RelayCast: Scalable Multicast Routing in Delay Tolerant Coalition Networks

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***Abstract*— Mobile wireless networks with intermittent connectivity, often called Delay/Disruption Tolerant Networks (DTNs), have recently received a lot of attention because of their applicability in various applications, including multicasting. To overcome intermittent connectivity, DTN routing protocols utilize mobility-assist routing by letting the nodes carry and forward the data. In this paper, we study the scalability of DTN multicast routing. As Gupta and Kumar showed that unicast routing is not scalable, recent reports on multicast routing also showed that the use of a multicast tree results in a poor scaling behavior. However, Grossglauser and Tse showed that in delay tolerant applications, the unicast routing overhead can be relaxed using the two-hop relay routing where a source forwards packets to relay nodes and the relay nodes in turn deliver packets to the destination via *mobility*, thus achieving a perfect scaling behavior of $\Theta(1)$. Inspired by this result, we seek to improve the throughput bound of wireless multicast in a delay tolerant setting using mobility-assist routing. In this paper, we propose RelayCast, a routing scheme that extends the two-hop relay algorithm in the multicast scenario. Given that there are n_s sources each of which is associated with n_d random destinations, our results show that RelayCast can achieve the throughput upper bound of $\Theta(\min(1, \frac{n}{n_s n_d}))$. RelayCast is then extended to delay tolerant coalition networks where multiple domains exist, and nodes communicate with other nodes in different domains via gateways due to security concerns and policy reasons. We find the throughput and delay scaling properties of inter-domain RelayCast and report that there is an optimal inter-domain networking configuration that achieves the same scaling behavior as single domain multicast.**

I. Introduction

Protocols that can withstand intermittent connectivity caused by mobility and low node density, often called Delay Tolerant Network (DTN) Protocols, are becoming increasingly important in disruptive Mobile Ad Hoc Network (MANET) scenarios such as inter-vehicle communications, *pocket switched* personal networking among pedestrians, tactical communications in the battlefield and disaster recovery operations. In those scenarios, there has been a growing interest in DTN multicast protocols that enable distribution of situational data to multiple receivers, such as real-time traffic information reporting, diffusion of participatory sensor data, or software patch over multiple devices, in spite of the disruptive nature and intermittent connectivity of tactical MANETs.

Routing in a DTN is challenging because conventional MANET protocols can withstand only very short term path interruptions; they systematically fail when the network stays disconnected for a prolonged time. In favorable motion conditions, DTN routing protocols can overcome such intermittent connectivity by exploiting a *mobility-assist routing* strategy: nodes receive packets, hold them in storage, and wait for opportunities to transfer stored packets to remote nodes. If the characteristics of a network (e.g., node mobility and traffic pattern) are known in advance, we can design *predictive* DTN unicast/multicast routing algorithms that efficiently route packets over a *time-varying connectivity* graph [11], [27], [26]. In practice, however, only limited information is available about network connectivity as a function of time. In view of this, researchers have investigated meaningful mobility statistics that allow one to make a better routing decision such as encounter history [19]. In addition, redundancy and coding techniques have been used to further improve reliability and reduce latency of DTN routing [24].

Scalability is a very important metric when designing a routing protocol both in MANETs and in DTNs. For unicast, the scaling behavior is well understood. In their seminal work, Gupta and Kumar [7] showed that the scalability of *wireless multi-hop routing* is limited; in fact, in a wireless network with n static nodes, each engaged in a data transfer to a random destination the per-node throughput decays as $\Theta(1/\sqrt{n \log n})$.[1] Realizing that the increasing hop length of a path is the key limiting factor when the number of nodes increases, Grossglauser and Tse [6] showed that under random mobility assumptions, a two-hop relay routing strategy, a mobility-assisted routing protocol that exploits mobility and carry-forward to reduce number of hops can achieve $\Theta(1)$ throughput per node, thus exhibiting a perfect scaling behavior. However, the throughput improvement comes at the cost of increased delay. This result has been followed by a flurry of research activities that tried to characterize the delay/capacity relationship as a function of node mobility [4], [20], [23]. Due to the increased end-to-end delay, the need to buffer the

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[1]Recall that (i) $f(n) = O(g(n))$ means that $\exists c$ and $\exists N$ such that $f(n) \leq cg(n)$ for $n > N$ (i.e., asymptotic upper bound); (ii) $f(n) = \Omega(g(n))$ means that $\exists c$ and $\exists N$ such that $f(n) \geq cg(n)$ for $n > N$ (i.e., asymptotic lower bound); (iii) $f(n) = \Theta(g(n))$ means that $f(n) \in O(g(n)) \cap \Omega(g(n))$ (i.e., asymptotic tight bound); (iv) $f(n) = o(g(n))$ means that $\lim_{n\to\infty} f(n)/g(n) = 0$ (i.e., asymptotic insignificance); and (v) $f(n) = \omega(g(n))$ means $\lim_{n\to\infty} f(n)/g(n) = \infty$ (i.e., asymptotic dominance).

packets until delivery to destination has prompted the study of the impact of finite node buffers on performance [8].

