Available online at www.sciencedirect.com
ScienceDirect
Computer Communications xxx (2007) xxx–xxx
computer communications
www.elsevier.com/locate/comcom

A hybrid meshed multipath forwarding scheme in wireless ad hoc networks

Swades De [a,*], Chunming Qiao [b]

[a] *Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA*
[b] *Department of Computer Science and Engineering, State University of New York at Buffalo, Buffalo, NY 14260, USA*

UNCORRECTED PROOF

Abstract

Flexibility and robustness are the two key features of multipath routing in multihop wireless networks. While robustness to node failures and link errors is important to achieve high end-to-end throughput, it is also important to judiciously use the routing flexibility to achieve a better traffic load distribution among the network nodes, so that the network lifetime can be extended.

In this paper, we study point-to-point multipath forwarding strategies in relatively static but highly error-prone wireless sensor networks. We investigate a multipath forwarding scheme, called selective random forwarding (SRF), and compare its end-to-end throughput and traffic load distribution with respect to selective preferential forwarding (SPF) (or forwarding along primary/secondary routes). We first show that in node disjoint multipath routes SRF has a better overall performance. When considering meshed multipath routes [14], SRF offers a much better load balancing performance but a poorer throughput. Aiming at achieving a good performance trade-off in meshed multipath routes, we introduce a new hybrid packet forwarding scheme that takes the advantages of higher end-to-end throughput in SPF and more uniform load distribution in SRF. Our network performance studies show that while the hybrid approach always offers the throughput performance nearly as good as SPF, its improved load distribution performance becomes more significant with more inhomogeneous network activity. Our approach is guided by analytic intuition and verified by simulations.

© 2006 Published by Elsevier B.V.

Keywords: Meshed multipath; Selective random forwarding; Selective preferential forwarding; Hybrid forwarding; Throughput; Traffic load balancing; Ad hoc networks; Sensor networks

---

1. Introduction

Wireless networks are generally characterized by error-prone communication medium, limited channel bandwidth, and limited battery power of nodes. As a result, communication range of a node is limited, and in a scenario of ad hoc deployed nodes, for setting up a communication session between any two nodes, it may be frequently necessary to go through multiple intermediate nodes. Despite having limited channel and nodal resources, to cope with unreliable connections and due to the lack of dedicated routers in ad hoc wireless networks, various approaches to setting up multiple routes have been proposed for reliable multihop communication.

Given a point-to-point communication scenario, multipath routes could be node disjoint – where each multihop route is independent of the others, and the decision on selection of one or more routes is taken at an end node (either the source or the destination). Alternatively, the routes could be meshed (i.e., partially disjoint) – where an intermediate node could be responsible for more than one route to the destination, and some routing decisions could be taken at the intermediate nodes. While both disjoint and meshed multipath routes can ensure higher guarantee of real-time or non-real-time quality-of-service compared to the single-path routes, the meshed multipath routes provide additional flexibility of distributed routing decisions. Besides, if judiciously used, the flexibility of meshed multipath routes could enable achieve several

---

* Corresponding author. Tel.: +1 9735965710.
E-mail addresses: swadesd@njit.edu (S. De), qiao@cse.buffalo.edu (C. Qiao).

0140-3664/$ - see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.comcom.2006.12.015

benefits, including robustness to frequent node failure and link outage, increased network lifetime, and providing message security at the routing-level. In this paper, we will address two such benefits, namely, end-to-end throughput as a measure of routing robustness and traffic load balancing as a measure of network lifetime. Note that load balancing is closely related to energy efficiency and reliability issues, as a load-unbalanced strategy could lead to uneven energy drain among the nodes, and thus shortening the network lifetime.

We consider a relatively static but highly error-prone wireless network, wherein the example applications include remote/hazardous field information monitoring and control via tiny, low-cost sensors [1–3], multimedia support in wireless ad hoc networks [4–6], and cooperative campus network with multiple hand-held devices [7]. The field nodes form a network among themselves and communicate via multiple hops to either exchange message with each other or respond/listen to the control center (or a clusterhead). Two basic forms of point-to-point multihop routes – disjoint multipath and meshed multipath – are considered available. Various forwarding schemes can be considered to successfully deliver a message via multipath routes at an end node. For reliability of communication and simplicity, however at the cost of more network resource usage, oftentimes packets are replicated along predetermined multiple routes to the destination (as noted in [8,9]). In another approach, the transmission is attempted along a predetermined 'preferred' (or primary) route, while the alternative (secondary) disjoint or meshed routes are kept standby for failure recovery [10,9]. We call this approach selective preferential forwarding (SPF) (or primary/secondary routing). In a third alternative, which we broadly call selective random forwarding (SRF), each packet may be sent along one of the randomly-selected multiple (two or more) alternative routes [11–14]. It may be pointed out that, for delay tolerant applications and/or in relatively mobile environments, location aware nodes can effect SRF without setting up multipath routes a priori. In this work, however, we will not focus on route construction issues.

In this paper, given a set of multipath routes, our goal is to determine the best packet forwarding strategy in terms of robustness of packet delivery in presence of node and link failures, and traffic load distribution that would help extend the network lifetime. To this end, first, considering point-to-point multipath routes (disjoint or meshed) between individual source–destination pairs, we study the relative throughput and traffic load distribution performances of the SRF and SPF approaches, and then we investigate on improved forwarding strategies. Our main contributions in this paper are the following: (1) Via simple analysis and supported by point-to-point traffic simulations, we show that the SRF has the overall better performance when the given multiple routes are disjoint. (2) We also find that when considering meshed multipath, SRF offers a much better load balancing performance but a poorer throughput. (3) Aiming at achieving a good forwarding performance trade-off along meshed multipath routes, we introduce a novel hybrid packet forwarding scheme that takes the advantages of higher end-to-end throughput in SPF and more uniform traffic load distribution in SRF. (4) Through network performance simulation studies we show that, while the hybrid approach always offers the throughput performance nearly as good as in SPF, its improved load distribution performance becomes more significant with more inhomogeneous network activity.

