On Throughput and Load Balancing of Multipath Routing in Wireless Networks

Swades De† and Chunming Qiao‡
†Department of Electrical Engineering
‡Department of Computer Science and Engineering
State University of New York at Buffalo, Buffalo, NY 14260
{swadesd, qiao}@cse.buffalo.edu

Abstract— **In this paper we investigate the relative performance of two multipath routing schemes in relatively static and highly error-prone wireless networks (e.g., sensor networks), namely, selective preferential forwarding (SPF) (or primary/ secondary routing) and recently proposed selective random forwarding (SRF), in terms of their packet throughput and traffic load distribution. For meshed multipath, aiming at achieving a good performance trade-off, we introduce a novel hybrid packet forwarding scheme that takes advantage of more uniform load distribution of SRF and a higher end-to-end throughput of SPF. Our approach is guided by analytic intuition and verified by simulations.**

I. Introduction and Motivation

We consider a relatively static but highly error-prone wireless networks, wherein the example applications include remote/hazardous field information monitoring and control via tiny, low-cost sensors [1]-[3]. The field sensors (also called nodes) form a network among themselves and communicate with the command and control center (or a clusterhead) via multiple hops. Numerous routing approaches have been proposed in the literature for sensor applications (see e.g., [4]-[11]). For robust end-to-end communication in a failure-prone network, some sort of multipath routing along either disjoint [6],[7],[10] or meshed (i.e., partially disjoint) [6],[9],[11] routes are generally considered, where either (i) a packet could be replicated along all routes (as observed in [4],[6]) in an approach called packet replication, or (ii) it could be sent along one of the different alternative routes [7],[9],[10] in an approach called *selective random forwarding (SRF)*, or (iii) transmission is attempted along a predetermined 'preferred' route, while the alternative routes are kept standby for failure recovery [6],[11] in an approach called *selective preferential forwarding (SPF)* (or primary/secondary routing). Although there have been prior comparative studies on packet replication versus SRF [12] and in general, disjoint multipath routing versus meshed multipath routing [9], no thorough investigation has been reported in the literature on the relative performance of SRF and SPF. Below, we elaborate on the SRF and SPF approaches in the context of our subsequent development in this paper.

The common characteristics of the SRF and SPF approaches considered in this paper are the following: (a) To *minimize the network-wide signaling*, frequent global or end-to-end routing message exchange (as in [13]) is avoided. Instead, once multipath routes are determined, a routing decision is taken based on the local neighborhood information collected prior to routing a data packet. (b) To *minimize the nodal buffer requirement*, *reduce or avoid the additional trans-receive power consumption*, and *keep the packet scheduling mechanism simple*, link layer acknowledgment or negative acknowledgment based retransmission/rerouting (as in [6],[8]) is not practiced. Instead, at any point along the route, if a packet cannot be forwarded to a next downstream node, the packet is dropped (without any buffering). To support a specified quality-of-service (QoS), appropriate forward error correction (FEC) schemes can be adopted. In this paper, however, we will only focus on the raw packet throughput and traffic load balancing.

The additional unique features of SRF and SPF are described below.

Selective random forwarding (SRF): In SRF, given a choice of equally good next hop directions, a packet picks up one randomly. With disjoint multipath, the route selection is done by the source node only. Such a scheme is also called diversity routing [7] or split multipath routing [10]. With meshed (or non-disjoint) multipath, SRF offers distributed routing control [9], where a packet forwarding decision is taken at an intermediate node depending on the condition of immediate downstream neighbors.

Selective preferential forwarding (SPF): In SPF, on the other hand, a predefined route is designated as the primary (or preferred) route along which a packet transmission is attempted first. With disjoint multipath, the preferred route will be used as long as the first hop is healthy and a packet is dropped if any of the intermediate nodes fails or a link error occurs. With meshed multipath, SPF offers distributed control as in SRF, but priority is given to the next hop along (or toward) the preferred route.

