reliability. We have set $\rho = 0$ and $\rho_e = 1$.
The total transmissions in DDA are now:

$$Tx_D = \lambda_{ED} * P_e * (h_{Avg} + 1) * n * (\zeta_{Avg} + 1) \quad (24)$$

$$Rx_D = \lambda_{ED} * P_e * (h_{Avg} + 1) * n \quad (25)$$

$$Rx_D(Overheard) = Rx_D * d(x_{Avg}) * (\zeta_{Avg} + 1) \quad (26)$$

Finally the total transmissions in NDDA are now:

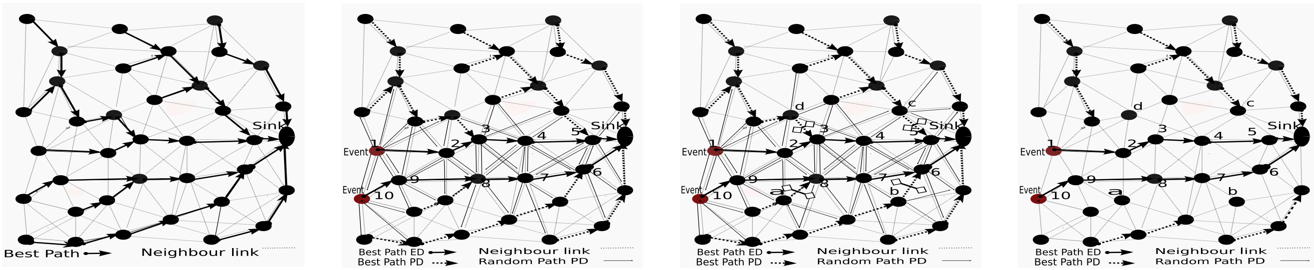
$$Tx_{ND} = (\lambda_{PD}*(1-P_e)(1-P_f)+\lambda_{ED}*P_e)h_{Avg}*n*(\zeta_{Avg}+1) \quad (27)$$

B. *Analytical Results for PB-RRR*

This section presents analysis of our model to provide us with an initial view of the relative performance of PB-RRR in 100 nodes network.

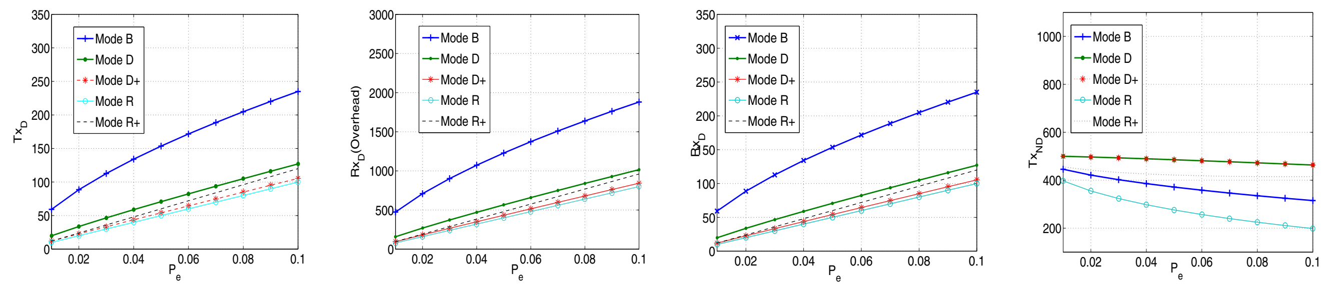
Figure 2-a shows total number of transmission messages through the nodes that constitute the priority fastest route area (DDA) for all (priority and non-priority) messages in all five QoS modes for 100 nodes. As expected, as the probability of an event increases so too does the total number of transmissions of packets as more of the network becomes the DDA and more packets require high-priority routing. We can clearly see that we significantly improve the number of messages to be transmitted compared with that of the basic mode (B) by affecting a priority path. We also see that Modes D+ and R improve this further, however this graph highlights that the Mode R+ transmissions are slightly higher because of the redundancy in duplicate priority packets being injected into the network. Given that the graph represents only transmissions through the DDA one would expect that R+ would be closer to the performance of R. However, the poorer performance is because as a duplicate message is generated in the DDA it has to be sent through to the NDDA, it must be routed to that area and that passage is being counted here. Nevertheless, Mode R+'s performance remains significantly better than, not only the base mode, but Mode D; highlighting its usefulness where reliability and priority is paramount. Figure 2-c as well as Figure 2-b further reflect these performance characteristics in terms of numbers of received messages and overheads respectively.