The rest of the paper is organized as follows. Related works are briefly surveyed in Section 2. In Section 3, we elaborate on the SRF and SPF approaches in the context of our current work. Section 4 contains the analytic performance evaluation of SRF and SPF in terms of throughput and traffic load distribution. Performance results of SRF and SPF are presented in Section 5. A new hybrid packet forwarding protocol is introduced and its performance is studied by network simulations in Section 6. Finally, we conclude in Section 7.

2. Related work

Various multipath routing strategies have been proposed in wireline high-speed networks as well as in wireless ad hoc networks in the research literature. In wireline high-speed networks, the objective has been finding an end-to-end route quickly at the call admission stage of a real-time (delay and jitter constrained) session (see e.g., [15,16]). Here, traffic congestion is the primary concern rather than the possibility of node and link failures. On the other hand, the multipath routing approaches in multihop wireless networks aim at maintaining an uninterrupted end-to-end logical path for a session (real-time or non-real-time) [4–6,9,10,12–14,17,18]. The concern here is the dynamic reconfiguration of the network due to nodal mobility, node failure, and error-prone channel conditions, and the objective is to find nodes that would help provide a more stable end-to-end route. Below we will however highlight the prior non-flooding based multipath forwarding approaches and summarize the contrast of our current work.

For load balancing purpose, [12] proposed traffic splitting along multiple disjoint routes. This approach does not have a way to locally decide about the condition of a route before choosing it for sending a packet. In a similar approach, called diversity routing, [13] studied optimum number of disjoint routes required to ensure a certain throughput in traffic splitting in multihop wireless networks. Here also, the end-to-end route quality was not considered as a criteria for choosing an individual route. For QoS support in mobile ad hoc networks, [18] proposed maintaining multiple disjoint routes, called secondary routes, while the packets are transmitted along the primary route. We call this approach SPF along *disjoint* multipath. [10,9] proposed maintaining non-disjoint secondary routes while the primary route is in use. The authors in [9] identified the merits of braiding the disjoint routes and suggested

UNCORRECTED PROOF

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

that the flexibility of distributed routing decision at intermediate stages could be achieved if the failure of nodes along the primary routes could be accommodated by back up nodes in the braided routes. We broadly call this approach SPF along *meshed* multipath. The meshed multipath routing approach in [14] focused on the relative throughput performances of disjoint and meshed multipath routing strategies and showed that meshed multipath routing performs better compared to its disjoint counterpart. It also inferred that although packet replication has a higher throughput performance along any form of multipath routes, the effective energy expended to achieve a target throughput level is lower in case of selectively forwarding a packet (without replication) along a given multipath route.

In this paper, we focus on a different multipath forwarding strategy along a given set of multipath routes, called *selective random forwarding* (or SRF), and compare it with SPF in terms of throughput and traffic load distribution. We also propose a hybrid forwarding approach for routing along meshed multipath that simultaneously achieves robustness of packet delivery and more uniform traffic load distribution. Below, we first describe the features SRF as well as SPF and then compare them both qualitatively and quantitatively.

3. Features of multipath forwarding approaches

Our SRF approach is defined as follows: Along a multipath route if more than one alternative downstream alternative options are available, the best one is selected for packet forwarding. In case of a tie, i.e., if both options are equally good, one is selected by flipping a fair coin.

The following are the assumptions and common characteristics of the SRF and SPF approaches:

(a) All nodes are assumed aware of their own as well as destination's location information, based on which downstream forwarding alternatives are decided.
(b) To *minimize the network-wide signaling*, frequent global or end-to-end routing message exchange (as in [20]) is avoided. Instead, with the known downstream options along the multipath routes, a forwarding decision is taken based on the local neighborhood information collected proactively at each node.
(c) 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 [9,19]) is not considered. 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.

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

- 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. With meshed (or non-disjoint) multipath, SRF offers distributed routing control, where a packet forwarding decision is taken at an intermediate node depending on the condition of immediate downstream neighbors.
- 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. Note that in SPF, the primary route selection approach is similar to that in [9]. However, we consider local neighborhood knowledge based failure detection instead of negative acknowledge based rerouting.

4. Routing performance analysis

In this section, we evaluate the throughput and load balancing performances of SRF and SPF schemes along disjoint multipath and meshed multipath.

For measuring throughput (or packet delivery rate) performance, we introduce the term *normalized throughput T*, which is defined as the probability of successful arrival of a packet at the destination.

As a measure of traffic load balancing along the multipath route, we introduce the term *load distribution ratio L*, which 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., $L = \frac{P(\min)}{P(\max)}$, 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 forwarding strategy. Note that, given a set of multipath routes – disjoint or meshed – and network conditions (i.e., node failure rate and link error probability), $P(\max)$ remains more or less constant while $P(\min)$ becomes different with different forwarding strategies (which will be clearer in the subsequent analysis of $P(\max)$ and $P(\min)$). Therefore, along a given multipath, our defined load balancing index L is a fair measure of performance of different forwarding strategies.[1] The

---

[1] Otherwise, if for example one forwarding approach offers $P(\max) = 0.5$ and $P(\min) = 0$, while another offers $P(\max) = 0.99$ and $P(\min) = 0$, in both cases, according to our definition, $L = 0$ – which is an unfair relative performance measure.

UNCORRECTED PROOF

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

expressions for T and L (or equivalently, $P(\max)$ and $P(\min)$) are computed in our following analysis.