The scaling throughput properties in static wireless networks were recently generalized also to multicast and broadcast [22], [18], [25]. Assuming that there are n_s sources each of which is associated with n_d random destinations and that the packets are delivered on multicast trees, the throughput per multicast source is $\Theta(\frac{\sqrt{n}}{n_s\sqrt{\log n}}\frac{1}{\sqrt{n_d}})$. The penalty of using a multicast tree is high; namely, it corresponds to a factor of $\sqrt{n_d}$ throughput decrement. When the number of multicast receivers is above a threshold value of $\Omega(n/\log n)$, multicasting scales as network wide broadcasting. Thus, its throughput becomes $\Theta(1/n_s)$ [13]. This follows from the fact that above the threshold the multicast protocol can fully benefit from the wireless broadcasting effects [13].

Our goal is to improve the throughput bound of wireless multicast using a mobility-assist routing algorithm. Namely, we propose RelayCast, a routing scheme that extends the Grossglauser and Tse's two-hop relay strategy by requiring that a relay node be responsible for delivering packets directly to each multicast receiver. This extended protocol is analyzed under the assumption that inter-contact time of an arbitrary pair of nodes follows an exponential distribution with rate λ. We compare throughput and delay properties of RelayCast with those of conventional multicast. We then extend our single domain DTN multicast analysis to multi-coalition environments where a node in one domain communicates with other nodes in different domains via its own gateways that are capable of communicating with other gateways in different domains [2]. In our scenario, inter-domain traffic is delivered over a virtual mobile DTN backbone of gateways using RelayCast. In favorable mobility conditions, RelayCast offers two main benefits: it improves throughput scalability with increasing number of nodes, and; it provides reliable delivery even in DTN scenarios with intermittent connectivity.

The following is the preview of the key contributions of this paper.

- We find the throughput upper bound of DTN multicast routing and propose RelayCast, a two-hop relay based DTN multicast routing protocol. RelayCast achieves the upper bound, namely throughput = $\Theta(n\lambda)$ for the case $n_sn_d = O(n)$ and $\Theta(\frac{n^2\lambda}{n_sn_d})$ for the case $n_sn_d = \omega(n)$, or simply $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_sn_d}))$. The delay of RelayCast is $\Theta(\max(\frac{\log n_d}{\lambda}, \frac{n_sn_d}{n}\frac{\log n_d}{\lambda}))$. For a DTN with $\lambda = \Theta(1/n)$, the throughput and delay of RelayCast are $\Theta(\min(1, \frac{n}{n_sn_d}))$ and $\Theta(\max(n\log n_d, n_sn_d\log n_d))$ respectively. We compare a throughput/delay of RelayCast with that of conventional multicast routing [22], [18].
- Given that there are k domains each of which has g members and m mobile gateways, inter-domain traffic patterns are defined as: each domain has g_s sources each of which chooses d random domains and there are g_d random destinations per domain (i.e., $n_s = g_sk$ sources, and $n_d = g_dk$ destinations per source). We report the optimal inter-domain networking configuration that achieves the same scaling behavior as single domain multicast; namely, the number of gateways is $\Theta(gk)$ and radio range is $\Theta(1/\sqrt{gk})$. In general, when the number of gateways per domain scales as $m = O(gk)$, the throughput of inter-domain RelayCast per multicast source is $\Theta(\min(m\lambda, \frac{m^2\lambda}{n_sn_d}))$ and the average delay of inter-domain RelayCast is $\Theta(\max(\frac{\log n_d}{m\lambda} + \frac{\log g_d}{\lambda}, \frac{n_sd}{k}\frac{\log d}{m\lambda} + \frac{n_sn_d}{kg}\frac{\log g_d}{\lambda}))$.

This paper significantly extends our earlier work on DTN multicast routing [16], by considering delay tolerant coalition networks. The rest of the paper is organized as follows. In Section II, we present the network model. In Section III, we compute the throughput and delay of RelayCast and compare it with conventional multicast. In Section IV, we present the throughput and delay of inter-domain RelayCast in delay tolerant coalition networks. Finally, we present the conclusion in Section VI.

II. NETWORK MODEL

In this section, we review communication model and traffic patterns, define throughput and delay, and introduce a simple mobility model all of which will lead to represent a DTN in general.

