The Stability of Multihop Transport with Autonomous Cooperation

Thomas R. Halford*
*TrellisWare Technologies, Inc.
16516 Via Esprillo, Suite 300
San Diego, CA 92127–1708
Email: {thalford,kchugg}@trellisware.com

Keith M. Chugg†*
†Communication Sciences Institute
Ming Hsieh Dept. of Electrical Engineering
University of Southern California
Los Angeles, CA 90089–2565
Email: chugg@usc.edu

***Abstract*—Cooperative communications is a critical component of a number of emerging mobile ad hoc network (MANET) architectures including opportunistic large arrays (OLAs), barrage relay networks (BRNs), and the path access control (PAC) protocols described by Ramanathan and Yackoski, *et al.* BRNs in particular employ an autonomous decode-and-forward cooperation scheme that is being used operationally at the tactical edge. This paper studies the stability of multihop routes in MANETs employing such autonomous cooperative communications at the physical layer. Specifically, a combination of analysis and simulation is used to quantify end-to-end availability probability under a variant of the random direction mobility model. Much as an understanding of unicast route lifetimes is important to reactive routing protocol design in traditional architectures, the expected lifetime of cooperative multihop routes informs the design of multihop access control protocols in OLAs and BRNs.**

I. INTRODUCTION

The past decade has seen a significant research focus on both the theoretical capabilities of and protocol designs for mobile ad hoc networks. Much of the impetus for this activity has been provided by the potential applications for MANETs, one of the most compelling of which is communications at the *tactical edge*. A squadron of soldiers seeking to maintain connectivity in a challenging RF propagation environment is an example of edge networking; first-responder communications is another. This *tactical* MANET application assumes no supporting infrastructure for missions that are typically short enough to make power consumption a secondary concern. Since nodes are both mobile and are typically in rich scattering environments, link-level connectivity is unreliable and tactical networking topologies are highly dynamic. The traffic patterns and key performance metrics for tactical MANETs also differ substantially from those typically considered for ad hoc or sensor networks. In particular, latency-critical traffic such as push-to-talk voice and real-time streaming video is primal.

MANETs employing traditional link-based architectures have heretofore seen limited success in tactical applications (cf., [1]). The overhead required to compensate for topological dynamics at the medium access control (MAC) and networking layers can overwhelm network resources (e.g., overhead traffic consumes as much as 99 percent of bandwidth in some military prototype systems [2]). Furthermore, the per-packet and per-hop contention delays incurred in strictly layered architectures can result in unacceptable delays for multihop, latency-critical traffic [3]. A number of authors have therefore called for a radical reconsideration of how MANETs ought be theoretically characterized [2] and designed [3] for tactical scenarios.

TrellisWare Technologies, Inc. first proposed barrage relay networks (BRNs) in [4] as one such alternative approach to tactical MANET design. BRNs utilize coarse time synchronization and autonomous cooperative communications as the basis of an efficient broadcast protocol wherein packets ripple out from the source in pipelined spatial waves. A *cooperative* decode-and-forward protocol is employed so that simultaneous wireless transmissions serve to improve reliability and need not be avoided by any link-based access control mechanism. BRNs are closely related[1] to the opportunistic large array (OLA) concept that was introduced in [7] and which has been subsequently refined and extended by Ingram, *et al.* (cf., [8]).

For strictly broadcast applications, BRNs and OLAs need only coordinate which node acts as the (sole) source at any given time. Simple control protocols can be used to time-multiplex access to the efficient broadcast mechanism afforded by cooperative communications [9]. More generally, *controlled barrage regions* (CBRs) [10, 11] – and their OLA analogs [12] – can be used as building blocks for spatial flow containment. Briefly, a set of buffer nodes act to separate a portion of the network containing a unicast source-destination pair from the rest of the network. Within a CBR, relaying nodes cooperate by the barrage broadcast mechanism to transport data from source to destination. When appropriately coordinated via distributed *space-time* barrage access control (BAC) protocols, multiple localized unicast flows can operate simultaneously, thereby enhancing the network capacity offered by barrage relay networks. Space-time BAC protocols reserve the channel for multiple packets over multiple hops; Ramanathan cited such *path* access control (PAC) as a critical component of next-generation MANET architectures in [3]. Recently, Yackoski, *et al.* demonstrated the efficacy of the PAC concept in a modified IEEE 802.11 stack [13].