For analytic tractability, without affecting the conclusions, we consider equal length multiple (disjoint or meshed) routes and a regular mesh, and present the case for meshed routes with an even number of hops (see Fig. 1). As we will observe in Section 6, these idealized route structures in analysis also help is drawing interesting conclusions of different packet forwarding properties. Based on the observation in [21] that having *two* downstream forwarding options achieves a good trade-off between routing success and the associated control overhead, we consider a meshed route between two communicating end nodes (i.e., a source–destination pair) along which there are at most two incoming links and two outgoing links at an intermediate node. It may be noted that there could be several other possibilities of constructing idealized meshed routes, such as, two disjoint routes interleaved together, or a perfectly braided multipath route [9]. However, we have found that analysis with a different form of meshed routes does not give us any additional insight on relative performance benefits of SRF and SPF. In Section 5, we will study via simulations the performance of SRF and SPF along disjoint as well as meshed routes under a practical network setting, 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)

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. The end node (i.e., the destination) is considered ready to receive (i.e., $p_\mathrm{n} = 0$) 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 bit error probability (or BER) due to channel error and B is the packet size (in bits), then

$$p_\mathrm{l} = 1 - (1 - p_\mathrm{b})^B \tag{1}$$

That is, after a downstream node is selected and packet is forwarded, the packet could be corrupted, hence assumed lost in our studies, with probability p_l.

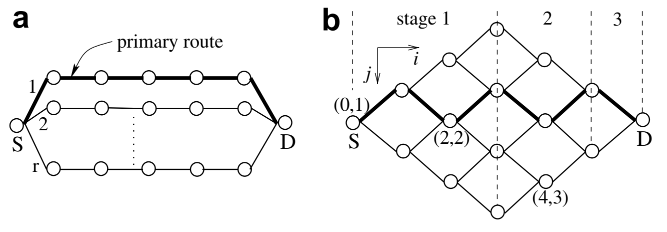

Fig. 1. Examples of 6-hop multiple routes. The thick lines joining *S* and *D* form the primary route in SPF.

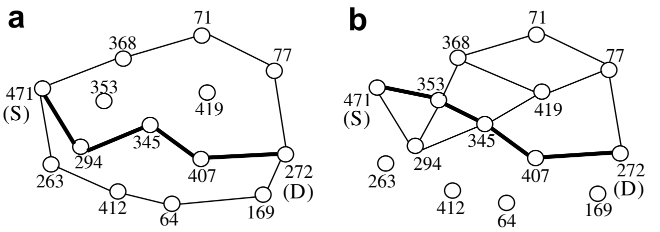

Fig. 2. Sketches of disjoint multipath and meshed multipath, drawn from the network connectivity trace.

4.1. Disjoint multipath

Let us refer to Fig. 1(a) showing r equal length disjoint routes between a source and its destination node.

4.1.1. 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:

$$T^{(\mathrm{d})}_{\mathrm{SRF}} = (1 - p_\mathrm{l})^H (1 - p_\mathrm{n}^r)(1 - p_\mathrm{n})^{H-2} \tag{2}$$

where $(1 - p_\mathrm{l})(1 - p_\mathrm{n}^r)$ is the probability of reaching to a next node from the source, and $(1 - p_\mathrm{l})^{H-1}$ $(1 - p_\mathrm{n})^{H-2}$ 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

$$P^{(\mathrm{d})}_{\mathrm{SRF}}(\max) = (1 - p_\mathrm{n})(1 - p_\mathrm{l}) \sum_{i=0}^{r-1} \left(\frac{1}{i+1}\right) \binom{r-1}{i} (1 - p_\mathrm{n})^i p_\mathrm{n}^{r-1-i} \tag{3}$$

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

$$P^{(\mathrm{d})}_{\mathrm{SRF}}(\min) = P^{(\mathrm{d})}_{\mathrm{SRF}}(\max) \times (1 - p_\mathrm{n})^{H-2} (1 - p_\mathrm{l})^{H-2} \tag{4}$$

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 traffic 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

UNCORRECTED PROOF

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

$$P^{(\mathrm{d})}_{\mathrm{SPF}}(\max) = (1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}}) \tag{5}$$

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

$$P^{(\mathrm{d})}_{\mathrm{SPF}}(\min) = p_{\mathrm{n}}^{r-1}(1 - p_{\mathrm{n}})^{H-1}(1 - p_{\mathrm{l}})^{H-1} \tag{6}$$

Relative throughput and traffic distribution results are shown in Table 1.

4.2. Meshed multipath

We consider the ideal meshed multipath with even number of hops as shown in Fig. 1(b), where $N_{i,j}$ denotes a node i hops away from the source and at a depth j (starting from the top with depth 1), and $P_{i,j}$ denotes the probability of receiving a packet at that node.

4.2.1. 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 $P_{\mathrm{s}}(i)$, 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 $(1 - p_{\mathrm{n}}^2)$, and the channel is good during the packet transmission, with probability $(1 - p_{\mathrm{l}})$. Since Stage 1 has $\frac{H}{2}$ hops, $P_{\mathrm{s}}(1)$ is given by

$$P_{\mathrm{s}}(1) = \left[(1 - p_{\mathrm{l}})(1 - p_{\mathrm{n}}^2)\right]^{\frac{H}{2}} \tag{7}$$

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

$$P_{h,j+1} = \frac{1}{2^h}\binom{h}{j} \tag{8}$$

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

Stage 2: $P_{\mathrm{s}}(2)$ 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. The recursive algorithm is shown in Appendix A.

Finally, counting Stage 3, normalized throughput is given by

$$T^{(\mathrm{m})}_{\mathrm{SRF}} = (1 - p_{\mathrm{l}})\prod_{i=1}^{2} P_{\mathrm{s}}(i) \tag{9}$$

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 $P^{(\mathrm{m})}_{\mathrm{SRF}}(\max)$, 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

$$P^{(\mathrm{m})}_{\mathrm{SRF}}(\min) = \frac{1}{2^h}\binom{h}{j}\left[(1 - p_{\mathrm{l}})(1 - p_{\mathrm{n}}^2)\right]^h \tag{10}$$

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

4.2.2. Selective preferential forwarding (SPF)

Normalized throughput: In this case, the throughput performance is obtained with the understanding that the downstream node closer to the primary route is tried first. Referring to Fig. 1(b), where the primary route is shown by thick connected links, the end-to-end normalized throughput $T^{(\mathrm{m})}_{\mathrm{SPF}}$ is obtained following the recursive algorithm in Appendix B.