Figures 2-d highlights the cost of the various modes in terms of numbers of low-priority message transmissions through the NDDA. Here we can see that as the probability of event data increases, the numbers of non-priority message transmissions decrease as compared. This is especially the case for mode R where non-priority messages are essentially being dropped and no retransmission is assumed. However, note the performance of mode R+ in figures 2-a to 2-d. Here we can clearly see its extra costs in terms of the duplication of messages being sent through both the DDA and NDDA area as its numbers of transmissions here are much higher. The basic (B) mode is less favourable to low-priority packets than both the D and D+ modes (both D and D+ are superimposed on the graph confirming that their behaviour for low-priority messages is identical). This is because the D and D+ modes are essentially isolating the DDA and NDDA therefore allowing more low-priority messages to flow through the NDDA. We analyze



(a) ModeB (b) ModeD (c) ModeD+ (d) ModeR

Fig. 1. PB-RRR, In ModeB where all nodes send data over best path. In ModeD where event nodes send data to sink by choosing best path nodes 2 to 10 as forwarder nodes and all forwarder nodes directs non-event data to random neighbours. In ModeD+ where event data is forwarded over best path as in ModeD but one hop neighbours of event data forwarder nodes also directs non-event data to random neighbours instead of best path that creates extended decision area. In ModeR all nodes in Extended decision area drops non-event data to avoid overhearing traffic.



(a) n = 100 (b) n = 100 (c) n = 100 (d) n = 100

Fig. 2. PB-RRR, the packet rate for event data (ED) per sensor node is $\lambda_{ED} = 2$;the packet rate for periodic data (PD) per sensor node is $\lambda_{PD} = 1$; P_e is probability of source node to be an event node; $0 \leq P_e \leq 1$; n represents total number of nodes; when (n = 100) average hops for packets $h_Avg = 5$ and $d(x_{Avg}) = 8$; (a) Shows total number of packets transmissions in DDA region Tx_D ; (b) Shows total number of packets overhead in DDA region $Rx_{DDR}(Overheard)$;(c) Shows total number of packets reception in DDA region Rx_D when n=100 ; (d)& (h) Shows total number of packets transmissions in NDDA region Tx_{ND}

analytical model to observe relative mode performance and the effects of scale to 1000 nodes and found similar behaviour[2] .

In summary, our analytical models show that there is great value to be obtained from introducing QoS modes to routing protocols for WSN. However, analytical models do not give us a feel for how affects such as packet loss and other dynamic behaviours affect the protocol. Therefore in next section we deploy the same model, PB-RRR's B [3] and D mode on actual WSN nodes. This also helps validate our models.

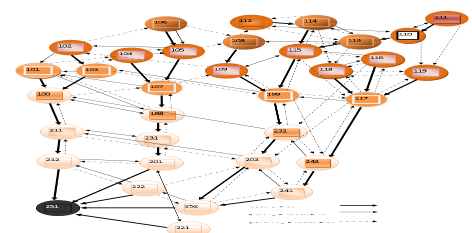


Fig. 3. Snapshot of Experiment Setup Topology, the black node is sink

III. Experimental evaluation

We have carried out PB-RRR algorithm evaluations on our testbed composed of 34 Telosb motes placed randomly in our laboratory. Each mote is connected to the testbed's server over the Ethernet. For the purposes of this experiment, we have programmed the motes so that we have four types of nodes: unusual event data [4] generating nodes N_E, routine data [5]generating nodes N_R , forwarding nodes N_F(forwarding nodes are dedicated for forward operation not generating their own data) and a receiver (Sink) node.