---

[1] The primary distinction between BRNs and OLAs lies in the cooperative communications mechanism. In a BRN, cooperating nodes employ random phase dithering and modern coding so that spatial diversity can be translated into time diversity over a common channel [5]. Conversely, cooperating nodes in an OLA typically transmit on orthogonal channels [6].

978-1-4673-0081-0/11/$26.00 ©2011 IEEE

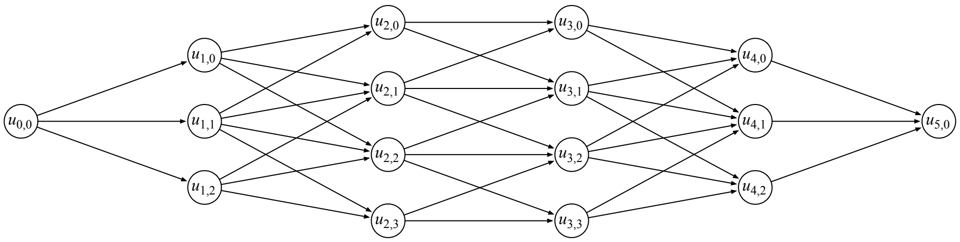

Fig. 1. An idealized linear network model of a controlled barrage region. This example models a 5-hop transmission ($N = 5$) with a maximum of 4 cooperating nodes per hop ($L = 4$) and fan-out parameter $F = 1$.

This paper compares the stability of multihop unicast transmission via CBRs to traditional link-based routes. Much as the study of route lifetimes is important to protocol design in traditional MANET architectures (cf., [14]), the expected lifetime of CBRs informs the design of space-time BAC protocols (e.g., [11]). More generally, the expected lifetime of multihop cooperative routes influences the design of access control protocols for OLAs and MANET architectures employing Ramanathan's path access control concept. A simple linear network model forms the basis of the investigation; a number of measures for the end-to-end availability probability of CBRs are then considered under a variant of the random direction mobility model studied recently in [15]. Whereas multihop cooperative transmission might be expected to be *less* stable than traditional routing due the sensitivity of *conventional* cooperative communications schemes (e.g., distributed space-time coding) to node position, the *autonomous* cooperation scheme used in BRNs is shown to afford *enhanced* robustness to node mobility. For example, for up to 10 hops, a simple linear CBR with two cooperating nodes per hop maintains a greater than 90% availability probability approximately twice as long as that of a traditional route (in a scenario representative of pedestrian motion).

II. RELATED WORK

Motivated by the study of techniques that can mitigate the effects of route repair in MANETs, multihop route stability has been examined by a number of authors (e.g., [16, 17]). Bai, *et al.* concluded via simulation that the probability distribution of multihop route duration can be modeled as exponential across a wide range of mobility models [14]; more recent work by Han, *et al.* provided an analytical justification for this phenomenon [18]. The present work focuses on the probability that there exists an end-to-end path from source to destination as a measure of multihop stability. This *path availability* metric was studied previously in [15, 19]; recent work by Carofilgio, *et al.* [15], in particular, motivates the approach taken herein. Previous work has largely focused on traditional multihop routing. While the robustness to mobility of multihop transmission in OLAs was demonstrated implicitly via simulation in [8], the present work is the first explicit investigation of multihop path availability in wireless networks employing cooperative communications known to its authors.

III. CONTROLLED BARRAGE REGION MODEL

For the sake of analytical tractability, the nodes that form a controlled barrage region are modeled as an N-hop idealized linear network (cf., [20]) where $N-1$ clusters of relay nodes are located between a source and destination node. The model of a 5-hop CBR pictured in Figure 1 is used in this section to illustrate notation. The j^{th} node in the i^{th} cluster is denoted $u_{i,j}$ so that the source and destination nodes of the CBR are $u_{0,0}$ and $u_{N,0}$, respectively. Each of the $N-1$ relay clusters contains at most L nodes; observe that $L = 4$ in Figure 1. In order to capture the shape of the CBR (cf., [11]), not all relay clusters contain L nodes. Rather, the CBR is parameterized by a fan-out parameter F such that the number of nodes in the i^{th} relay cluster L_i is

$$L_i \triangleq \min\left(L, 2F\min(i, N-i)+1\right), \tag{1}$$

for $i \in [0, N]$. Equation (1) models CBRs as growing in width from source to center and then narrowing again from center to destination; a larger value of F yields faster growth (i.e., the index i of the first relay cluster for which $L_i = L$ decreases with increasing F). In Figure 1, $F = 1$ so that $L_0 = L_5 = 1$, $L_1 = L_4 = 3$, and $L_2 = L_3 = 4$.

