Does Packet Replication Along Multipath Really Help ?

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—**For reliability of communication and simplicity, oftentimes packets are replicated along predetermined multiple routes to the destination. Alternatively, for traffic load balancing, data traffic is distributed along disjoint or meshed multiple routes to the destination – called selective forwarding. In this paper, we study and quantify the resource usage in these schemes, namely,** ***packet replication*** **and** ***selective forwarding*** **approaches. Our evaluation shows that for successfully routing a message using forward error correction coding technique, packet replication wastes much higher network resource, such as channel bandwidth and battery power.**

I. Introduction

Wireless networks are limited by channel bandwidth as well as battery power. Despite this fact, due to error-prone communication channel and lack of dedicated routers in ad hoc wireless networks, multiple routes are set up and maintained for reliable multihop communication. For reliable data delivery, packets may be replicated and sent along multiple routes to the destination (as noted in [6],[5]). Alternatively, when traffic load balancing is targeted, packets may be distributed along multiple routes [1],[8],[10]. In this approach, along a route if more than one alternative downstream links are available, the best one is selected for packet forwarding. In case of a tie, one is selected by flipping a fair coin. We call this approach of packet distribution as *selective forwarding* (SF).

While it is apparent that *packet replication* (PR) may give higher throughput compared to SF, it is also intuitive that PR would require more network resource (e.g., channel bandwidth, transceiver power) per packet transmission. It is however not clear which of these two schemes would give us the overall benefit on a common performance scale. Therefore, we would like to ask the question that for successfully routing a message (consisting of a number of packets) to the destination, what will be the resource usage in the above two cases.

We consider two forms of end-to-end multihop routes – *disjoint multipath* and *meshed multipath*. To successfully route a message with PR and SF approaches, we make use of forward error correction (FEC) coding technique. Our evaluation shows that for successfully routing a message to the destination PR has substantially higher resource requirement over SF, for disjoint as well as meshed multipath. For example, in a 6-hop route with link error probability 10^{-3} and node failure probability 10^{-2}, PR along disjoint multipath requires nearly 170% more additional transmit and receive operations compared to the SF approach. For meshed multipath, this factor is nearly 230%.

In Section II, we briefly discuss different multipath routing techniques. Section III contains throughput analyses of PR and SF along disjoint and meshed multipath, respectively, and numerical results. Equivalent resource requirements are quantified in Section IV. We conduct simulations in Section V. Section VI concludes the paper.

II. Overview of Different Multipath Schemes

The authors in [6] presented different approaches for improving on simple flooding technique for sensor networks by introducing node-to-node co-ordination, thereby reducing chances of overlapped data collection and data implosion. For load balancing purpose, [8] proposed traffic splitting along multiple disjoint routes. [10] studied optimum number of disjoint routes required to ensure a certain throughput in traffic splitting in multihop wireless networks. For QoS support in mobile ad hoc networks, [3] proposed maintaining multiple disjoint routes, called secondary routes, while the packets are transmitted along the primary route. [9],[5] proposed maintaining non-disjoint secondary routes while the primary route is in use. In [7], multicasting along mesh based route to a group of nodes in multihop wireless networks has been proposed. Packet replication along meshed multipath is similar to the distributed parallel processing in bussed interconnection network [2], where the data to be operated on is copied to all the operators (networks nodes), thus faster computation speed is achieved at the cost of communication bandwidth and nodal memory.

In multihop wireless networks, such as mobile ad hoc networks and sensor networks, for reliable data transmission we assume that predetermined multiple routes are used. If the field nodes are clustered, and the nodes in each cluster form routing mesh among themselves, a meshed point-to-point route between a field sensor and the clusterhead can be formed. Otherwise, disjoint multi-

0-7803-7802-4/03/$17.00 © 2003 IEEE

ple routes can be formed (for example, following the approach in [3]). We do not consider request-reply based data flow. Instead, we assume that the packets are either replicated along multiple routes, or they are distributed via SF approach. These approaches do not require any explicit secondary route maintenance. It may be worthwhile to mention here that a comparison of routing performances could be drawn between disjoint multipath and meshed multipath. We however do not focus this aspect in this paper. Rather, in this presentation we are interested in comparing PR and SF approaches, along either disjoint or meshed multipath.