The node positions are distributed at random within a 10×10 square metre area, while the sink is located at the center of the square. The experiments we conduct evaluate a WSN which collects and reports routine data to the sink constantly. Any of the sensors has a probability p_e to be the source of an Unusual Event, i.e. $p_e = N_E/N$, where $N = N_R + N_F + N_E$, and generates data independently of the others[6].

Figures 4-a through to 4-f show the results of our experi-

[2]Graphs for 1000 nodes are not presented here due to space limit

[3]Mode B also referred as SPF elsewhere in this paper

[4]Also referred as simply unusual data or event or event data or high priority data elsewhere in this paper

[5]Also referred as simply low priority data or non-priority data elsewhere in this paper

[6]Note that this independence assumption may be unreasonable when uncorrelated events are being reported across a sensory field.

ments. Figure 4-a presents the round-trip delays for messages for a 100 second run of the protocols when decision threshold θ for PB-RRR in mode D is set to 2 pkts/s. The SPF line represents all the messages being routed through the network, that is PB-RRR in mode B where decision threshold $\theta \approx \infty$, when all packets follow the same path. We can also clearly see the operation of the mode D protocol in terms of the division between the low-priority packets and high-priority packets in terms of delay; i.e. the high priority messages not only have a significantly lower delay than average SPF data, but also the performance improvement over the basic protocol is obvious. Figure 4-d shows the effects of the protocol when the decision threshold θ for PB-RRR in mode D is set to 10 pkts/s. We begin to see that the gap between low and high priority packet delay is reduced. Also, the delays for the periodic data begin to increase, quite drastically in parts (see the spikes). However, for all of these event messages incur the least delay on average. Figures 4-b and 4-e show how the system reacts when we double the event data source probability, P_e to 0.18, with decision threshold θ for PB-RRR in mode D set to 2 and 10 pkts/s respectively. For the most part, we can see that the priority packets achieve less delay than the non-priority and perform better on average than that of the original basic protocol. However, as figure 4-e shows, as the decision threshold θ becomes 10 pkts/s the priority messages average a delay similar to that of the original basic protocol, with low-priority messages performing worse than with the basic protocol. This is because all nodes in the decision dominated area (DDA) are generating and forwarding a total number of packets per second less than the decision threshold, which makes all packets follow the best path; same as mode B or SPF.

Figures 4-c and 4-f show the round-trip delays for the probability a node generating event P_e that has been increased to 0.27. This shows where the protocol becomes unable to cope with an event-saturated network. This implies that our mode R (and perhaps R+) would be a better option here therefore improving this performance at a larger cost to the low-priority packets.

IV. Related Work

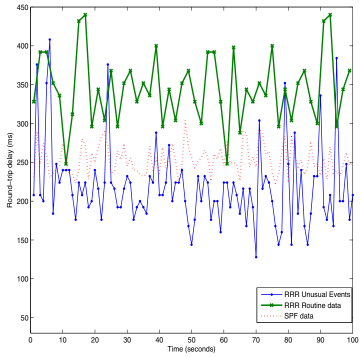
The implementation details of the random re-routing algorithm in a fixed asymmetric network where each node takes its own independent decision on the basis of rate of high priority packets reaching at that node is studied in [1]. [2] evaluates the performance of random re-routing by simulating algorithm in NS2. The NS2 simulation here considers a fixed packet loss probability and the MAC layer considered is 802.11, that gives the behaviour of algorithm in general wireless networks, but not for wireless sensor networks where communication media has low bandwidth. The challenges of bursty convergecast in multi-hop wireless networks are addressed in [9] and a Reliable Bursty Convergecast (RBC) protocol is designed to improve channel utilization using a window-less block acknowledgement scheme. A sink centric transport protocol is proposed in [8], in which packet loss is detected by the sink from the discontinuous packet sequence numbers, and sequence numbers of lost packets are then sent back towards the sources through virtual backward channels. This protocol considers only event packets in the network not the background data packets, so it assumes each event packet has only one path towards the sink, that assumption does not fit exactly in real-time dense wireless sensor networks where numbers of event nodes can be more than one and the sink receives different data streams. Energy-Efficient routing framework is proposed in [6] that adapts to fit in application specific scenarios. A Congestion aware algorithm is proposed in [4], which addresses the data delivery issue in congested networks by simulating the algorithm in NS-2 to evaluate the performance for general wireless sensor networks. [7] simulated three service differentiation schemes to evaluate the packet delivery ratio and end-to-end delay for high priority packets. The single end-to-end path is reserved for high priority packets. This approach suffers with the major drawback that if an intermediate node fails in the path then all high priority packets will be lost.