Communication Model and Traffic Patterns: We use the protocol model to abstract interference between transmissions [7]. Suppose that node i transmits to node j. Node j receives the transmission successfully if every other node that transmits simultaneously is at a distance of at least $(1+\Delta)r(n)$ from j where Δ is some positive number and $r(n)$ is the radio range. In the network, n_s nodes are randomly selected as multicast sources and each of these sources is associated with n_d multicast receivers, thus making a total of n_sn_d source-destination pairs in the system. In the coalition environment, we assume that there are k domains each of which has g members and m gateways that have the same mobility pattern as members. Each domain has g_s sources each of which chooses d random domains and there are g_d random destinations per domain (i.e., $n_s = g_sk$ sources, and $n_d = g_dk$ destinations per source).

Definition of Throughput and Delay: For a given scheduling algorithm π, a throughput $\gamma > 0$ is said to be feasible/achievable if every node can send at a rate of γ bits per seconds to its chosen destination. Let $T^\pi(n)$ denote the maximum feasible per-node throughput under scheduling algorithm π. The delay of a packet in a network is the time for a packet to reach the destination after it leaves the source. Let $D^\pi(n)$ denote the average packet delay for a network with n nodes under scheduling algorithm π. Note that a scheduling algorithm is $stable$ if the rate $T^\pi(n)$ is satisfied by all users such that one's queue does not grow infinity; i.e., $D^\pi(n)$ is bounded.

Modeling Mobility: DTN protocols leverage node mobility as a means of data delivery, i.e., *carry-and-forward* and thus, the performance mainly depends on the encounter pattern. In this paper, we describe the mobility model using the pairwise inter-contact time, i.e., the time interval between two successive encounters of a pair of nodes. For analysis, we consider a class of random mobility models where each node independently makes decision on its movement, e.g., each node independently chooses a random *direction* (Random Direction). Groenevelt et al. showed that the inter-contact stochastic process of these mobility models can be captured using an independent homogeneous Poisson process with a meeting rate λ [5]. In other words, inter-contact time distributions of any pairs are exponentially distributed with rate λ. This concept can be generalized using heterogeneous meeting rates with λ_{ij} for $i, j = 1, \cdots, n$. We present the following theorem from [5] to provide a basis for estimating the λ value for different mobility models.

Theorem 1: Given that two nodes move randomly in a $1{\times}1$ unit area ($1{\times}1m^2$) with the average speed v, if the transmission range $r \ll 1$ and the position of a node at time $t + \Delta$ is independent of its position at time t for small Δ, then the inter-contact time between two nodes is exponentially distributed with parameter $\lambda = \alpha r v$ where α is a mobility model dependent constant.

DTN Model: We model an arbitrary DTN in a unit area of ($1{\times}1$) using the pairwise inter-contact rate $\lambda = \Theta(rv)$ where r is radio range and v is speed. We note that it is possible to map any delay tolerant network to a wireless network in a unit area by appropriately scaling the radio range and average speed. In our study, we consider two cases: (a) when λ is given and fixed and (b) when λ scales according to r and v.

When λ is given, Theorem 1 shows that the contact rate is independent of the number of nodes. As shown later, this allows us to predict the performance of DTN as a function of the number of nodes in the network. However, increasing the number of nodes over a certain limit will reduce the effective capacity due to wireless interference. Also, the node increase will eventually change the connectivity of the network from a DTN state to a fully connected state.[2] Thus, in order for the network to remain in a delay tolerant state and maximize the throughput, the number of nodes should be bounded. We can identify this bound as follows. Assume that the nodes are uniformly distributed on a unit square. The radio range determines the number of simultaneous transmissions, and thus the network-wide aggregate throughput. Since the number of transmissions is approximately the same as the total number of non-overlapping circles with radius r that fills $1{\times}1$ area, the network-wide aggregate throughput $\mathcal{T}$ is bounded by $\Theta(1/r^2)$. Therefore, the aggregate throughput can be expressed in terms of λ: i.e., $\mathcal{T} \leq \Theta(1/r^2) = \Theta(1/\lambda)$. For a DTN with the radio range r, the upper bound of the per-node throughput can be maximized, when the number of nodes is in the same order as the aggregate throughput, i.e., $\Theta(1/r^2) = \Theta(n)$ and thus, $r = \Theta(1/\sqrt{n})$. In this paper, we analyze more general scaling behavior with the radio range of $O(1/\sqrt{n})$.