Connectivity in the CBR model is defined by Euclidean distance. The *initial* location of a node $u_{i,j}$ is

$$\mathbf{x}(i,j,t=0) = \left(is_x, \left(\frac{L_i-1}{2} - j\right)s_y\right), \tag{2}$$

where s_x is the inter-cluster node separation, s_y is the intra-cluster node separation, and L_i is, again, the number of cooperating nodes in the i^{th} relay cluster for $i \in [0, N]$, defined as per (1). A link connects $u_{i,j}$ to $u_{i+1,k}$ if and only if they are separated by a distance of at most R, i.e., iff

$$\|\mathbf{x}(i,j,t=0) - \mathbf{x}(i+1,k,t=0)\| \le R, \tag{3}$$

where $\|\cdot\|$ is the l_2-norm. It is readily verified that the link connectivity illustrated in Figure 1 can be achieved by setting $s_x = 60$ meters (m), $s_y = 20$ m, and $R = 70$ m.

In the special case of $L = 2$, the initial source and destination node positions are altered slightly so as to permit fair comparisons between traditional routes and CBRs:

$$\begin{aligned}\mathbf{x}(0,0,t=0) &= \left(s_x - \sqrt{s_x^2 - s_y^2/4}, 0\right)\\ \mathbf{x}(N,0,t=0) &= \left((M-1)s_x + \sqrt{s_x^2 - s_y^2/4}, 0\right)\end{aligned}. \tag{4}$$

In particular, this modification ensures that in an $L = 2$ CBR there exists an N-hop path from source to destination composed entirely of length s_x links at time 0.

Finally, the transmission of packets from source $u_{0,0}$ to destination $u_{N,0}$ proceeds via the barrage relay mechanism described in [4, 9–11]. Briefly, an M-slot time division multiple access (TDMA) format structure is assumed for some $M \geq 3$. If $M = 3$ in the CBR illustrated in Figure 1, then the slots in each frame may be labeled A, B, and C. Suppose that node $u_{0,0}$ transmits a packet on slot A of the first frame. This packet is then relayed by nodes $u_{1,0}$, $u_{1,1}$, and $u_{1,2}$ on slot B of the first frame, and again by nodes $u_{2,0}, \ldots, u_{2,3}$ on slot C. On slot A of the second frame, $u_{0,0}$ transmits a second packet while nodes $u_{3,0}, \ldots, u_{3,3}$ relay the first. Since 3 hops separate $u_{0,0}$ from the third relay cluster, this concurrent, pipelined transmission of different packets does not result in collisions. Continuing in this manner, a space-time BAC protocol must reserve the CBR for a total of

$$M(P-1) + N = 3P + 2 \tag{5}$$

time slots in order to transmit P packets over N hops. The average throughput of multihop transmission implied by (5) increases with P. Furthermore, the average overhead requirements per transmitted data packet decreases with increasing P. These considerations motivate the study of how large P can be made while still guaranteeing the availability of a given CBR as nodes move – i.e., the expected lifetime of a CBR.

IV. MULTIHOP STABILITY IN BRNS

The stability of a CBR is studied via the *end-to-end availability probability* metric (cf., [19]) in this paper. Given the initial node geometry specified in (2) and (4), nodes move according to some prescribed mobility model and the probability of the existence of an end-to-end path connecting $u_{0,0}$ to $u_{N,0}$ is studied. In the case of a traditional N-hop route, an end-to-end path exists at time t if and only if:

$$\|\mathbf{x}(i,0,t) - \mathbf{x}(i+1,0,t)\| \leq R, \quad \forall i \in [0, N-1]. \tag{6}$$

As discussed below, the interpretation of end-to-end availability for CBRs is somewhat more involved.