III. Analytic Performance Evaluation

In this section, we evaluate the throughput performances of PR and SF along disjoint and meshed multipath, respectively.

In throughput analysis, we do not distinguish the data packets (blocks) from possible error correcting blocks. We define *normalized throughput* (T) as the probability of successful arrival of a packet to the destination. For analytical tractability, we assume that multiple disjoint or meshed routes are of equal hop length, denoted by H, and the meshed multipath is mostly regular (see Figs. 1 and 2). More realistic simulations will be conducted in section V to verify the analysis.

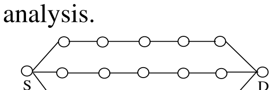

Fig. 1. Example of 6-hop disjoint multiple routes. $r = 3$.

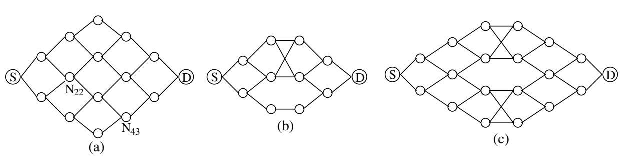

Fig. 2. Examples of meshed multipath. (a) H even; (b) H odd, $\lfloor \frac{H}{2} \rfloor$ even; (c) H odd, $\lfloor \frac{H}{2} \rfloor$ odd. Maximum degree of incoming and outgoing connectivities of a node are limited to *two*.

Hereafter, for each packet transmission, link error and intermediate node failure probabilities are denoted by p_l and p_n, respectively. Note that p_l captures multiuser interference caused by medium access conflict, and p_n captures the packet loss due to input buffer overflow along with node failure.

A. Packet Replication (PR)

Now, we consider the PR approach. We assume that if an intermediate node receives multiple copies of a packet (e.g., in M-MPR-PR), it forwards only one copy of it to its downstream nodes.

A.1 Disjoint Multipath Routing (D-MPR-PR)

Referring to Fig. 1, in D-MPR-PR (with r parallel H-hop routes), the normalized throughput $T_{PR}^{(D)}$ can be obtained as:

$$T_{PR}^{(D)} = 1 - \left[1 - (1-p_l)^H (1-p_n)^{H-1}\right]^r \quad (1)$$

where $(1-p_l)^H (1-p_n)^{H-1}$ is the probability of success along a particular route.

A.2 Meshed Multipath Routing (M-MPR-PR)

There could be different ways of meshed route formation. We consider the meshed routes as shown in Fig. 2. We denote the intermediate nodes by N_{ij} where i stands for the hop length from source and j stands for its position from top of the mesh. Also, successful packet arrival probability at the (i, j)-th node is denoted by P_{ij}. Depending on the hop length there are three cases with possible different mesh formation: (a) H even, (b) H odd, $\lfloor \frac{H}{2} \rfloor$ even, and (c) H odd, $\lfloor \frac{H}{2} \rfloor$ odd. Referring to Fig. 2, there can be up to four categories of intermediate nodes: (i) The nodes having only one predecessor node. For example, nodes N_{ij} in Fig. 2(a), where $(i, j) = (1, 1), (1, 2), (2, 1), (2, 3), (3, 1), (3, 4)$. In general, $i = 1, 2, \cdots \lceil \frac{H}{2} \rceil$ and $j = 1$ or $j = i + 1$; (ii) the remaining nodes in the left half of the mesh (i.e., the nodes with $i \le \lfloor \frac{H}{2} \rfloor$ and $1 < j < i + 1$), which have two predecessor nodes; (iii) for H odd, the nodes $N_{\lceil \frac{H}{2} \rceil, j}$, where $j \le \lfloor \frac{H}{2} \rfloor$; and (iv) all other nodes in the right half of the mesh side, i.e., nodes from $\lfloor \frac{H}{2} \rfloor + 1$ hop to $H - 1$ hop.

Category (i) nodes : A packet successfully reaches to the next node, N_{ij}, if N_{ij} is good (i.e., capable of receiving), and its incoming link is error-free during transmission of the packet. Here, P_{ij} is given by

$$P_{ij} = (1-p_l)^i (1-p_n)^i$$

Note that P_{ij} is only a function of i, i.e., the hop distance of N_{ij} from S.