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 B. The maxima of packet distribution will occur at the first downstream node in the primary route (node $N_{1,1}$ in Fig. 1(b)) with packet arrival probability $P^{(\mathrm{m})}_{\mathrm{SPF}}(\max)$, 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 $N_{3,4}$ in Fig. 1(b)) with probability

$$P^{(\mathrm{m})}_{\mathrm{SPF}}(\min) = [p_{\mathrm{n}}(1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})]^{\frac{H}{2}} \tag{11}$$

5. Performance results

In this section, we present the numerical results on normalized throughput and load distribution ratio from analysis and verify them via discrete event network simulations

UNCORRECTED PROOF

Table 1
Throughput and load balancing performance of SPF and SRF

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

In analysis $H = 4$ and $r = 3$. Simulated multipath routes are shown in Fig. 2.

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

using C. It is assumed, an intermediate node fails or is not ready for a packet forwarding with probability p_{n}. To attain the network steady state it is also assumed that a previously failed (or not ready) node can be good to forward a later packet. Examples of such scenarios in practice are: (i) a node may declare often to go to ‘sleep state’ to save its energy, or (ii) an exhausted node may have some mechanism to re-charge itself. If a node is found good before starting to receive a packet (based on a priori local neighborhood information), it remains good throughout the packet reception period. However, channel noise can still corrupt a packet (with BER p_{b}), and in this study we consider a packet is corrupted if at least a single bit error occurs. At any point along the route, a packet is considered lost if it could not be forwarded due to unavailability of a downstream node or if it is corrupted due to channel error. Multipath routes are constructed based on greedy hop count based approach [22], and the primary route to the destination (in case of SPF) is considered the one with minimum hop count. This is however not a limitation, as any other criteria (such as minimum energy, maximum stability, etc.) could be considered for a primary route selection.

Unless otherwise stated, the following parameter values are considered in the simulation: number of nodes is 500, uniformly random distributed over a $500 \times 500\ \mathrm{m}^2$ location space; the range of disk coverage of each node is 40 m; white Gaussian channel with BER $p_{\mathrm{b}} = 10^{-6}$; packet size is 50 Bytes (fixed); number of packets per session is 1000. 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 1, 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.

Plots in Fig. 3 show analytically obtained throughput and traffic load distribution in SRF and SPF at different node failure rates in an 8-hop route. With the set network parameters, the trends of simulation results for multiple sessions in Fig. 4 verify the analysis. Observe is that for a given (average) source-to-destination distance although the throughput degrades sharply with node failure rates,

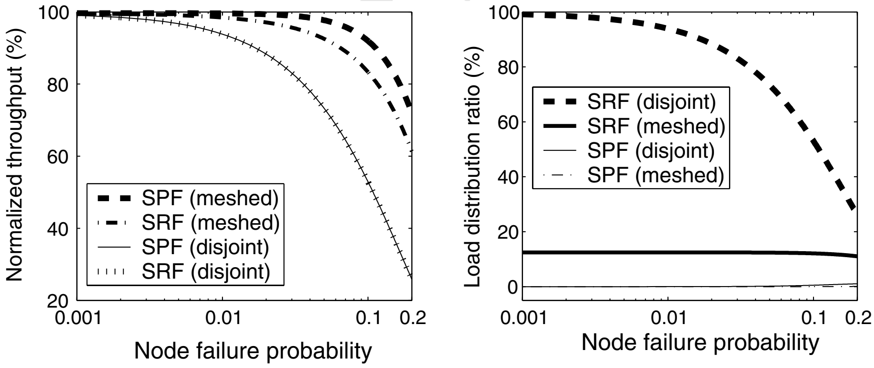

Fig. 3. Throughput and load balancing performance of SRF and SPF at different node failure rates – from analysis. $H = 8$ hops.

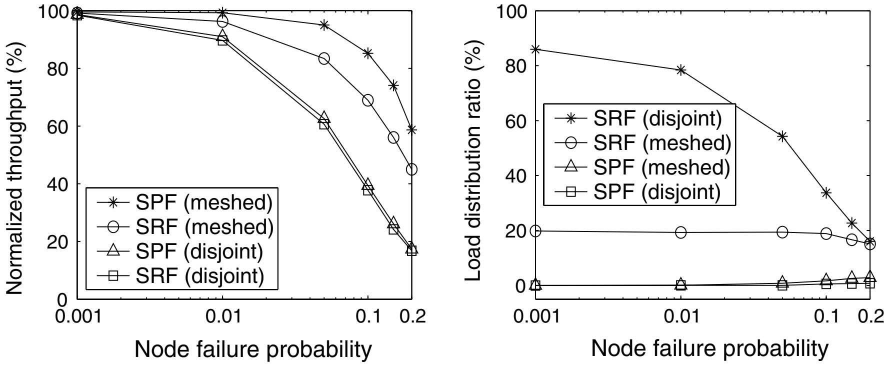

Fig. 4. Throughput and load balancing performance of SRF and SPF at different node failure rates – from simulation. $H^{(\mathrm{d})}(\mathrm{avg}) = 9.3$ hops, $H^{(\mathrm{m})}(\mathrm{avg}) = 13.03$ hops.

UNCORRECTED PROOF

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

UNCORRECTED PROOF

the traffic load distribution in SPF remains very poor and changes nearly insignificantly. It is straightforward to note why the load distribution ratio in SPF is very low with respect to SRF along a given multipath (disjoint or meshed) – the first approach tries to stick to a preferred route whereas the second approach attempts to distribute the workload along multiple paths whenever equally good forwarding options are found.