In this work, we study the relative throughput and traffic load distribution performance of the SRF and SPF approaches. Besides comparing the performances of SRF and SPF along disjoint as well as meshed multipath, we introduce a novel hybrid routing approach for meshed multipath that combines the benefits of more uniform traffic load distribution associated with SRF and higher packet throughput associated with SPF, thereby achieving higher throughput performance along with better traffic load distribution.

The rest of the paper is organized as follows. Section II contains the analytic performance evaluation of SRF and SPF in

 0-7803-8344-3/04/$20.00

terms of throughput and traffic load distribution. Performance results of SRF and SPF are presented in Section III. A new hybrid packet forwarding protocol is introduced and its performance is studied in Section IV. Finally, a few concluding remarks are made in Section V.

II. Routing Performance Analysis

We evaluate the throughput and load balancing performances of selective random forwarding (SRF) and selective preferential forwarding (SPF) schemes along disjoint multipath and meshed multipath. We define *Normalized throughput* T as the probability of successful arrival of a packet at the destination. *Load distribution ratio* is defined as the ratio of minimum number of packets carried by a node along a route to the maximum number of packets carried by another node along the same multipath route, i.e., *load distribution ratio* $= \frac{P(min)}{P(max)}$, where $P(min)$ and $P(max)$ are respectively the minimum and maximum probability of routing a packet by two different nodes along the multipath. The higher the ratio, the better the load distribution performance of a packet forwarding strategy. The expressions for T, $P(max)$, and $P(min)$ are computed in our following analysis.

For simplicity, we consider equal length multiple routes and a regular mesh, and present the case for meshed routes with an even number of hops (see Fig. 1). Based on the findings in [14] that having *two* downstream forwarding options achieves a good trade-off between routing success and the associated control overhead, we consider a meshed route from a field node (source) to a clusterhead (sink), along which there are at most two incoming links and two outgoing links at an intermediate node. In Section III, we will study the performance of SRF and SPF under more practical assumptions on the disjoint and meshed routes via simulations, where due to random location of field sensors all routes between a source to the destination may not be of equal length, and (for meshed routes), not all intermediate nodes may have two incoming as well as two outgoing links (see Fig. 2)

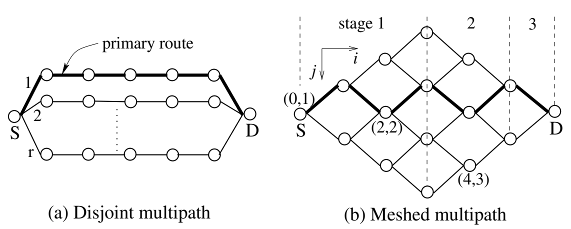


Fig. 1. Examples of 6-hop multiple routes. The thick lines joining S and D form the primary route in SPF.

Henceforth, source-to-destination distance is denoted by H and for each packet transmission link error and intermediate node failure probabilities are denoted by p_l and p_n, respectively. Note that the end node (i.e., the destination) is considered ready to receive (i.e., $p_n = 0$) all packets. p_l captures Gaussian channel noise as well as the error due to medium access conflict, and p_n captures the packet loss due to input buffer overflow and node failure. A link is modeled as an additive white Gaussian noise (AWGN) channel. If p_b is the average bit error probability (or BER) due to channel error and B is the packet size (in bits), then

$$p_l = 1 - (1 - p_b)^B. \tag{1}$$

A. *Disjoint multipath*

Refer to the the Fig. 1(a).

A.1 Selective random forwarding (SRF)

Normalized throughput: In case of disjoint multipath, routing decision flexibility is available only at the source. The corresponding normalized throughput (or end-to-end successful packet arrival probability) is:

$$T_{SRF}^{(d)} = (1 - p_l)^H \, (1 - p_n^r) \, (1 - p_n)^{H-2} \tag{2}$$

where $(1 - p_l)\,(1 - p_n^r)$ is the probability of reaching to a next node from the source, and $(1 - p_l)^{H-1}\ (1 - p_n)^{H-2}$ is the probability of successfully covering the remaining $(H - 1)$ hops.