V. Conclusions

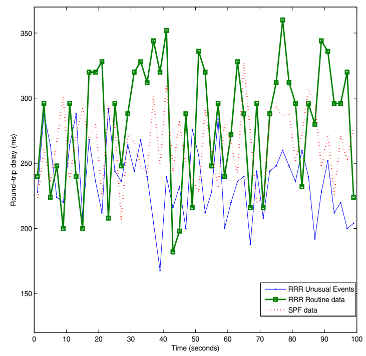
As Wireless Sensor Networks mature to become relied upon to effectively save lives etc., routing protocols must reflect the Quality of Service requirements that these class of applications demand. This paper presents the PB-RRR protocol that contains five modes to differentiate QoS, based on prioritizing event data over periodic (background) messages. Here, mode D (Decision) is where event data is routed via the fastest path and all other non-priority data is routed randomly in a traditional multi-hop fashion. Mode D+ (extended D) further prioritizes event data in that it places a barrier on the fastest path and therefore rejecting low-priority messages who found their way to the nodes on that fastest path. These messages move to the low priority nodes instead. Where an application wishes to have the fastest path essentially reserved, we have mode R (Reserved). This is similar to D in that it bars low-priority messages, but it does this by dropping the low-priority messages. Given the typical unreliability of WSN due to transient environmental conditions, battery life etc, there may be a need for a more reliable reservation mode. This we call R+, which extends R in that all messages routed in the fastest path area are also duplicated to the nodes outside this path and routed randomly.

Initially, we used an analytical model to observe relative mode performance and the effects of scale to 100 nodes. We show that we can achieve an average of 30-40% improvement in performance of our protocol over the basic (non-re-routing) protocol. From this, our QoS modes further improve this performance, though less dramatically and can achieve reliability for the event data (as a cost to the periodic data).

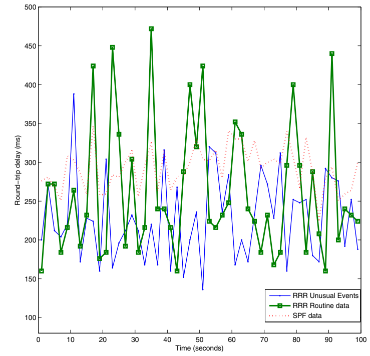
From this we are then able to examine the system on actual WSN nodes and observed that when we experience a relatively extreme number of events in the network the average round-trip delay is reduced using our protocol. We have analyzed the congestion in the network by varying the number of event nodes that increases the event traffic load in the network. We found that as we increase the number of event nodes we



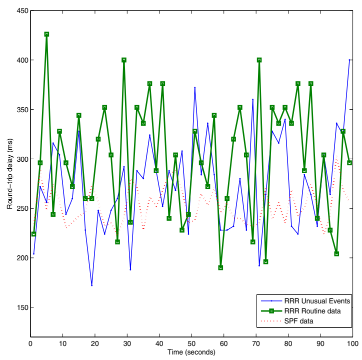
(a) Threshold $\theta = 2$ and Event Probability p_e=0.09.



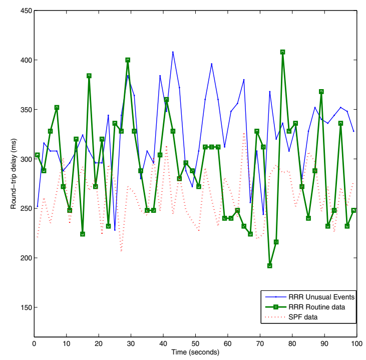
(b) Threshold $\theta = 2$ and Event Probability p_e=0.18.