A relevant overall observation is in place: When the given multipath routes are disjoint, irrespective of the node failure rate, SRF offers significantly better traffic load distribution and yet it has equally good throughput performance as in SPF. Therefore, it can be fairly stated that *along disjoint multipath routes SRF has the overall better performance*.

In case of meshed multipath routes, however, a direct conclusion on the overall performance of a forwarding approach cannot be made, because, as analytically predicted and corroborated via simulations in Figs. 3 and 4, SPF has the higher throughput but SRF offers better load balancing performance.

The analytically obtained plots in Fig. 5 also indicate that with the increased source-to-destination distance the throughput as well as load balancing performance of SRF degrade at a sharper rate than in the case of SPF. In other words, with longer source-to-destination distance, throughput of SRF is even poorer compared to SPF, and the load balancing of SRF is not significantly better any more. Simulated data with varying average source-to-destination distance was not collected because of the run-time complexity involved in it and also because it does not limit the scope of our conclusions and further investigations.

The reason for poorer load balancing in SPF is intuitive and has been explained earlier. The better throughput performance of SPF over SRF in the simulated scenario can be explained by the fact that by virtue of its inherent property SPF tries to stick 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 (Figs. 3 and 5) 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 of SPF is significantly higher. This is more prominent with higher node failure rates (see Fig. 3) and longer source-to-destination distance (see Fig. 5).

In the following section, we investigate the reason for poorer throughput performance in SRF and why its throughput and load balancing performance degrades with increase in distance.

6. A hybrid packet forwarding approach along meshed multipath

A closer look into the packet distribution process along the idealized meshed multipath 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 and hence more packet loss probability. 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:

$$T^{(\mathrm{m})}[\text{given successful up to } H-2 \text{ hop}] = (1-p_1)^2(1-p_\mathrm{n})(1+p_2p_\mathrm{n})$$

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 2 confirms that this is indeed the case for SPF, which is also supported by the results in Figs. 3 and 5.

The analytically obtained data in Table 2 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 quite 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 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 to carry substantial amount of traffic – sometimes even higher than that carried by the nodes inside the meshed route. Note that in an idealized meshed

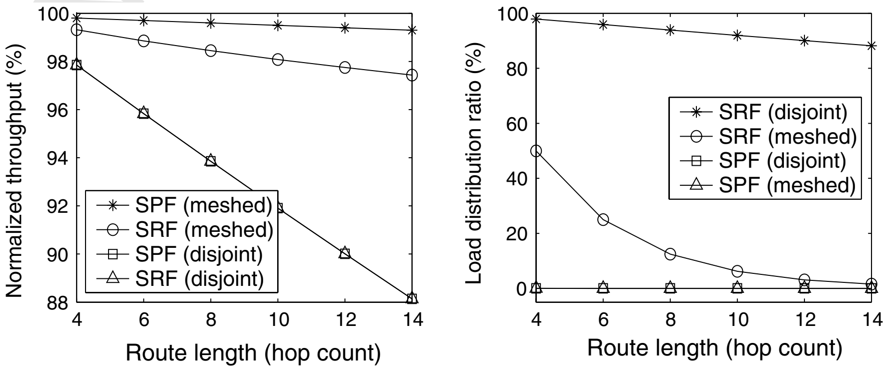

Fig. 5. Throughput and load balancing of SRF and SPF at different route lengths – from analysis. $p_\mathrm{n} = 10^{-2}$.

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

Table 2
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

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 to receive traffic from an inside node and from its predecessor edge node, and the total traffic is forwarded to its single downstream edge node.

Motivated by the above observations, we approach to find a forwarding scheme that would achieve higher throughput and greater load balancing at the same time.

6.1. Possible enhancement to 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.

6.2. Enhancement to 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 4.2.1, 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 forwarding approach*. Theoretical performance evaluation of this hybrid approach will remain 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 would be replaced by the corresponding calculation for SPF. Particularly, for analytic throughput calculation we obtain the probability of successful arrival of packet $P_{h,j+1}$ at a node $N_{h,j+1}$ at the end of first half by (8). Using this, the successful packet arrival probability at the destination, i.e., the normalized throughput $T^{(m)}_{\mathrm{HYB}}$, is recursively computed following the approach in Appendix B for the second half of the route. Traffic load distribution performance in an idealized mesh route will be the same as in SRF, with the $P^{(m)}_{\mathrm{HYB}}(\max)$ given by the right hand side of (3), where $r = 2$, and $P^{(m)}_{\mathrm{HYB}}(\min)$ is given by (10).

Analytic throughput and load balancing performance results of the proposed hybrid approach are shown in Fig. 6 that are verified by simulations as shown in Fig. 7. The throughput performance of the hybrid approach is found to be almost as good as in SPF. As also noted in Section 5, the analytic load balancing performance does not match well with that from simulations (as also noted in Table 1, columns 9 and 10), which are mainly due to irregular meshed route in practice. Nevertheless, as observed via simulations, the evenness of traffic load distribution (up to 10%) via the hybrid approach could be sufficient enough to supplant the need for additional keep-alive signals in SPF for maintaining the meshed route.

In the simulation of the hybrid approach location awareness of nodes is assumed, which is rather feasible with the recent advancement of localization techniques. Accordingly a node along the multipath route decides on random forwarding or preferential forwarding based on whether it is closer to the source node or the destination.