Traffic load distribution: The maximum probability of routing a packet via a node in SRF is given by

$$P_{SRF}^{(d)}(max) = (1-p_n)(1-p_l) \sum_{i=0}^{r-1} \left(\frac{1}{i+1}\right) \binom{r-1}{i} (1-p_n)^i p_n^{r-1-i}. \tag{3}$$

Clearly, the maximum probability will be at a first hop downstream node. Also, in case more than one first hop downstream nodes are ready, since one is selected by flipping a coin, the minimum probability at a first hop downstream node will be the same as the maximum. Packet arrival probability will reduce further downstream along a route. The minimum probability will occur $H - 2$ hops away from the first downstream node, which is given by

$$P_{SRF}^{(d)}(min) = P_{SRF}^{(d)}(max) \times (1 - p_n)^{H-2} (1 - p_l)^{H-2}. \tag{4}$$

A.2 Selective preferential forwarding (SPF)

Normalized throughput: Since all routes are considered to be of equal hop length and node failure and link error are equiprobable, the throughput performance in SPF will remain exactly the same as in SRF.

Traffic load distribution: To quantify the difference in load distribution in SPF, we denote r parallel routes as *route 1* through *route r*, with *route 1* as the first priority route (denoted by the thick lines connecting the source-destination pair in Fig. 1(a)). The maximum number of packets will be received by the first downstream node in *route 1*, with probability

$$P_{SPF}^{(d)}(max) = (1 - p_n)(1 - p_l). \tag{5}$$

The minimum number of packets will be received by the last downstream node in *route* r (before the destination), with probability

$$P^{(d)}_{SPF}(min) = p_n^{r-1}(1-p_n)^{H-1}(1-p_l)^{H-1}. \qquad (6)$$

Relative throughput and traffic distribution results are shown in Table I.

B. Meshed Multipath

We consider the ideal meshed multipath with even number of hops as shown in Fig. 1(b).

B.1 Selective random forwarding (SRF)

Normalized throughput: The multipath is divided into three stages. Stage 1 covers the nodes from the source up to those $\frac{H}{2}$ hops away, Stage 2 covers hops between $\frac{H}{2}$ and $H-1$, and Stage 3 is the last hop. Successful packet arrival probabilities at the end of first two stages, denoted by $P_s(i)$, where $i = 1$ and 2, are obtained as follows:

Stage 1: In this stage, a packet successfully reaches the next node if at least one of two downstream nodes is ready to receive, with probability $\left(1-p_n^2\right)$, and the channel is good during the packet transmission, with probability $(1-p_l)$. Since Stage 1 has $\frac{H}{2}$ hops, $P_s(1)$ is given by

$$P_s(1) = \left[(1-p_l)\left(1-p_n^2\right)\right]^{\left(\frac{H}{2}\right)}. \qquad (7)$$

The probability with which a successful packet arrives at a node $N_{h,j+1}$ at the end of Stage 1 is binomially distributed:

$$P_{h,j+1} = \frac{1}{2^h}\binom{h}{j}. \qquad (8)$$

where $h = \frac{H}{2}$ and $j = 0,\ 1,\ \cdots,\ h$.

Stage 2: $P_s(2)$ is obtained recursively with the observation that the edge nodes in the meshed route have two incoming links but only one outgoing link, whereas the nodes inside the mesh have two incoming as well as two outgoing links. Due to lack of space we do not present the actual algorithm here.

Finally, counting Stage 3, normalized throughput is given by

$$T^{(m)}_{SRF} = (1-p_l)\prod_{i=1}^{2} P_s(i) \qquad (9)$$

Traffic load distribution: Referring to Fig. 1(b), since the edge nodes up to $h = \frac{H}{2}$ have only one predecessor node, the maximum number of packets will be received by the first hop nodes with probability $P^{(m)}_{SRF}(max)$, which is given by the right hand side of (3), where $r = 2$. The minimum number of packets will be received by the by the nodes $N_{h,j+1}$ with probability

$$P^{(m)}_{SRF}(min) = \frac{1}{2^h}\binom{h}{j}\left[(1-p_l)\left(1-p_n^2\right)\right]^h \qquad (10)$$

where $h = \frac{H}{2}$ and $i = 0,\ h$.