Category (ii) nodes: P_{ij} is recursively obtained as:

$$P_{ij} = (1-p_n)\left[1 - (1-(1-p_l)P_{i-1,j-1})(1-(1-p_l)P_{i-1,j})\right]$$

Here, $(1-p_n)$ is the probability that the node N_{ij} is good. The remaining term within the parenthesis is the successful packet arrival probability from at least one incoming directions, given that N_{ij} is good.

Category (iii) nodes (H odd): In this category, depending on whether $\lfloor H/2 \rfloor$ is odd or even, P_{ij} is obtained differently, as shown below.

$i \leftarrow \lceil \frac{H}{2} \rceil$
FOR $j = 1$ through $\lfloor \frac{H}{2} \rfloor$, with increment of 2,
$P_{ij} \leftarrow (1-p_n)\left[1 - (1-(1-p_l)P_{i-1,j}) \times (1-(1-p_l)P_{i-1,j+1})\right]$

$P_{i,j+1} \leftarrow P_{ij}$

IF $\lfloor \frac{H}{2} \rfloor$ even,

$P_{ii} \leftarrow (1-p_l)(1-p_n)P_{i-1,i}$

Category (iv) nodes: All nodes in this category have two predecessor nodes (like the category (ii) nodes, but with the difference of predecessor node indices). The corresponding P_{ij} is given by

$$P_{ij} = (1-p_n)\left[1-(1-(1-p_l)P_{i-1,j})(1-(1-p_l)P_{i-1,j+1})\right]$$

Following the above steps we obtain the probabilities $P_{H-1,1}$ and $P_{H-1,2}$. Finally, the end-to-end successful arrival of a packet, or normalized throughput in M-MPR-PR is given by (similar as P_{ij} for the nodes in categories (ii) and (iv)):

$$T_{PR}^{(M)} = 1-(1-(1-p_l)P_{H-1,1})(1-(1-p_l)P_{H-1,2}) \quad (2)$$

Note that the destination node is presumed good for all packets, as it is a primary entity (along with the source) in the communication process.

B. Selective Forwarding (SF)

Throughput analysis with SF is followed from [4]. Due to limited space we only show the end results.

Normalized throughput in D-MPR-SF is given by

$$T_{SF}^{(D)} = (1-p_l)^H (1-p_n^r)(1-p_n)^{H-2} \quad (3)$$

Normalized throughput in M-MPR-SF is given by

$$T_{SF}^{(M)} = (1-p_l)\prod_{i=1}^{3} P_s(i) \quad (4)$$

C. Numerical Results

Throughput performances of M-MPR and D-MPR with PR and SF, respectively, for varying node failure probabilities, are shown in Fig. 3, where the higher packet-by-packet throughput with PR over SF is apparent in D-MPR as well as in M-MPR. This is intuitive also, as sending a packet along multiple error-prone routes (rather than along a chosen route) surely increases the chance of successful arrival of at least a copy of the packet.

IV. Equivalent Resource Requirements

We are now in a position to compare the resource requirements in PR and SF, respectively, where end-to-end FEC coding is assumed. To compare these two approaches on the same baseline, we define the *equivalent energy resource usage* (NRG) as the number of transmit and receive operations that take place in successfully routing a message. We assume that a message consists of D data blocks. In PR approach, let $p_{PR} = 1 - T_{PR}$ be the

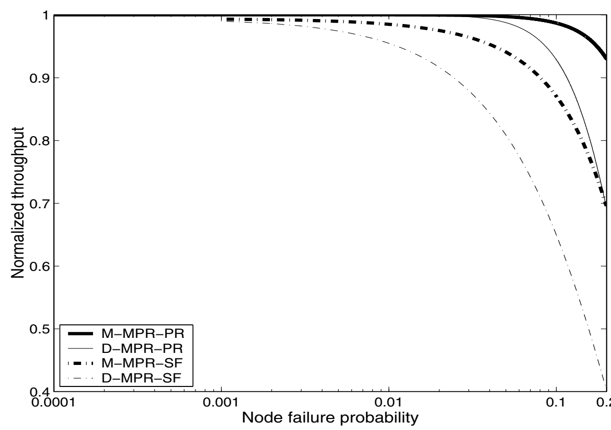

Fig. 3. Normalized throughput performances with PR and SF – from analysis. $p_l = 10^{-3}$, $H = 6$.