In order to provide focus for the study, a specific mobility model is considered: the random direction model (cf., [21]) in two dimensions with pauses (RD^{2}P). Under this model, nodes independently alternate between periods of movement (the *motion* phase) and rest (the *pause* phase). The time spent in a given motion (resp., pause) phase is exponentially distributed with mean $1/\mu$ (resp., $1/\lambda$). At the beginning of each move phase, a node selects a random velocity that is kept constant throughout that move phase. Specifically, a random velocity vector $\mathbf{v} = (v_x, v_y)$ is chosen where v_x and v_y are drawn independently from a continuous uniform distribution[2] with minimum $-V_{\max}$ and maximum $V_{\max}$.

Building on earlier work concerning the temporal evolution of node position under random mobility models [22], Carofiglio, *et al.* described an analytical framework for studying the availability of links and traditional routes under the RD^{2}P model in [15]. Briefly, assuming a node is at steady-state at time 0, then the variance (per-dimension) in the node spatial distribution at time t is:

$$\sigma^2(t) = \frac{2}{3}\frac{\lambda V_{\max}^2}{\mu^2(\mu+\lambda)}\left(\mu t + e^{-\mu t} - 1\right). \tag{7}$$

Carofiglio, *et al.* observed that the spatial distribution of the position of a given node $u_{i,j}$ over time can then be approximated as bivariate (white) Gaussian with mean $\mathbf{x}(i,j,0)$ and variance per-dimension defined by (7). Given the initial position of two nodes $u_{i,j}$ and $u_{i+1,k}$, an approximation of the probability of link availability at time t can then be determined by appropriately integrating over the product spatial distributions of the positions of the respective nodes (i.e., over the region satisfying $\|\mathbf{x}(i,j,t) - \mathbf{x}(i+1,k,t)\| < R$). Extending this single link case to an N-hop traditional route requires a $2(N+1)$-dimensional integration over an extremely complex region (i.e., that satisfying (6)). However, it was demonstrated in [15] that approximating this integration via a recursive formula that accounts only for the correlation between *adjacent* links is reasonable.

In Section V, results for a number of methods of measuring end-to-end availability in the Euclidean CBR model under RD^{2}P mobility are presented. These analysis- and simulation-based methods are described in turn here.

Independent Route Approximation: The most straightforward end-to-end availability measure considers the availability of all braided traditional routes comprising the CBR. Formally, let $j_1, \ldots, j_{N-1}$ be relay node indices such that $u_{0,0}, u_{1,j_1}, \ldots, u_{N-1,j_{N-1}}, u_{N,0}$ form a traditional N-hop route at time 0. The techniques of [15] provide the end-to-end availability probability of that route as a function of time:

$$A_{\text{route}}\left(t; j_1, \ldots, j_{N-1}\right). \tag{8}$$

There then exists an end-to-end path from $u_{0,0}$ to $u_{N,0}$ in the CBR provided *any* such route is available. Assuming independent availability probabilities across routes yields a simple analytical approximation to the CBR availability:

$$1 - \prod_{j_1,\ldots,j_{N-1}} \left(1 - A_{\text{route}}\left(t; j_1, \ldots, j_{N-1}\right)\right). \tag{9}$$

While the independence assumption ignores the correlation between between braided routes in a CBR, it provides a conceptual linkage to multipath routing: were the braided routes instead independent, (9) would be a good approximation.

Multiroute Diversity (MD): The correlation between braided routes in a CBR not modeled by (9) can be captured via a Monte Carlo simulation wherein nodes move according to the RD^{2}P model and an indicator function for whether *any* of the routes described above is available is measured as a function of time. Observe that under this model all of the braided routes comprising the CBR are explored simultaneously, but no cooperative diversity gain is captured.

---

[2] While the RD^{2}P model indeed supports generic velocity distributions [15], a uniform distribution is assailumed here to simplify the exposition.