B.2 Selective preferential forwarding (SPF)

Normalized throughput: In this case, referring to Fig. 1(b), where the primary route is shown by thick connected links, the end-to-end normalized throughput $T^{(m)}_{SPF}$ is obtained following the recursive algorithm as in case of SRF with the understanding that the downstream node closer to the primary route is tried first. For space limitation, we omit the detailed algorithm in this paper.

Traffic load distribution: For a predefined primary route as shown in Fig. 1(b), packet distribution in SPF along meshed multipath is obtained following the throughput analysis approach presented in Appendix II. The maxima of packet distribution will occur at the first downstream node in the primary route (node N_{11} in Fig. 1(b)) with packet arrival probability $P^{(m)}_{SPF}(max)$, which is given by the right hand side of (5).

The minima will be half way in the route, at the farthest away node from the primary route (node N_{34} in Fig. 1(b)) with probability

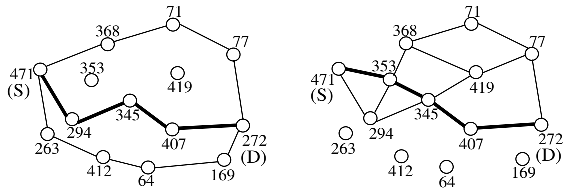
$$P^{(m)}_{SPF}(min) = \left[p_n(1-p_n)(1-p_l)\right]^{\frac{H}{2}}. \qquad (11)$$

III. Performance Results

In this section, we present the numerical results on throughput and traffic load distribution ratio from the analysis and verify them via discrete event simulation. The intermediate nodes are assumed to fail intermittently (with probability p_n). If a node is found ready to receive before transmitting a packet (based on a priori local neighborhood information), it remains ready throughout the packet transmission period. However, channel noise can still corrupt a packet (with BER p_b). We construct multipath routes based on the number of hops, and consider the primary route (in case of SPF) as the one with minimum hop length. This is however not a limitation, as any other criteria (such as minimum energy, maximum stability) could be considered as a preferred route selection.

Unless otherwise stated, the parameter values considered in the simulation are the following: Number of nodes is 500, uniformly randomly distributed over a $500 \times 500 m^2$ location space; the range of circular coverage of each node is 40 m; white Gaussian channel with BER $p_b = 10^{-6}$; packet size is 50 *Bytes* (fixed); number of packets per session is 10^4. 1000 such sessions are simulated and by varying the seed value it is ensured to achieve throughput within 95% confidence interval. For multiple sessions, since in the simulation end-to-end distance and multipath formation (disjoint as well as meshed) vary widely for each session, instead of quantitative verification we compare the analytically obtained performance trends with those from simulations.

First, we consider an example 4-hop source-to-destination route (disjoint as well as meshed). From the simulated network, disjoint multipath and meshed multipath for a 4-hop source-to-destination pair are shown in Fig. 2. The analytic throughput and load distribution results for two extreme cases of node failure rates are shown in Table I, which are verified by simulations. Slightly different throughput load distribution performance in simulations are mainly due to the non-ideal disjoint and meshed routes in practice.



(a) disjoint multipath (b) meshed multipath

Fig. 2. Sketches of disjoint multipath and meshed multipath, drawn from the network connectivity trace.

Plots in Fig. 3 show analytically obtained throughput and traffic load distribution in SRF and SPF with respect to varying node failure probability in an 8-hop route. With the set network parameters, the trends simulated results for multiple sessions in Fig. 4 verify the analysis. The general observation is that for a given (average) source-to-destination distance although the throughput degrades sharply with node failure rates, the traffic load distribution changes nearly insignificantly. In Fig. 5, analytically obtained system performance with respect to varying source-to-destination distance is shown. It is straightforward to note why the load distribution ratio in SPF is very low with respect to SRF — the first approach tries to stick to a preferred route whereas the second approach attempts to distribute the workload along multiple paths.