The comparative analytic performance results of the hybrid approach with respect to SRF and SPF with varying source-to-destination hop count are also shown in Fig. 8. The throughput performance degradation in the hybrid approach is quite graceful, which indicates the learning from SPF. Likewise, the load balancing

UNCORRECTED PROOF

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

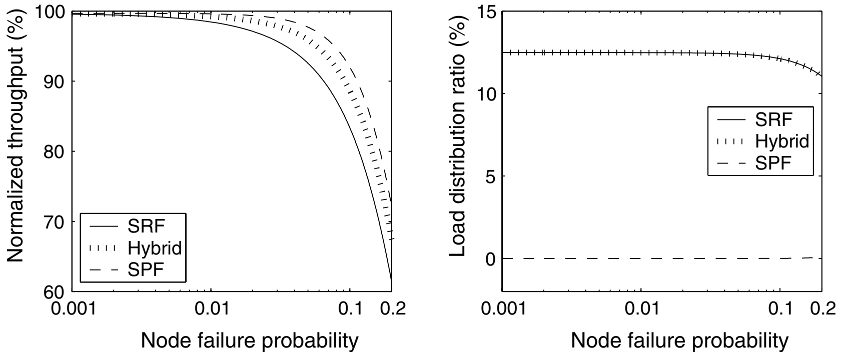

Fig. 6. Throughput and load balancing performance of hybrid packet forwarding along meshed multipath at different node failure rates – from analysis. $H = 8$ hops.

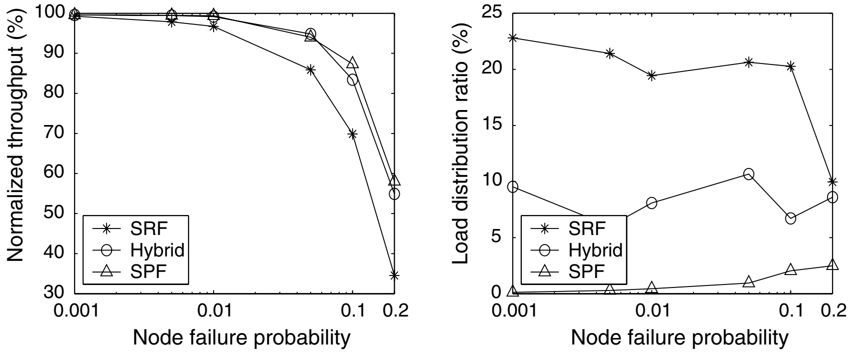

Fig. 7. Throughput and load balancing performance of a hybrid approach along meshed multipath at different node failure rates – from simulation. $H_{\mathrm{avg}} \approx 13$ hops.

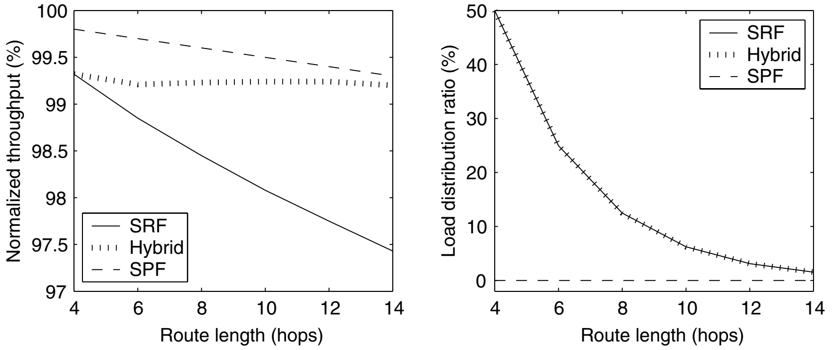

Fig. 8. Throughput and load balancing performance of a hybrid packet forwarding along meshed multipath at different route length – from analysis. $p_{\mathrm{n}} = 10^{-2}$.

performance also depicts the gain from the SRF approach. Instead of simulating performance with the varying hop distance, which is rather complex and not much informative from the overall network performance viewpoint, below, we conduct the simulation of multiple sessions with varying degree of node failure and inhomogeneity of network activity.

In our studies so far we concentrated on average throughput and load balancing along a multipath and did not monitor the network-wide effects. While the average throughput measure remains the same as the average of multiple individual sessions, the nature of network-wide load has to be captured differently. To compute the network-side load balancing effect we define the mean and variance of traffic load (in terms of the number of packets forwarded by the participating nodes) in the network at different activity level. The network activity level is defined by the number of sessions running in the network. The lesser the number of sessions, the more inhomogeneous the network activity is. A *normalized mean traffic load of a node* is defined which effectively captures the probability of handling a packet by an active node which has participated in at least one of the ongoing sessions. The normalized traffic load variance correspondingly captures the evenness of network load.

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

In Fig. 9, normalized traffic load and its variation in terms of number of packets handled by an active node are plotted against node failure rate. The mean load of the hybrid approach is noted to be lower than that in SRF and comparable to SPF, which is because by attempting to disperse traffic all the way up to the destination, the number of nodes encountered to reach the destination via SRF becomes higher, and as a result a node on average has to handle a little more traffic in SRF. The hybrid forwarding on the other hand tries to narrow down the traffic closer to the primary route, causing it to tend toward the shortest hop route. The variance of traffic load in SRF is however the lowest, which indicates that the evenness of load distribution in SRF is still better. However, the hybrid approach clearly shows gain over the SPF.

In Fig. 10, traffic load variation is plotted against the number of network sessions. The mean traffic load at a node in the hybrid approach is always lesser with respect to SRF. The gain with 5 sessions is nearly 14% whereas with 100 sessions it is up to 25%. The reduction in traffic load variance in the hybrid approach compared to SPF is more at low load – with 5 sessions the reduction is 20% where as with 100 sessions it is 12%, which implies that the benefit of the hybrid approach could be significant when the network traffic is sparse and more inhomogeneous.

The benefit of load balancing achieved by the hybrid approach is important considering the fact that in many ad hoc network applications the nodes are energy constrained and certain portions of the network could be more used at times than the others, and thus, without any load balancing effort, certain nodes could drain their energy much faster than the other nodes, leading to network partition.

7. Conclusion

Load balancing is important in energy constrained wireless networks, because without it the energy of some nodes may be drained much faster than the others, eventually leading to network partition. Therefore, along with higher throughput, better load balancing should also be a criteria of a good packet forwarding scheme.