Dynamic MD: The MD simulation does not model the topology agnostic behavior of multihop barrage relay transmission. The autonomous cooperation scheme employed in BRNs is such that nodes can seamlessly change their hop distance from the source on a per-packet basis. For example, after some period of time, it is conceivable that the nodes illustrated in Figure 2 have moved sufficiently so as to allow a path from $u_{0,0}$ to $u_{3,0}$ to go through $u_{1,0}$ and $u_{1,1}$ (so that no node in the initial $i = 2$ relay cluster is involved). Such a route is clearly not considered in the MD simulation. Modifying the simple simulation to measure not only the *initial* routes, but all possible paths from source to destination regardless of the initial topology yields an end-to-end availability measure that is more indicative of BRN operation.

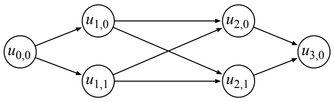

Fig. 2. Simple 3-hop Euclidean CBR at time 0.

Barrage Relay Simulation: Finally, the dynamic multiroute diversity simulation fails to capture the performance gains afforded by cooperative communications. For example, if two nodes in a CBR each at a distance $R+\delta$ from a third transmit the same packet simultaneously, then it is likely that successful reception will result, even though the respective pairwise links are not modeled. This can be formalized by assuming a standard path loss model for transmission on individual links wherein the power received at a given node P_R decays with distance from the transmitter d as $P_R \propto P_T d^{-\beta}$, where P_T is the transmitted power and β the path loss exponent. Setting P_T at all nodes to unity enables the range threshold R for radio reception in the CBR model to be translated into a threshold on received power. The barrage relay simulation uses a reception model such that if a set of nodes at distances $\{d_i\}$ from a given *potential* receiver transmit the same packet at the same time, then reception is successful if and only if:

$$\sum_i d_i^{-\beta} \geq R^{-\beta}. \qquad (10)$$

Equation (10) models fully coherent combining of the powers from the individual signals at the receiver.

V. NUMERICAL RESULTS AND DISCUSSION

Figures 3 and 4 compare the end-to-end path availability over time for an $L = 2$ CBR under the different measures described above to that of a traditional route for $M = 2$ and 10 hops, respectively. Note that when $L = 1$, the MD simulation considers only the single initial route. The parameters of the RD^{2}P model are set to $1/\lambda = 1/\mu = 10$ seconds (s) and $V_{\max} = 2$ m/s (which was cited in [15] as being representative of foot mobility), while the CBR geometry is determined by $s_x = 60$ m, $s_y = 20$ m, and $R = 100$ m.

In all cases, the analytical approximation for CBR availability (under the *independent routes* assumption) is overly optimistic when compared to the MD simulation. For sufficiently large values of t, however, even the dynamic MD simulation outperforms the independent route curve, indicating the gains afforded by autonomous cooperative communications in BRNs outstrip those of route diversity alone.

Focusing in on the region of interest to protocol designers (i.e., the high availability regime), the ratio of the times at which the CBR and traditional route availabilities reach 90% is approximately 1.67 and 2.22, for $M = 2$ and 10, respectively (under the dynamic MD measure). At 80% availability, these ratios increase to approximately 1.80 and 2.59 due to the differences in slope between the traditional route and CBR curves. Finally, under the $\beta = 2$ barrage relay simulation measure, the relative stability improvement for the CBR with respect to traditional routing is 2.15 and 3.86 for $M = 2$ and 10 hops, respectively, at 90% availability.

Figure 5 studies a 5-hop scenario that is more representative of tactical operations in an urban environment. The initial CBR geometry is set to $s_x = s_y = 500$ m to model city blocks. The mobility parameters are $1/\mu = 40$ s, $1/\lambda = 10$ s, and $V_{\max} = 15$ m/s to model vehicle mobility with pausing at intersections. The initial range of the radio is set to 750 m. Only the barrage relay simulation metric with $\beta = 4$ is shown for CBRs. The multihop transmission stability improvements afforded by the barrage relay mechanism is illustrated in Figure 5. For example, the traditional route reaches 90% availability probability at approximately 10 seconds, while the $L = 2$ and $L = 3$ CBRs reach this value at approximately 18 and 21 seconds, respectively.