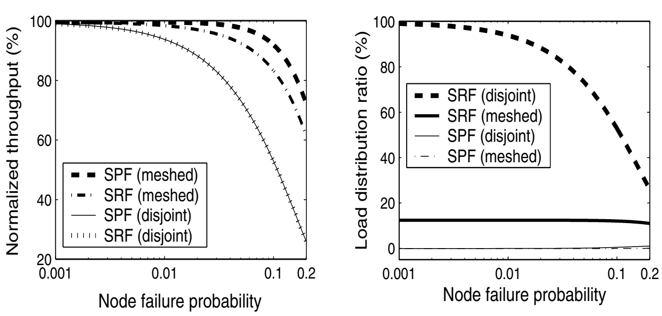


Fig. 3. Throughput and load balancing performance of SRF and SPF for different node failure rates – from analysis. $H = 8$ *hops*.

For disjoint multipath routes, it is observed that SRF does significantly better traffic load distribution and yet it has nearly equally good throughput performance as in SPF. Therefore, one can state that *in disjoint multipath routes SRF has overall superior performance*.

For meshed multipath, better throughput performance of SPF over the SRF in the simulation can be explained by the fact that by virtue of its inherent property SPF sticks to the shortest route (see Fig. 2), thereby facing lesser number of error-prone nodes. However, rather counter-intuitively we observe from the analytic results that although a packet traverses equal number of hops from a source to the destination in both SRF and SPF (because of idealized mesh), the throughput performance of SPF is significantly better. This is more prominent with higher node failure rates (see Fig. 4) and for longer source-to-destination distance (see Fig. 5). A closer look reveals that since SRF strives to disperse the packets along the mesh, a higher number of packets end up following the edge of the meshed route where there is lesser flexibility for alternate routing. Put mathematically, referring to Fig. 1(b), let us assume the probability distribution of a packet at the nodes $N_{H-2,1}$, $N_{H-2,2}$, and $N_{H-2,3}$ be p_1, p_2, and p_3, respectively, given that it successfully traverses $H-2$ hops. Then, for both SRF and SPF, the conditional packet throughput would be:

$$T^{(m)}[\text{given successful up to } (H-2) \text{ hop}] = (1-p_l)^2 (1-p_n)(1+p_2 p_n)$$

which implies that for a given channel condition and node failure rate the throughput can be maximized if p_2 is maximum. The analytic data in Table II confirms that this is indeed the case for SPF, which is also supported by the results in Figs. 3 and 4.

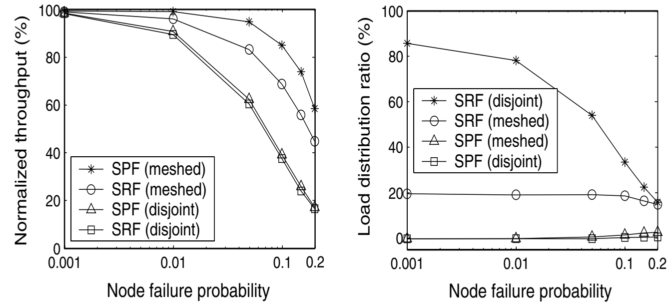


Fig. 4. Throughput and load balancing performance of SRF and SPF for different node failure rates – from simulation. $H^{(d)}(avg) = 9.3$ *hops*, $H^{(m)}(avg) = 13.03$ *hops*.

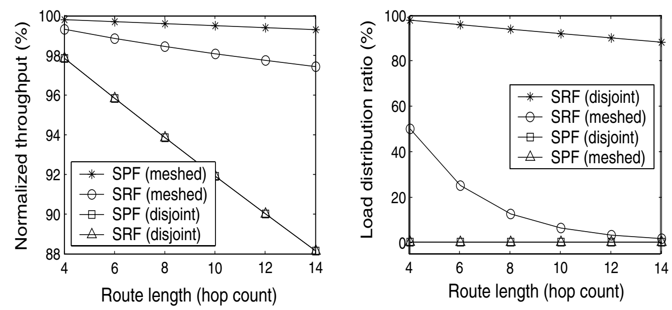


Fig. 5. Throughput and load balancing performance of SRF and SPF for different route length – from analysis. $p_n = 10^{-2}$.