probability that a packet is corrupted before reaching the receiver, where T_{PR} is the normalized throughput in PR (obtained in Eqs. (1) and (2)) and E_{PR} be the number of error correction blocks required to correctly retrieve the message (i.e., all D data blocks). The corresponding notations in SF are, respectively, $p_{SF} = 1 - T_{SF}$ and E_{SF}. Then, by [1],

$$(D+E_{PR})p_{PR} \leq E_{PR}$$
$$(D+E_{SF})p_{SF} \leq E_{SF}$$

I.e., as long as the number of errored blocks is less than the number or error correction blocks, the message can be fully recovered at the receiver.

Taking the limiting cases and simplifying them, the minimum number of error correction blocks required in the two cases are:

$$E_{PR} = \left\lceil \frac{D(1-T_{PR})}{T_{PR}} \right\rceil \quad (5)$$

$$E_{SF} = \left\lceil \frac{D(1-T_{SF})}{T_{SF}} \right\rceil \quad (5')$$

For calculating the number of transmit and receive operations, we make the following observations: (1) To reach more than one neighbors, a node requires only *one* transmit operation, which is the same as that for reaching a single neighbor. (2) If a node is an intended receiver, it undergoes *one* receive operation per transmission of packet. Otherwise, the node does not undergo any receive operation. (3) In PR approach, all nodes constituting the multipath route (disjoint or meshed) undergo transmit and receive operations. As already mntioned earlier, it is assumed that in M-MPR-PR, if an intermediate node receives more than one copy of a packet (known from the packet ID), it forwards only one copy. This process in a way controls the data implosion at the destination and also saves battery power. With these observations, if the number of transmit (TX) and receive (RX) operations in PR is N_{PR} (i.e., $N_{PR} = TX_{PR} + RX_{PR}$) and that in SF is N_{SF} (i.e., $N_{SF} = TX_{SF} + RX_{SF}$), then the NRG's in these two approaches are obtained as follows:

$$NRG_{PR} = (D + E_{PR})N_{PR} \quad (6)$$

$$NRG_{SF} = (D + E_{SF})N_{SF} \quad (6')$$

Note that the number of TX operations per end-to-end packet routing gives a measure of equivalent channel resource (e.g., bandwidth) usage (CHL). More specifically, $CHL = (D + E)TX$. For PR and SF, this can also be similarly obtained (as in Eqs. (6) and (6′)) and compared.

Referring to Figs. 1 and 2, we note that for each packet routing D-MPR-PR requires 16 TX and 18 RX operations, respectively, while M-MPR-PR requires 15 TX and 24 RX operations, respectively. On the other hand, with SF, both of the multipath schemes require 6 each TX and RX operations. For 6-hop disjoint multipath and meshed multipath, equivalent energy resources used in PR and SF, respectively, are shown in Table I. Note, for example, from the table that for a given $p_l = 10^{-3}$, $p_n = 10^{-1}$, and $H = 6$ *hops*, to successfully receive a 1000 *block* long message, D-MPR-PR requires at least 77 error correction blocks, and the equivalent energy usage is 36618 (in arbitrary units). In the identical scenario, D-MPR-SF requires at least 535 error correction blocks and has the equivalent energy usage 18420 units. Correspondingly, M-MPR-PR requires 39546 units of energy resource, while M-MPR-SF requires 13776 units. It is apparent that PR effectively wastes more network resource (in terms of battery power as well as channel bandwidth) compared to the SF, for achieving the same error performance limit. It is also noted that M-MPR-SF has lesser resource requirement with respect to D-MPR-SF (with equal number of nodes).

V. Simulation

We verify our analytic observations via simulation. The parameter values considered are: 500 static nodes uniformly randomly distributed over a 500m square location space; range of circular coverage of each node 40m; white Gaussian channel with BER 10^{-6}; packet size 50 *Bytes* (fixed); 1000 data blocks per message. Sufficient messages per session and iterations are simulated to achieve throughput and error correction overhead within respective 95% confidence intervals.