VI. CONCLUSION

Unlike traditional link-based approaches to MANET design, barrage relay networks (BRNs) utilize an autonomous cooperative communication scheme that affords a radically different building block for protocol design: robust, low-latency broadcast. BRNs employ controlled barrage regions (CBRs) to contain unicast and localized multicast flows spatially, while barrage access (BAC) protocols are used to coordinate simultaneous flows in space and time. Using a simple model for CBRs, this work explored the gains in stability of multihop transmission that can be achieved in barrage relay networks.

In order to provide a meaningful distillation of the benefits afforded by autonomous cooperation, fairly simple models were employed in this work. Future work will extend the study of stability to incorporate, for example, richer node topologies, more realistic RF propagation effects (e.g., explicit models for path-loss and shadowing), losses due to non-ideal cooperative communication, and one-to-many traffic (i.e., multicast). Furthermore, while the stability of multihop transmission in BRNs indeed depends on the position of the nodes that are *interior* to a CBR, the position of the buffer and exterior nodes also influences path lifetime. Future work will consider more sophisticated measures of CBR stability so as to better inform space-time BAC protocol design.

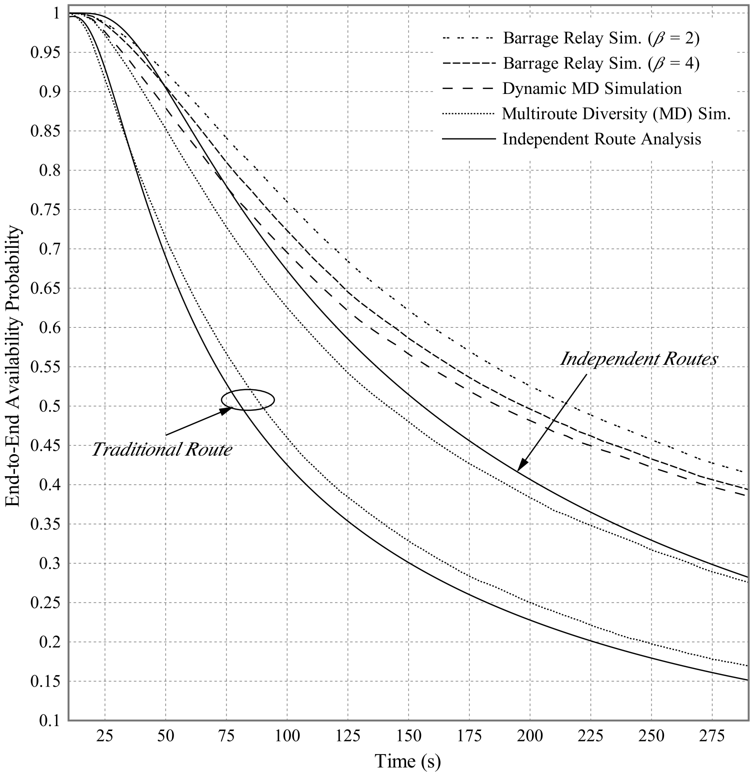

Fig. 3. End-to-end availability in an $L = 2$ CBR for $M = 2$ hops with $1/\lambda = 1/\mu = 10$ seconds (s), $V_{\max} = 2$ m/s, $s_x = 60$ m, $s_y = 20$ m, and $R = 100$ m.