IV. A Hybrid Packet Forwarding Approach Along Meshed Multipath

The analytically obtained data in Table II also reveals the following interesting facts: (i) The load distribution in SPF is not only very poor ($p_1, p_3 \ll p_2$) but also very uneven along the two sides of the primary route ($p_1 \neq p_3$). (ii) The load distribution in SRF is even ($p_1 = p_3$) and substantially fair (p_1, p_3

TABLE I

Performance of SPF and SRF along disjoint and meshed multipath routes, respectively. In analysis $H = 4$ and $r = 3$.

p_n	Packet forwarding type	Disjoint multipath				Meshed multipath			
		Throughput (%)		Load distribution ratio (%)		Throughput (%)		Load distribution ratio (%)	
		analysis	simulation	analysis	simulation	analysis	simulation	analysis	simulation
10^{-5}	SPF	99.84	99.79	0	0	99.84	99.84	0	0
	SRF	99.84	99.78	99.9	98.6	99.84	99.80	49.9	25.0
10^{-1}	SPF	80.80	65.40	0.8	0.7	96.07	95.79	0.9	1.4
	SRF	80.80	63.40	80.9	71.8	92.47	89.90	40.5	24.4

TABLE II

Analytically obtained probability distribution of packets arriving at the three nodes after successfully traversing $H - 2$ hops (see Fig. 1(b)).

H	$p_n = 0.001$						$p_n = 0.2$					
	SRF			SPF			SRF			SPF		
	p_1	p_2	p_3	p_1	p_2	p_3	p_1	p_2	p_3	p_1	p_2	p_3
4	0.249	0.499	0.249	9.97×10^{-4}	0.998	9.9×10^{-7}	0.23	0.46	0.23	0.13	0.77	0.026
8	0.343	0.312	0.343	9.97×10^{-4}	0.997	9.97×10^{-7}	0.237	0.244	0.237	0.123	0.628	0.025
12	0.375	0.245	0.375	9.95×10^{-4}	0.995	9.95×10^{-7}	0.202	0.163	0.202	0.106	0.53	0.021

are on the same order of p_2), but as the source-to-destination distance increases and/or at lower node failure probability the random packet distribution causes the edge nodes carry substantial amount of traffic – sometimes even higher than that carried by the nodes inside the meshed route. Note that in an idealized meshed route (see Fig. 1(b)) p_1, p_3 could be even greater than p_2 in SRF because the edge nodes beyond $\frac{H}{2}$ distance from the source have two incoming links but only one outgoing link, which causes an edge node receiving traffic from an inside node and from its predecessor edge node, and the total traffic is forwarded to its single downstream edge node.

Attempt to enhance SPF: We note that although SPF has a higher end-to-end throughput, its poor load distribution characteristics would have the detrimental effects of (a) possibly draining too much energy of certain strategic nodes along the route too fast (leading to network partitioning) and (b) requiring additional signaling overhead for keeping alive the portion of the meshed multipath that does not carry sufficient amount of traffic. The poor and uneven traffic load distribution problem becomes more severe if the sink is not located centrally in the network and/or only a fraction of field nodes actually participate in communication at a time. Even if the problem of uneven power drainage is discounted, one needs to devise how additional keep-alive signals can be transmitted efficiently such that for a source-to-destination meshed multipath is maintained with least amount of additional signaling overhead. A straightforward approach is to send frequent keep-alive signals using the *reverse SPF* approach, i.e., giving priority to the nodes that are further away from the 'primary route'. However, our numerical simulation of a regular mesh network shows that in this approach certain nodes in the meshed route receive neither the data packets nor the keep-alive signals sufficiently enough to remain associated in mesh. Hence the reverse SPF approach may not work well in practice. Due to lack of space we will not elaborate on it any further.