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. Along disjoint multipath routes, it has been clearly shown that the overall performance of SRF is better compared to the SPF approach. Along meshed multipath routes, we have shown that SRF offers better load distribution property but has poorer throughput. SPF on the other hand has a higher throughput but inferior load distribution property. Aiming at achieving a higher throughput and better load balancing simultaneously, we have introduced a hybrid algorithm that takes advantage of better load

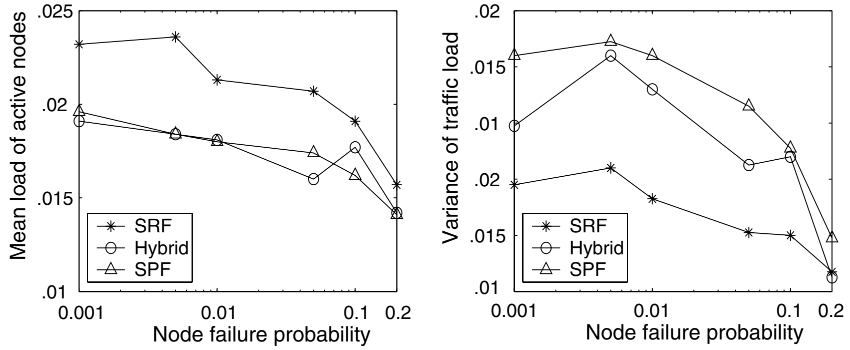

Fig. 9. Traffic load variation across all active nodes at different node failure rates. 1000 point-to-point sessions, each generating 1000 packets, considered.

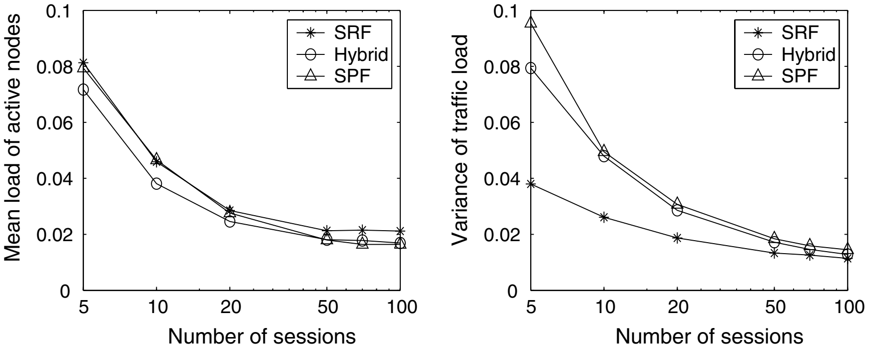

Fig. 10. Traffic load variation across all active nodes at different levels of network activity. Each session generates 1000 packets. $p_n = 10^{-2}$.

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

UNCORRECTED PROOF

distribution property of SRF and gain in throughput from the traffic concentration property of SPF. To study the network-wide load balancing performance, we have conducted further network simulations with varying number of sessions. We have shown that, while the hybrid approach always offers the throughput performance nearly as good as in SPF, its improved load distribution performance becomes more significant with more inhomogeneous network activity. 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.

Appendix A. Calculation of $P_{\mathrm{s}}(2)$ in SRF along meshed multipath

Probability of receiving a packet at node $N_{\frac{H}{2},j+1}, P_{\frac{H}{2},j+1},\ 0 \leqslant j \leqslant \frac{H}{2}$, are obtained from (8).

```
BEGIN
  FOR $i = \frac{H}{2} + 1$ through $H - 1$,
    $P_{i,1} \leftarrow [P_{i-1,1} + \frac{P_{i-1,2}}{2}(1 + p_{\mathrm{n}})](1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})$
    $j \leftarrow H + 1 - i$
    $P_{i,j} \leftarrow [\frac{P_{i-1,j}}{2}(1 + p_{\mathrm{n}}) + P_{i-1,j+1}](1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})$
    FOR $j = 2$ through $H - i$,
      $P_{i,j} \leftarrow \frac{P_{i-1,j} + P_{i-1,j+1}}{2}(1 - p_{\mathrm{n}}^2)(1 - p_{\mathrm{l}})$
    end FOR
  end FOR
  $P_{\mathrm{s}}(2) = P_{H-1,1} + P_{H-1,2}$
END
```

Appendix B. Calculation of $T_{\mathrm{SPF}}^{(\mathrm{m})}$ in SPF

Read the *j*-indices of the primary route in an array `PR[i]` for $1 \leqslant i \leqslant H$, where *i* denotes the hop count of the node $N_{i,j}$, and $P_{i,j}$ is the probability of receiving a packet at that node.

```
BEGIN
  $P_{i,j} = 0\ \forall i,j$
  $P_{0,1} = 1.$
  /* First half of the route */
  FOR $i = 1$ through $\frac{H}{2}$,
    FOR $j = 1$ through $i$,
      IF $|j -$ PR[i]$| < |(j + 1) -$ PR[i]$|$   /* $N_{i,j}$ is closer to the primary route */
        $P_{i,j} \leftarrow P_{i,j} + P_{i-1,j}(1 - p_n)(1 - p_{\mathrm{l}})$
        $P_{i,j+1} \leftarrow P_{i,j+1} + P_{i-1,j}p_{\mathrm{n}}(1 - p_{\mathrm{n}})(1 - p_l)$
      else /*$N_{i,j+1}$ is closer to the primary route*/
        $P_{i,j} \leftarrow P_{i,j} + P_{i-1,j}p_{\mathrm{n}}(1 - p_{\mathrm{n}})(1 - p_l)$
        $P_{i,j+1} \leftarrow P_{i,j+1} + P_{i-1,j}(1 - p_n)(1 - p_{\mathrm{l}})$
      end IF
    end FOR
  end FOR/* Second half of the route */
  FOR $i = \frac{H}{2} + 1$ through $H - 1$,
    $P_{i,1} \leftarrow P_{i-1,1}(1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})$
    $j \leftarrow H + 1 - i$
    $P_{i,j} \leftarrow P_{i-1,j+1}(1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})$
    FOR $j = 2$ through $H + 1 - i$
      IF $|(j - 1) -$ PR[i]$| < |j -$ PR[i]$|$   /* $N_{i,j-1}$ is closer to the primary route */
        $P_{i,j-1} \leftarrow P_{i,j-1} + P_{i-1,j}(1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})$
        $P_{i,j} \leftarrow P_{i,j} + P_{i-1,j}p_{\mathrm{n}}(1 - p_{\mathrm{n}})(1 - p_{\mathrm{l}})$
      else   /* $N_{i,j}$ is closer to the primary route */
        $P_{i,j-1} \leftarrow P_{i,j-1} + P_{i-1,j}p_{\mathrm{n}}(1 - p_n)(1 - p_{\mathrm{l}})$
        $P_{i,j} \leftarrow P_{i,j} + P_{i-1,j}(1 - p_n)(1 - p_{\mathrm{l}})$
      end IF
    end FOR
  end FOR
  $T_{\mathrm{SPF}}^{(\mathrm{m})} = (P_{H-1,1} + P_{H-1,2})(1 - p_{\mathrm{l}})$
END
```