On the other hand, if λ scales with the node speed and the radio range (which are functions of the number of nodes), we have $\lambda = \Theta(rv)$. In this case, we scale the node speed based on the radio range such that the contact duration of two nodes is constant as in [4], [23]. Unless otherwise mentioned, we assume that the radio range is $r = O(1/\sqrt{n})$, and the speed $v = O(1/\sqrt{n})$ (thus, $\lambda = O(1/n)$). We then can easily show that the node density within one's radio range is bounded by $\Theta(1)$. Note that Grossglauser and Tse showed that when we scale the radio range as $r = \Theta(1/\sqrt{n})$, a class of DTNs with $\lambda = \Theta(1/n)$, we can achieve the throughput of $\Theta(1)$ using the two-hop relay "unicast" routing protocol. We assume that the network area is partitioned into C non-overlapping cells with size $s_n \times s_n$ where we have $s_n = 1/\sqrt{n}$ to have the node density per cell $O(1)$.

In a coalition network, the total number of nodes is $n = gk + mk$ where gk is the number of member nodes and mk is the number of gateways. Since gateways will not generate traffic, but simply relay packets, we assume that the total number of nodes is $n = gk$. In Section IV, we will show that the above arguments still hold under this assumption, thus covering from single domain to multi-domain scenarios.

In this paper, we slightly abuse the asymptotic notation for simplicity. For instance, when we denote that the throughput per multicast source of RelayCast is $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$, this statement is always true only when λ scales with n. However, when λ is fixed, it is true only when $n \leq 1/\lambda$. This conditional rule applies to all asymptotic notations in this paper.

III. Throughput and Delay of DTN Multicast Routing

We derive the upper bound on the throughput of DTN multicast routing. We then proceed to present RelayCast, a 2-hop relay-based DTN multicast routing protocol. We analyze the throughput and delay of RelayCast and show that RelayCast achieves the throughput upper bound. Finally, we compare the throughput and delay of RelayCast with those of conventional wireless multi-hop multicast.

A. Multicast Throughput Upper Bound in DTNs

The below theorem shows the throughput upper bound of DTN multicast routing where we have n_s multicast sources and n_d multicast receivers.

Theorem 2: The throughput upper bound of DTN multicast is $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$.

Proof: We use a derivation that is similar to that in [7]. In the network, n_s nodes are randomly selected as multicast sources and each of these sources is associated with n_d multicast receivers. Consider a bit b originating at a source. In our network setting, there are a constant number of nodes in each cell.[3] The chance of transmission is equally shared by c interfering nodes under the protocol model [14]. Thus, the minimum number of transmissions required to deliver a bit b to n_d destinations is $\Theta(n_d)$, even with broadcasting effects. Under any scheduling algorithm, we need $H(b) = \Omega(n_d)$ transmissions to deliver a bit b. For a given time slot, node i encounters a random node with probability $n\lambda$. Considering the interference, the node can transmit with probability $n\lambda/c$. This transmission opportunity is denoted as an indicator random variable S_i. The total number of simultaneous transmissions is given as $S = \sum_{j=1}^{n} S_j$. Its expectation is $\mathbb{E}[S] = n\mathbb{E}[S_i] = n^2\lambda/c$. Each source generates bits with rate $T(n)$. For a given period τ, the total number of bits generated in the network is $n_s T(n)\tau$. The total number of hops required to support these bits during time interval τ is $n_s T(n)\tau H(b)$. This is

[2] A network is connected with high probability if its transmission range is set to $\Theta(\sqrt{\log n/n})$ [7]. Thus, for a given transmission range, we can find the number of nodes that make the network connected.

[3] For a given contact, the number of interfering nodes is given as $\Theta(n/r^2) = \Theta(1)$

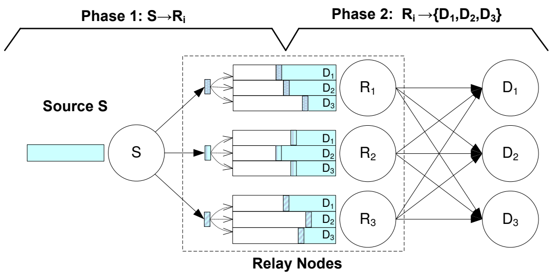

Fig. 1. RelayCast: DTN multicast based on 2-hop relay. Relay node R_i delivers a packet to all the multicast receivers. Note that receiver D_i can also be a relay node.

bounded by the total number of feasible transmissions in the network during time interval τ that is τS. Hence, we have $n_s T(n)\tau H(b) \leq \tau S$. By substituting $H(b)$ and S, we have $T(n) \leq \frac{n^2\lambda}{cn_s n_d}$ and thus, $T(n) = O(\frac{n^2\lambda}{n_s n_d})$. The DTN multicast throughput is bounded by its unicast throughput, especially when $n_s n_d \leq n$. Since the unicast throughput is a special case of multicast (i.e., $n_s = n$ and $n_d = 1$), the throughput is given as $O(n\lambda)$. Thus, we have $T(n) = O(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$. ■

To contrast the multicast with the unicast, let us take the number of source destination pairs to be the same in both case; i.e., $n_s n_d = n$. We take $n_d = n^{1-\epsilon}$ and $n_s = n^\epsilon$ where $0 \leq \epsilon \leq 1$. As long as $n_s n_d = n$ is satisfied, the throughput is essentially the same as unicast throughput, i.e., $\Theta(n\lambda)$. As $\epsilon \to 1$ the multicast is the same as unicast whereas $\epsilon \to 0$, it becomes a delay tolerant broadcasting.