Attempt to enhance SRF: On the other hand, we note that in SRF, its better load distribution property could be negated by its poorer throughput performance. From our analysis in Section II-B.1 we observe that in an idealized meshed multipath successful packet arrival probability up to the half way along the route in SRF is exactly equal to that in SPF. Also, the advantage of random packet forwarding in SRF exists only up to the half way from the source, beyond which the edge nodes tend to carry more traffic as explained earlier in this section, leading to poorer throughput with respect to SPF. Intuitively, one could take advantage of load balancing via SRF in the first half of the meshed multipath, and for the remaining half SPF approach could be adopted to improve upon throughput performance. We call this scheme a *hybrid approach*. Theoretical performance evaluation of this hybrid approach remains the same as that of SRF, except for the calculation of routing success probability in the second half (i.e., for $i = \frac{H}{2} + 1$ to $H - 1$) which is replaced by the corresponding calculation for SPF.

Analytic performance results of the above hybrid approach are shown in Fig. 6 that are verified by simulations as shown in Fig. 7. It may be noted that in a sensor network the communication is mostly from field sensors to a controller node, where the approximate distance (in number of hops) between a source to the sink is known a priori. In simulations, this approximate information is used in deciding the packet forwarding change-over point in the hybrid approach. The analytic results for varying source-to-destination distance are also shown in Fig. 8. Significant improvement in throughput performance is observed through analysis and simulation. The analytic load balancing performance does not match well with that from simulations (as also noted from Table I, columns 9 and 10), which are mainly due to irregular meshed route in practice. Nevertheless, the traffic load distribution via the hybrid approach could be sufficiently even enough to supplant the need for additional keep-alive signals for maintaining the meshed route.

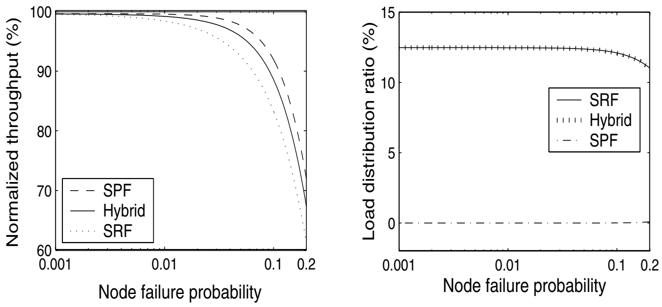


Fig. 6. Throughput and load balancing performance of hybrid packet forwarding along meshed multipath against different node failure rates – from analysis. $H = 8$ *hops*.

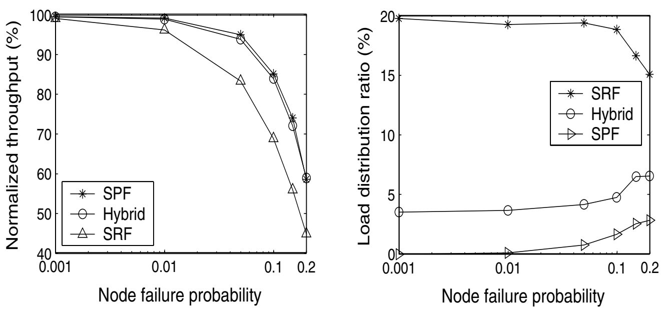


Fig. 7. Throughput and load balancing performance of a hybrid approach along meshed multipath for different node failure rates – from simulation. $H_{avg} \approx 13$ *hops*.

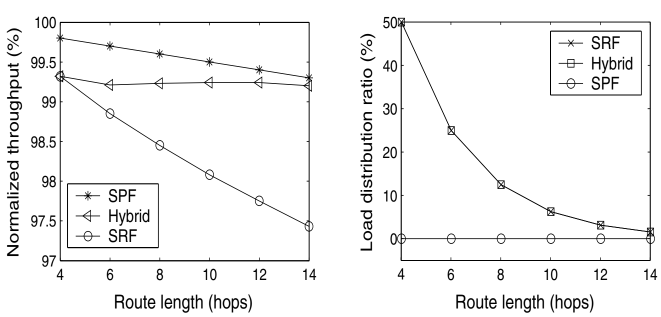


Fig. 8. Throughput and load balancing performance of a hybrid packet forwarding along meshed multipath for different route length – from analysis. $p_n = 10^{-2}$.