References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, IEEE Commun. Mag. 40 (8) (2002) 102–114.

[2] G. Asada, M. Dong, T.S. Lin, F. Newberg, G. Pottie, W.J. Kaiser, 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, J.R. Agre, Self-organizing distributed sensor networks, in: SPIE Conf. Unattended Ground Sensor Technologies and Applications, April 1999, pp. 229–237.

[4] T.-W. Chen, J.T. Tsai, M. Gerla, QoS routing performance in multihop, multimedia, wireless networks, in: Proc. IEEE ICUPC, San Diego, CA, October 1997, pp. 557–561.

[5] Y. Li, S. Mao, S.S. Panwar, The case for multipath multimedia transport over wireless ad hoc networks, in: Proc. IEEE BROADNETS, San Jose, CA, 2004, pp. 486–495.

[6] S. Mao, S. Lin, S.S. Panwar, Y. Wang, E. Celebi, Multipath video transport over wireless ad hoc networks, IEEE Wireless Commun. 12 (4) (2005) 42–49.

[7] T. Henderson, D. Kotz, I. Abyzov, The changing usage of a mature campus-wide wireless network, in: Proc. ACM MobiCom, Philadelphia, PA, September 2004.

[8] J. Kulik, W.R. Heinzelman, H. Balakrishnan, Negotiation-based protocols for disseminating information in wireless sensor networks, in: Proc. ACM MobiCom, 1999.

[9] D. Ganesan, R. Govindan, S. Shenker, D. Estrin, Highly-resilient, energy-efficient multipath routing in wireless sensor networks, ACM SIGMOBILE Mobile Comput. Commun. Rev. 5 (4) (2001).

[10] A. Nasipuri, S.R. Das, On-demand multipath routing for mobile ad hoc networks, in: Proc. Int. Conf. Computer Commun. Networks (ICCCN), October 1999, pp. 64–70.

[11] E. Ayanoglu, I. Chih-Lin, R.D. Gitlin, J.E. Mazo, Diversity coding for transparent self-healing and fault-tolerant communication networks, IEEE Trans. Commun. 41 (11) (1993).

[12] S.-J. Lee, M. Gerla, Split multipath routing with maximally disjoint paths in ad hoc networks, in: Proc. Int. Conf. Commun. (ICC), 2001.

[13] A. Tsirigos, Z.J. Hass, Multipath routing in the presence of frequent topological changes, IEEE Commun. Mag. (2001) 132–138.

[14] S. De, C. Qiao, H. Wu, Meshed multipath routing with selective forwarding: an efficient strategy in wireless sensor networks, Elsevier Comput. Netw. 43 (4) (2003) 481–497.

[15] H. Suzuki, F. Tobagi, Fast bandwidth reservation scheme with multi-link and multi-path routing in ATM networks, in: IEEE INFOCOM'92, Piscataway, USA, pp. 2233–2240.

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015

[16] I. Cidon, R. Rom, Y. Shavitt, Analysis of multi-path routing, IEEE/ACM Trans. Networking 7 (6) (1999) 885–896.

[17] A. Banerjea, Simulation study of the capacity effects of dispersity routing for fault tolerant real-time channels, ACM Computer Communication Review, vol. 26, ACM Press, 1996, pp. 195–205.

[18] S. Chen, K. Nahrstedt, Distributed quality-of-service routing in ad hoc networks, IEEE J. Selected Areas Commun. 17 (8) (1999) 1488–1505.

[19] C.-Y. Wan, A.T. Campbell, L. Krishnamurthy, PSFQ: a reliable transport protocol for wireless sensor networks, in: Proc. ACM Workshop on Wireless Sensor Networks and Applications (WSNA), September 2002, pp. 1–11.

[20] W. Su, M. Gerla, IPv6 flow handoff in ad hoc wireless networks using mobility prediction, in: Proc. IEEE GLOBECOM, Rio de Janeiro, Brazil, December 1999.

[21] S. De, C. Qiao, S.K. Das, A resource efficient QoS routing protocol for mobile ad hoc networks, Wiley J. Wireless Commun. Mobile Comput. 3 (4) (2003) 465–486.

[22] B. Karp, H.T. Kung, GPSR: greedy perimeter stateless routing for wireless networks, in: Proc. ACM/IEEE MobiCom, Boston, MA, August 2000, pp. 243–254.

UNCORRECTED PROOF

Please cite this article in press as: S. De, C. Qiao, A hybrid meshed multipath forwarding scheme in wireless ..., Comput. Commun. (2007), doi:10.1016/j.comcom.2006.12.015