Fig. 4 shows throughput variations with node failure rate, with average end-to-end distance 9.06 *hop*. Note that although the trends of results are similar as in Fig. 3, simulation gives a little poorer throughput performance because of larger average hop length, incomplete mesh, and unequal hop distance of multiple routes.

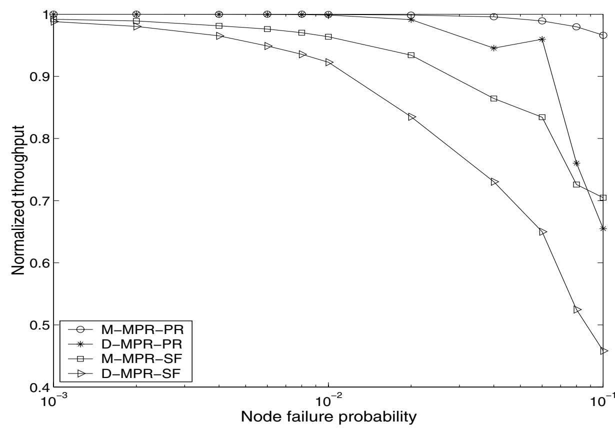

Fig. 4. Normalized throughput performance with PR and SF – from simulation. Average end-to-end distance 9.06 *hop*.

Next, to study the equivalent energy requirement (NRG), we consider a specific source-destination pair, 6 *hop* (shortest distance) away. The routes (disjoint and meshed), obtained from the network connectivity trace file, are shown in Fig. 5.

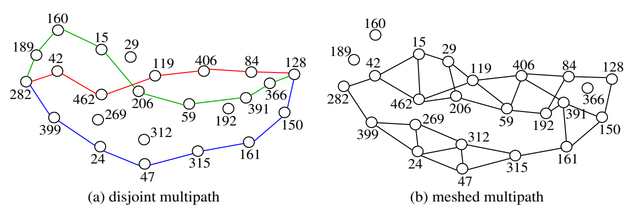

Fig. 5. Sketches of disjoint multipath and its node equivalent meshed multipath, drawn from the network connectivity trace. End-to-end (shortest) distance 6 *hop*.

For this specific case, minimum additional error code blocks and the associated NRG's required with PR and SF in D-MPR and M-MPR, respectively, are shown in Table II. Note that in D-MPR (Fig. 5(a)), number of TX and RX operations per packet (block) with PR is 40 and that with SF is 14 (average distance 7 *hop*). The corresponding values in M-MPR are 54 and 16 (obtained from packets' route traces). Note that since "equal length routes" and "ideal mesh" could not be ensured in practical multipath routes (due to random location of nodes), to route a message to the destination, the number of transmit-receive operations in simulations are higher than those obtained analytically.

Fig. 6, shows the NRG gain with SF in D-MPR and M-MPR, respectively. The relative NRG gain obtained from analysis is observed to closely follow the simulated results. Deviations in analytic and simulated data for M-MPR are more, which may be because the simulated meshed multipath is quite different from (i.e., incomplete compared to) the idealized mesh, considered in analysis. It is also observed that M-MPR-SF has the overall superior performance.

TABLE I

Equivalent energy resource required with PR and SF, respectively – from analysis. $D = 1000$, $H = 6$, $p_l = 10^{-3}$.

	D-MPR (Fig. 1)				M-MPR (Fig. 2(a))			
p_n	$E_{PR}^{(D)}$	$NRG_{PR}^{(D)}$	$E_{SF}^{(D)}$	$NRG_{SF}^{(D)}$	$E_{PR}^{(M)}$	$NRG_{PR}^{(M)}$	$E_{SF}^{(M)}$	$NRG_{SF}^{(M)}$
10^{-3}	1	34034	11	12132	1	39039	7	12084
10^{-2}	1	34034	48	12576	1	39039	16	12192
0.1	77	36618	535	18420	14	39546	148	13776
0.2	445	49130	1476	29712	75	41925	438	17256

TABLE II

NRG required with PR and SF, respectively – from simulation. End-to-end (shortest) distance 6 *hop*. $D = 1000$, $p_l = 10^{-3}$.