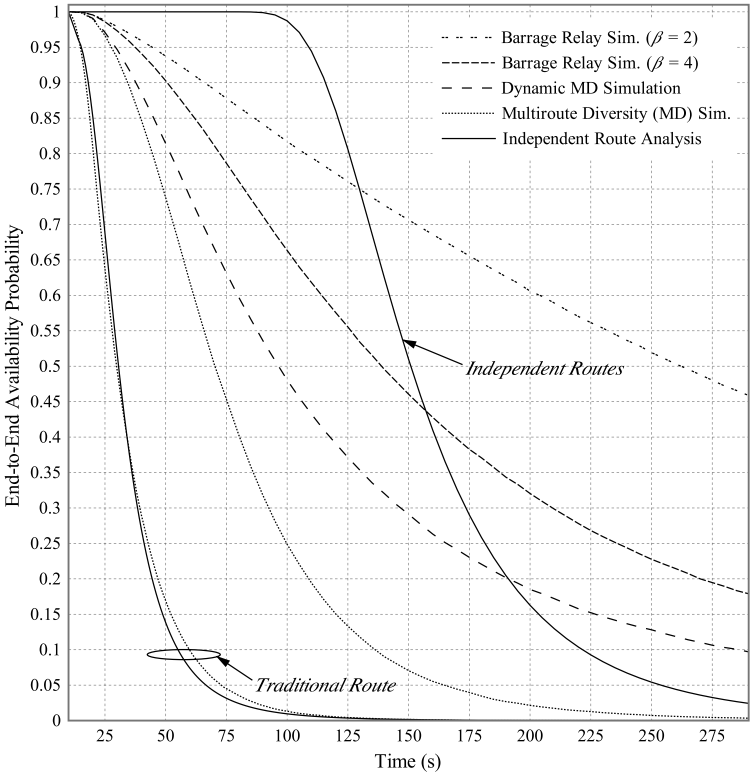

Fig. 4. End-to-end availability in an $L = 2$ CBR for $M = 10$ hops with $1/\lambda = 1/\mu = 10$ seconds (s), $V_{\max} = 2$ m/s, $s_x = 60$ m, $s_y = 20$ m, and $R = 100$ m.

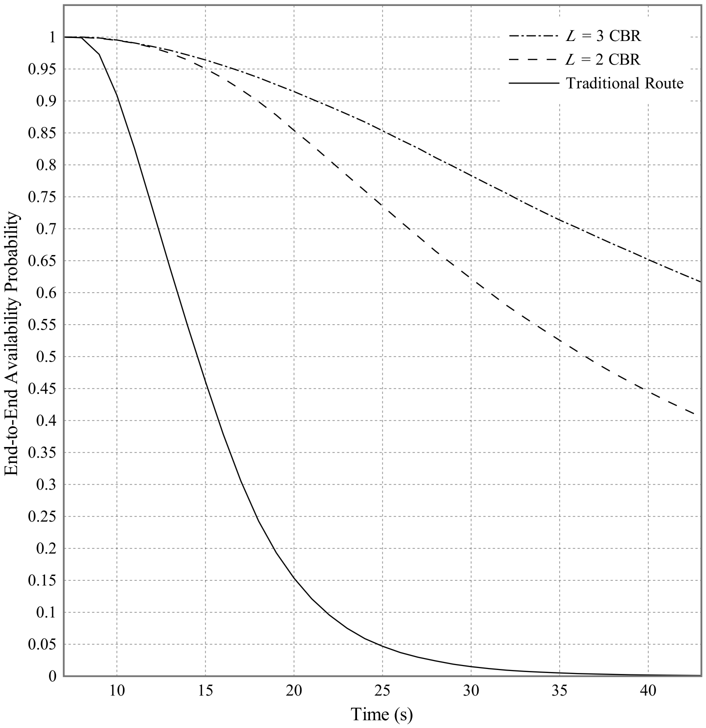

Fig. 5. End-to-end availability probability over 5 hops when $1/\lambda = 40$ s, $1/\mu = 10$ s, $V_{\max} = 15$ m/s, $s_x = s_y = 500$ m, and $R = 750$ m. CBR curves measure the barrage relay simulation metric with $\beta = 4$.

REFERENCES

[1] J. K. Burbank, P. F. Chimento, B. K. Haberman, and W. T. Kasch, "Key challenges of military tactical networking and the elusive promise of MANET technology," *IEEE Comms. Mag.*, pp. 39–45, November 2006.

[2] J. Andrews, N. Jindal, M. Haenggi, R. Berry, S. Jafar, D. Guo, S. Shakkottai, R. Heath, M. Neely, S. Weber, and A. Yener, "Rethinking information theory for mobile ad hoc networks," *IEEE Comms. Mag.*, vol. 46, no. 12, pp. 94–101, December 2008.

[3] R. Ramanathan, "Challenges: A radically new architecture for next generation mobile ad hoc networks," in *Proc. ACM/IEEE Int'l Conf. Mobile Comp. and Networking*, Cologne, Germany, August 2005, pp. 132–139.

[4] A. Blair, T. Brown, K. M. Chugg, and M. J. Johnson, "Tactical mobile mesh network system design," in *Proc. IEEE Military Comm. Conf.*, Orlando, FL, October 2007.