B. RelayCast: 2-Hop Relay-based DTN Multicast Routing

We present a DTN multicast protocol called RelayCast whose operations are based on 2-hop relay DTN routing. For each time slot a cell becomes active if it contains at least a pair of nodes that are within the radio range of each other. In each active cell, we randomly select a pair of nodes and perform either of the following operations. In Phase 1 (Relay), the multicast source sends a new packet to a relay node. The relay node could be one of the multicast receivers. In Phase 2 (Delivery), if there is a multicast receiver that has not received a packet yet, a relay node delivers the packet. The overall procedure is illustrated in Figure 1. Note that a relay node has a separate queue for each multicast destination and replicates an incoming packet to each of the relay queues (i.e., n_d replicas).

Theorem 3: The throughput of RelayCast per multicast source is $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$.

Proof: Consider a multicast stream: source s and a set of destinations d_i for $i = 1, \cdots, n_d$. The throughput per source is $\Theta(n\lambda)$ if each destination d_i can achieve $\Theta(n\lambda)$, which we will show in the following. During a small time interval Δt, a random node j encounters the destination d_i with probability $\lambda\Delta t + o(\Delta t)$. In our network setting, there are a constant number (c) of nodes in each cell under the protocol model. Since the chance of transmission is equally shared by c interfering nodes, node j can successfully deliver a packet with the probability $\lambda\Delta t/c$. Recall that we have n_s sources each of which is associated with n_d destinations chosen randomly. The probability that a node chooses a random node as a destination is $p = n_d/n$. We want to know how many sources out of $n_s - 1$ will choose node d_i as a destination as well. The probability that ℓ sources choose a certain node as a destination is given as $\binom{n_s-1}{\ell}p^\ell(1-p)^{n_s-1-\ell}$, and on average there will be $\frac{(n_s-1)n_d}{n}$ sources. Let n_x denote the total number of sources competing for the limited resources including the source s. Then, we have $n_x = \frac{(n_s-1)n_d}{n} + 1$. When $n_s n_d = O(n)$, we have $n_x = \Theta(1)$; and when $n_s n_d = \omega(n)$, we have $n_x = \omega(1)$. Assuming that each source equally shares the overall transmission opportunities, this packet belongs to a source i with probability $1/n_x$. Here, we are interested in the event that the receiver d_i is scheduled to receive node i's packet at time t. Let an indicator random variable $M_i(\Delta t, n)$ denote this event. Since d_i can meet any of the relay nodes, we have:

$$Pr\{M_i(\Delta t, n) = 1\} \tag{1}$$

$$= \sum_{j=1, j\neq d_i}^{n} Pr\{\text{node } j \text{ delivers a packet during } \Delta t\} \tag{2}$$

$$\approx \frac{(n-1)\lambda\Delta t}{n_x c} \tag{3}$$

Thus, the throughput is given as:

$$T_{d_i}(n) = \frac{\mathbb{E}[M_i(\Delta t, n)]}{\Delta t} = \frac{(n-1)\lambda\Delta t}{n_x c}\frac{1}{\Delta t} \tag{4}$$

$$= \begin{cases} \Theta(n\lambda), & n_s n_d = O(n) \\ \Theta(\frac{n^2\lambda}{n_s n_d}), & n_s n_d = \omega(n) \end{cases} \tag{5}$$

The above cases can be simplified as $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$. ■

When the radio range is scaled appropriately such that $r = \Theta(1/\sqrt{n})$, (and therefore $\lambda = \Theta(1/n)$), the throughput per source is given as $\Theta(\min(1, \frac{n}{n_s n_d}))$. If the number of source-destination pairs is less than $n_s n_d = O(n)$, the throughput per multicast source is $\Theta(1)$ as in two-hop relay where there are n source destination communication pairs.

Theorem 4: The average delay of RelayCast is $\Theta(\max(\frac{\log n_d}{\lambda}, \frac{n_s n_d}{n}\frac{\log n_d}{\lambda}))$.