	D-MPR (Fig. 5(a))				M-MPR (Fig. 5(b))			
p_n	$E_{PR}^{(D)}$	$NRG_{PR}^{(D)}$	$E_{SF}^{(D)}$	$NRG_{SF}^{(D)}$	$E_{PR}^{(M)}$	$NRG_{PR}^{(M)}$	$E_{SF}^{(M)}$	$NRG_{SF}^{(M)}$
10^{-3}	0	40000	8	14112	1	54054	5	16080
10^{-2}	1	40040	55	14770	1	54054	21	16336
0.1	186	47440	717	24038	35	55890	261	20176
0.2	1110	84400	2280	45920	188	64152	773	28368

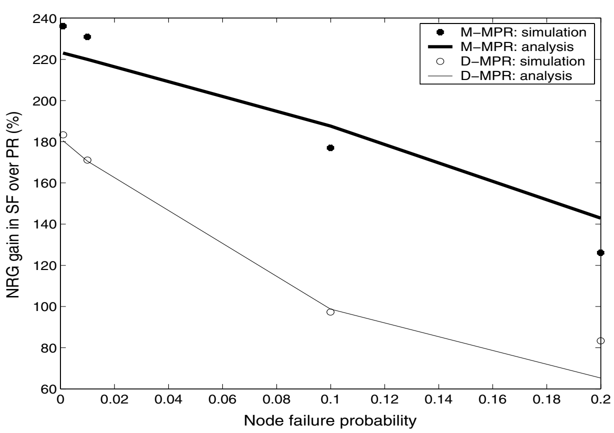

Fig. 6. Equivalent energy resource gain with SF over PR, in D-MPR and M-MPR, respectively. End-to-end (shortest) distance 6 *hop*.

VI. Conclusion

In this paper, we have studied multipath routing performances in a multihop wireless network, with packet replication and selective forwarding, respectively. For this purpose we considered two form of routes, namely, mutually disjoint multiple routes and meshed multiple routes. We have shown that although packet-by-packet throughput with packet replication is higher than that in selective forwarding, for successfully routing a message, packet replication has substantially high network resource requirements, such as channel bandwidth, battery power. It is also observed that meshed multipath routing with selective forwarding has the overall superior performance. It might therefore be worthwhile considering end-to-end forward error correction based packet distribution along meshed multipath in multihop wireless networks, such as sensor networks, specifically because it has a high premium over battery power.

References

[1] E. Ayanoglu, I. Chih-Lin, R. D. Gitlin, and J. E. Mazo, "Diversity Coding for Transparent Self-Healing and Fault-Tolerant Communication Networks," *IEEE Trans. Comm.*, vol. 41, no. 11, Nov. 1993.

[2] N. Carriero and D. Gelernter, "The S/Net's Linda Kernel," *ACM Transactions on Computer Systems*, vol. 4, no. 2, pp. 110-129, May 1986.

[3] S. Chen and K. Nahrstedt, "Distributed Quality-of-Service Routing in Ad Hoc Networks," *IEEE Journal on Selected Areas on Communications*, vol. 17, no. 8, pp. 1488-1505, Aug. 1999.

[4] S. De, C. Qiao, and H. Wu, "Meshed Multipath Routing: An Efficient Strategy in Sensor Networks," in *Proc. IEEE WCNC*, Mar. 2003.

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

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

[7] S.-J. Lee, M. Gerla, and C.-C. Chiang, "On-Demand Multicast Routing Protocol," in *Proc. IEEE WCNC*, pp. 1298-1302, Sep. 1999.

[8] S.-J. Lee and M. Gerla, "Split Multipath Routing with Maximally Disjoint Paths in Ad hoc Networks," in *Proceedings of International Conference on Communications (ICC)*, 2001.

[9] A. Nasipuri and S. R. Das, "On-Demand Multipath Routing for Mobile Ad Hoc Networks," in *Proceedings of International Conference on Computer Communications and Networks (ICCCN)*, pp. 64-70, Oct. 1999.

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