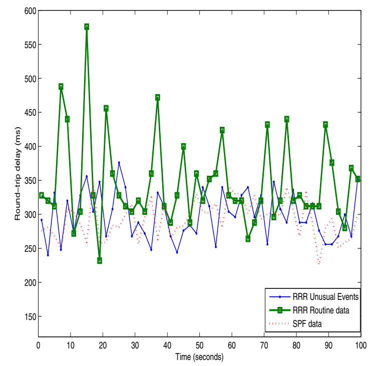
(c) Threshold $\theta = 2$ and Event Probability p_e=0.27



(d) Threshold $\theta = 10$ and Event Probability p_e=0.09.



(e) Threshold $\theta = 10$ and Event Probability p_e=0.18.



(f) Threshold $\theta = 10$ and Event Probability p_e=0.27

Fig. 4. The event data packet rate per node is $\lambda_{ED} = 2$ and the routine data packet rate per node is $\lambda_{PD} = 1$. the probability that a node generate event is specified by p_e, higher the value of p_e, more event traffic in the network. Experiments are conducted with three values of p_e = 0.09, 0.18 and 0.27. The other variable in the experiments is decision threshold θ. Experiments results shown above are with two values of θ = 2 and 10. In ModeB where all nodes send data over best path shown as SPF data in the figures. In ModeD where event nodes send data to sink by choosing best paths as forwarder nodes and all forwarder nodes directs non-event data to random neighbours, the round-trip delay of 7-8 hops of event data packets and routine data packets are considered

experience more packet loss due to congestion on the high packet delivery paths. We found the average delay difference was almost 30-50ms in an 8-hop network between routine and high priority data. As the TOSSIM simulator is not ideal for measuring accurate delays in simulation, for delay evaluation on real tested, we used end-to-end acknowledgements for measuring end-to-end delay only for reference nodes because time synchronization is not implemented as part of the algorithm. For more accurate performance evaluation of our protocol, the time synchronization protocol should be integrated with PB-RRR protocol.

REFERENCES

[1] E. Gelenbe, E. Ngai, and P. Yadav. Routing of high proiority packets in wireless sensor networks. In *SPIE*, 2009.

[2] E. Gelenbe and E. C.-H. Ngai. Adaptive qos routing for significant events in wireless sensor networks. *MASS'08: The 5th IEEE International Conference on Mobile Ad-Hoc and Sensor Systems*, 2008.

[3] P. Gupta and P.R.Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, 2000.

[4] R. Kumar, R. Crepaldi, H. Rowaihy, A. Harris, G. Cao, M. Zorzi, and T. La Porta. Mitigating performance degradation in congested sensor networks. In *IEEE Transactions on Mobile Computing*, volume 7, pages 682–697, 2008.

[5] T. Moscibroda. The worst-case capacity of wireless sensor networks. *IPSN'07: The 6th ACM International Symposium on Information Processing in Sensor Networks*, pages 1–10, 2007.

[6] A. Papadopoulous, A. Navarra, and J. A. McCann. Vibe: a virtual-infrastructure-based energy-efficient framework for routing over scalable wireless sensor networks. In *International Conference on Distributed Computing in Sensor Systems(DCOSS)*, 2008.

[7] W. L. Tan, O. Yue, and W. C. Lau. Performance evaluation of differentiated services mechanisms over wireless sensor networks. In *VTC'06: Proceedings of 64th IEEE Vehicular Technology Conference*, pages 1–5, 2006.

[8] X. Wang, X. Zhao, Z. Liang, and M. Tan. Deploying a wireless sensor network on the coal mines. pages 324–328, April 2007.

[9] H. Zhang, A. Arora, Y.-r. Choi, and M. G. Gouda. Reliable bursty convergecast in wireless sensor networks. In *MobiHoc '05: Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, pages 266–276, 2005.