Proof: We find the average delay to deliver a packet to all n_d receivers. The relay node encounters the first receiver with rate $n_d\lambda$. Since there are on average n_x competing sources to the receiver, the average rate is reduced to $n_d\lambda/n_x$. Recall that $n_x = \frac{(n_s-1)n_d}{n} + 1$. When $n_s n_d = O(n)$, we have $n_x = \Theta(1)$; and when $n_s n_d = \omega(n)$, we have $n_x = \omega(1)$. The average delay of the first encounter is $\frac{n_x}{n_d\lambda}$. After this, there are $n_d - 1$ receivers waiting for the packet. By the memoryless property, we can simply treat them as if they just begin. Thus, the average time to meet the second receiver is simply $\frac{n_x}{(n_d-1)\lambda}$. By repeating this process, we have:

$$E[D] = \frac{n_x}{n_d\lambda} + \frac{n_x}{(n_d-1)\lambda} + \cdots + \frac{n_x}{\lambda} \tag{6}$$

$$= \frac{n_x}{\lambda}\sum_{i=1}^{n_d}\frac{1}{i} \tag{7}$$

$$= \frac{n_x}{\lambda}\left(\log n_d + \gamma + O\left(\frac{1}{n_d}\right)\right) \tag{8}$$

$$= \Theta(\frac{n_x \log n_d}{\lambda}) \tag{9}$$

where γ is Euler's constant. By replacing n_x, we have $D(n) = \Theta(\max(\frac{\log n_d}{\lambda}, \frac{n_s n_d}{n}\frac{\log n_d}{\lambda}))$. Although the packet buffering at

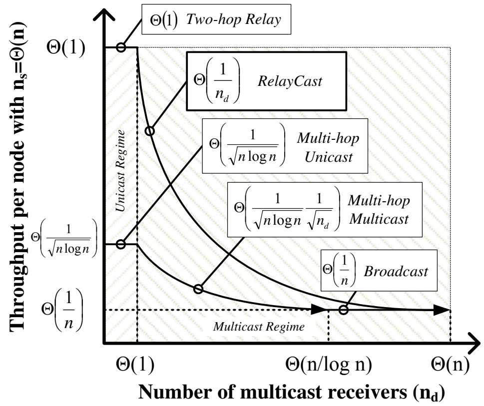

Fig. 2. Throughput scaling result comparison

each node will incur additional delay in the end-to-end delay computation, the queueing delay only increases the average delay of each step with a constant factor [17]. Thus, the order of the average delay does not change. ■

C. Comparison with Multi-hop Wireless Multicast Routing

We compare the throughput/delay scaling of conventional multi-hop wireless multicast routing with that of RelayCast. For this we first review the throughput scaling of multi-hop wireless multicast routing where the radio range scales with $\Theta(\sqrt{\log n/n})$. The following theorem by Li et al. [18] shows the throughput of multi-hop wireless multicast routing. Similar results have been reported in [22].

Theorem 5: The throughput per multicast source is upper bounded by $\Theta\left(\frac{\sqrt{n}}{n_s\sqrt{\log n}}\frac{1}{\sqrt{n_d}}\right)$ when $n_d = O(\frac{n}{\log n})$ and by $\Theta(\frac{1}{n_s})$ when $n_d = \Omega(\frac{n}{\log n})$.

As shown in Theorem 2, the key factor of determining the throughput upper bound is the number of transmissions (or hop count) $H(b)$ to deliver a bit. Du et al. [3] showed that the Euclidean distance of a minimum spanning tree covering n_d nodes is $\Theta(\sqrt{n_d})$, and thus, we have $H(b) = \Theta(\sqrt{n_d}/r(n))$. Interestingly, if the number of receivers is greater than $\Omega(\frac{n}{\log n})$, multicast becomes a network-wide broadcast whose throughput per node is $\Theta(1/n_s)$ [13], [25]. In Figure 2, we summarize the throughput per node with $n_s = \Theta(n)$ as a function of the number of multicast receivers. Unlike conventional multi-hop wireless multicast routing, the throughput per node of RelayCast is $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$; in particular, when the radio range scales as $\Theta(\min(1, \frac{n}{n_s n_d}))$, i.e., $\lambda = \Theta(1/n)$. Since the number of sources is $n_s = \Theta(n)$, the throughput per node of RelayCast is $\Theta(1/n_d)$. The throughput per node of conventional multi-hop multicast is $\Theta\left(\frac{1}{\sqrt{n\log n}}\frac{1}{\sqrt{n_d}}\right)$ when $n_d = o(\frac{n}{\log n})$. If the number of receivers is $n_d = \Omega(\frac{n}{\log n})$, the throughput per node is $\Theta(1/n)$. The throughput per source of RelayCast is better than that of conventional multi-hop wireless multicast routing. When the number of receivers is $n_d = \Theta(n)$, the throughput per node of wireless broadcast is the same as that of RelayCast. Note that readers can also find the delay comparison in the extended version of this paper [17].