V. Conclusion and Future Work

In this paper, we have investigated the relative throughput and load distribution performance of selective random forwarding (SRF) and selective preferential forwarding (SPF) along disjoint multipath as well as meshed multipath. For disjoint multipath routes, it has been clearly shown that SRF performance is superior to the SPF approach. For meshed multipath routes, we have shown that SRF has better load distribution property but with poorer throughput. SPF on the other hand has better throughput but with inferior load distribution property. We have introduced a hybrid algorithm that takes advantage of superior load distribution property of SRF and gain in throughput from the traffic concentration property of SPF. Our analytic intuition has been verified through more realistic simulations. Our results could be useful in improving energy efficiency of multipath routing and hence increasing network lifetime in multihop wireless scenarios where only a fraction of nodes take part in communication at a time. As a future work we intend to conduct further simulations for studying the effect of network size and quantifying the network lifetime associated with SPF, SRF, and the newly proposed hybrid packet forwarding approach.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102-114, Aug. 2002.

[2] G. Asada, M. Dong, T.S. Lin, F. Newberg, G. Pottie, W.J. Kaiser, and H.O. Marcy, "Wireless Integrated Network Sensors: Low Power Systems on a Chip," in *Proc. European Solid State Circuits Conf.*, 1998.

[3] L. P. Clare, G. J. Pottie, and J. R. Agre, "Self-Organizing Distributed Sensor Networks," in *SPIE Conf. Unattended Ground Sensor Technologies and Applications*, pp. 229-237, Apr. 1999.

[4] J. Kulik, W. R. Heinzelman, and H. Balakrishnan, "Negotiation-Based Protocols for Disseminating Information in Wireless Sensor Networks," in *Proc. of ACM MobiCom*, 1999.

[5] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," in *Proc. of ACM MobiCom*, 2000.

[6] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, "Highly-Resilient, Energy-Efficient Multipath Routing in Wireless Sensor Networks," *ACM SIGMOBILE Mobile Computing and Commun. Rev.*, vol. 5, issue 4, Oct. 2001.

[7] A. Tsirigos and Z. J. Hass, "Multipath Routing in The Presence of Frequent Topological Changes," *IEEE Commun. Mag.*, pp. 132-138, Nov. 2001.

[8] C.-Y. Wan, A. T. Campbell, and L. Krishnamurthy, "PSFQ: A Reliable Transport Protocol for Wireless Sensor Networks," in *Proc. ACM Workshop on Wireless Sensor Networks and Applications (WSNA)*, pp. 1-11, Sept. 2002.

[9] S. De, C. Qiao, and H. Wu, "Meshed multipath routing: An efficient strategy in sensor networks," in *Proc. IEEE WCNC*, New Orleans, LA, Mar. 2003.

[10] S.-J. Lee and M. Gerla, "Split Multipath Routing with Maximally Disjoint Paths in Ad hoc Networks," in *Proc. Intl. Conf. on Commun. (ICC)*, 2001.

[11] A. Nasipuri and S. R. Das, "On-Demand Multipath Routing for Mobile Ad Hoc Networks," in *Proc. Intl. Conf. on Computer Commun. and Networks (ICCCN)*, pp. 64-70, Oct. 1999.

[12] S. De and C. Qiao, "Does packet replication along multipath really help ?," in *Proc. IEEE ICC*, Anchorage, AK, May 2003.

[13] W. Su and M. Gerla, "IPv6 flow handoff in ad hoc wireless networks using mobility prediction," in *Proc. IEEE GLOBECOM*, Rio de Janeiro, Brazil, Dec. 1999.

[14] S. De, C. Qiao, and S. K. Das, "A resource efficient QoS routing protocol for mobile ad hoc networks," *Wiley J. Wireless Commun. and Mobile Computing*, vol. 3, no. 4, pp. 465–486, June 2003.