[5] D. K. Lee and K. M. Chugg, "Pragmatic cooperative diversity communications," in *Proc. IEEE Military Comm. Conf.*, Washington, DC, October 2006.

[6] Y. J. Chang, M. A. Ingram, and R. S. Frazier, "Cluster transmission time synchronization for cooperative transmission using software defined radio," in *Proc. International Conf. Comms.*, May 2010.

[7] A. Scaglione and Y.-W. Hong, "Opportunistic large arrays: Cooperative transmission in wireless multihop ad hoc networks to reach far distances," *IEEE Trans. Signal Proc.*, vol. 51, no. 8, pp. 2082–2092, 2003.

[8] L. Thanayankizil, A. Kailas, and M. A. Ingram, "Routing for wireless sensor networks with an opportunistic large array physical layer," *Ad Hoc & Sensor Wireless Networks*, vol. 8, no. 1-2, pp. 79–117, 2009.

[9] T. R. Halford and K. M. Chugg, "Barrage relay networks," in *Proc. Information Theory and Applications Workshop (UCSD)*, La Jolla, CA, February 2010, (invited).

[10] A. Blair, T. Brown, K. M. Chugg, T. R. Halford, and M. Johnson, "Barrage relay networks for cooperative routing in tactical MANETs," in *Proc. IEEE Military Comm. Conf.*, San Diego, CA, November 2008.

[11] T. R. Halford, K. M. Chugg, and A. Polydoros, "Barrage relay networks: System and protocol design," in *Proc. IEEE Int'l Symp. on Personal, Indoor, and Mobile Radio Comms.*, Istanbul, Turkey, September 2010, (invited).

[12] L. Thanayankizil, A. Kailas, and M. A. Ingram, "Opportunistic large array concentric routing algorithm for upstream routing in wireless sensor networks," *Ad Hoc & Sensor Wireless Networks*, January 2011.

[13] J. Yackoski, L. Zhang, C.-C. Shen, L. Cimini, and B. Gui, "Networking with cooperative communications: Holistic design and realistic evaluation," *IEEE Comms. Mag.*, pp. 113–119, August 2009.

[14] F. Bai, N. Sadagopan, B. Krishnamachari, and A. Helmy, "Modeling path duration distributions in MANETs and their impact on reactive routing protocols," *IEEE J. Select. Areas Commun.*, vol. 22, no. 7, pp. 1357–1373, September 2004.

[15] G. Carofiglio, C. Chiasserini, M. Garetto, and E. Leonardi, "Route stability in MANETs under the random direction model," *IEEE Trans. Mobile Comp.*, vol. 8, no. 9, pp. 1167–1179, September 2009.

[16] Y. C. Tseng, Y. F. Li, and Y. C. Chang, "On route lifetime in multihop mobile ad hoc networks," *IEEE Trans. Mobile Comp.*, vol. 2, no. 4, pp. 366–376, Oct. -Nov. 2003.

[17] S. Cho and J. P. Hayes, "Impact of mobility on connection stability in ad hoc networks," in *Proc. IEEE Wireless Comm. and Networking Conf.*, New Orleans, LA, March 2005, pp. 1650–1656.

[18] Y. Han, R. J. La, and H. Zhang, "Path selection in mobile ad-hoc networks and distribution of path duration," in *Proc. IEEE Conf. Computer Comms.*, Barcelona, Spain, April 2006.

[19] A. B. McDonald and T. F. Znati, "A mobility-based framework for adaptive clustering in wireless ad hoc networks," *IEEE J. Select. Areas Commun.*, vol. 17, no. 8, pp. 1466–1487, August 1999.

[20] B. Gui, L. Dai, and L. J. Cimini, Jr., "Routing strategies in multihop cooperative networks," *IEEE Trans. Wireless Communications*, vol. 8, no. 2, pp. 843–855, February 2009.

[21] P. Nain, D. Towsley, B. Liu, and Z. Liu, "Properties of random direction model," in *Proc. IEEE Conf. Computer Comms.*, Miami, FL, March 2005.

[22] M. Garetto and E. Leonardi, "Analysis of random mobility models partial differential equations," *IEEE Trans. Mobile Comp.*, vol. 6, no. 11, pp. 1204–1217, November 2007.