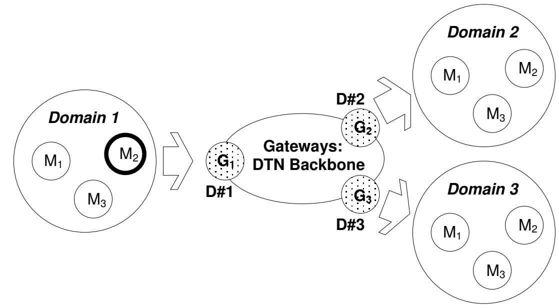

Fig. 3. Delay tolerant coalition network example: number of domains $k = 3$, number of nodes per domain $g = 3$, and number of gateways $m = 1$. M_2 in domain 1 sends data stream to all the nodes in domain 2 and domain 3 ($g_s = 1$, $d = 2$, and $g_d = 3$).

IV. Throughput and Delay of Inter-domain DTN Multicast Routing

In this section, we present an inter-domain DTN routing model and extend RelayCast to the inter-domain scenario. We find the optimum configuration such as the number of gateways and radio range that maximizes the throughput. Finally, we report the throughput and delay scalability of inter-domain RelayCast.

A. Inter-domain DTN Routing

We assume that there are k domains each of which has g members and m mobile gateways. Due to heterogeneous protocols, security concerns and policy reasons, a node that wants to communicate with nodes in other domains must communicate via its own gateways [2]. Gateways from different domains can communicate with one another. They form a *virtual* mobile DTN backbone to deliver inter-domain traffic. Like the single domain traffic pattern, we assume that each domain has g_s sources each of which chooses d random domains, and there are g_d random destinations per domain; i.e., $n_s = g_s k$ sources, and $n_d = g_d k$ destinations per source. For a given domain, each gateway maintains a list of g_d local multicast receivers. Gateways do not generate traffic, but only perform packet forwarding. Figure 3 shows an example with $k = 3$, $g = 3$, and $m = 1$.

B. Inter-domain RelayCast

We extend RelayCast to inter-domain DTN routing scenarios as follows. In each active cell, we randomly select a pair of nodes and perform either of the following operations. In Phase 1 (member-to-gateway), the multicast source sends a new packet to one of its gateway nodes. In Phase 2 (gateway-to-gateway), the gateway now performs RelayCast: if there is a gateway that belongs to one of d destination domains and that has not received a packet yet, the relay gateway delivers the packet. In Phase 3 (gateway-to-member), the destination gateway delivers the packet to all g_d multicast receivers in its domain. The overall procedure is illustrated in Figure 4 where a source node S in domain 1 multicast packets to all the members in domain 2 and domain 3. S first sends packets to its gateway G_1, and G_1 performs RelayCast in the gateway backbone to deliver the packets to G_2 and G_3. Then, both G_2 and G_3 perform RelayCast in their local domains and deliver received packets to its members.

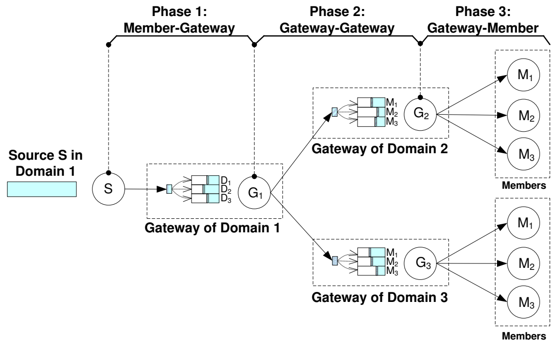

Fig. 4. Inter-domain DTN multicast routing example: Packets are forwarded to gateways (Phase 1), those gateways perform inter-domain RelayCast over the gateway backbone, delivering packets to gateways of d destination domains (Phase 2), and the destination gateways perform intra-domain RelayCast, delivering packets to g_d local multicast receivers (Phase 3).

We first find the optimum configuration that maximizes the throughput. This includes the number of gateways and radio range. Like RelayCast, inter-domain RelayCast considers the case of unicast routing to find such a configuration. The following theorem shows that we need $\Theta(gk)$ gateways per domain with radio range of $\Theta(1/\sqrt{gk})$ to achieve $\Theta(1)$ per-node throughput.

Theorem 6: The per-node throughput is maximized when the number of gateways per domain is $\Theta(gk)$, and the radio range is $\Theta(1/\sqrt{gk})$.

Proof: As shown in Theorem 3, the per-node throughput of inter-domain unicast routing is mainly determined by the aggregated meeting rate between a member node and m gateways, namely $\Theta(m\lambda)$. Since we assume constant contact duration (i.e., radio range scales the same as node speed), the per-node throughput can be represented as $\Theta(mr^2)$ where r is the radio range. Each domain has g members and there are k such domains (total gk traffic sources). As in two-hop relay, we can maximize throughput by enforcing $\Theta(1)$ member node in the contention domain. Moreover, there must be at least $\Omega(1)$ gateway to make Phase 1 and Phase 3 successful. We want to find the minimum number of gateways that achieves the maximum throughput. The inter-domain traffic causes wireless contention among nodes in different domains. For instance, a node in a domain 1 that transmits a packet to its gateway conflicts with another gateway in a domain 2 that delivers the packet to its local multicast receivers. We should schedule gk members such that we can maximize spatial reuse. This happens when we set the radio range as $\Theta(1/\sqrt{gk})$, guaranteeing that there is only $\Theta(1)$ member in the radio range. Inter-domain communications require existence of at least $O(1)$ gateways within one's radio range. The minimal number of gateways that satisfies this condition is given as $\Theta(gk)$. The per-node throughput linearly increases with the number of gateways per domain, and the maximum throughput is achieved with $m = \Theta(gk)$. ■

The results show that we need k times more gateways, namely $m = \Theta(gk)$ per domain to achieve the maximum throughput. Given that the number of members per domain g is fixed, the number of gateways linearly scales with the number of domains. This is due to the fact that as the number of domains increases, the overall system scales down as well. In particular, as $\lambda = r^2 = \frac{1}{gk}$, one's contact rate to its gateways decreases by factor of k. When the number of domains k increases, one has to put k times more gateways to sustain the same throughput.

A source node may select its own domain as one of the destination domains. In our scenario, the source node still transfers packets to its gateways instead of performing *intra-domain RelayCast among domain members*, because that cannot improve the per-node throughput. Since the radio range is given as $O(1/\sqrt{gk})$ and constant contact duration is assumed, the meeting rate is simply given as $O(1/gk)$. When the number of gateways is greater than that of members, the aggregate meeting rate of gateways is also greater than that of members. Thus, from the throughput scaling standpoint, it is always beneficial to forward packets to the gateways under this circumstance.

Note that the total number of nodes (members and gateways) in the network is $\Theta(gk + mk)$. Grossglauser and Tse's result shows that the network wide throughput is also $\Theta(gk + mk)$ where $\Theta(gk)$ is the aggregate throughput of all members and $\Theta(mk)$ is the aggregate throughput of all gateways. In our scenario, we can achieve such throughput scaling using TDMA scheduling: even slots are assigned to gateway-member traffic, and odd slots are assigned to gateway-gateway traffic. Recall that constant slot time scheduling does not affect the throughput scaling. As there are a factor of k more gateways, we need to use different radio range to schedule all the gateways, namely $\Theta(1/\sqrt{mk})$) to maximize throughput. However, there is no advantage of reducing the radio range from $\Theta(1/\sqrt{mk})$ to $\Theta(1/\sqrt{gk})$. For a given domain, the aggregate throughput is $\Theta(g)$, whereas that of one's gateways is $\Theta(gk)$. The backbone utilization is only $gk/mk = 1/k$. If we simply use $r = \Theta(1/\sqrt{gk})$, the backbone is fully utilized. As we will see, we can also reduce the average delay in Phase 2. Thus, we use the radio range of $O(1/\sqrt{gk})$ for the rest of analysis.

Theorem 7: The throughput of inter-domain RelayCast per multicast source is $\Theta(\min(m\lambda, \frac{m^2\lambda}{n_s n_d}))$.

We provide a proof sketch and details can be found in [17]. The overall proof is quite similar to Theorem 3. The key difference is that we now perform inter-domain RelayCast (Phase 2) and intra-domain RelayCast (Phase 3). The average number of competing sources per destination domain in Phase 2 is $n_x = n_s d/k$. Moreover, each of n_x competing sources per domain has g_d random receivers in the destination domain in Phase 3. For a given multicast receiver, there are $n_c = n_x g_d/g$ competing sources in the domain. Thus, the per-node throughput is reduced by a factor of $\Theta(n_x g_d/g) = \Theta(n_s n_d/m)$. We then find the average delay of inter-domain RelayCast by analyzing the delay in each phase.

Theorem 8: The average delay of inter-domain RelayCast is $\Theta(\max(\frac{\log n_d}{m\lambda} + \frac{\log g_d}{\lambda}, \frac{n_s d}{k}\frac{\log d}{m\lambda} + \frac{n_s n_d}{kg}\frac{\log g_d}{\lambda}))$.

The average delay is the sum of delays in three phases. The delay of Phase 1 is to deliver a packet to one of the m gateway nodes and thus, it is simply $E[D_{P1}] = \frac{1}{m\lambda}$. In the second phase, the gateway must deliver the packet to d destination domains. There will be n_x competing sources to a destination domain, but unlike single domain RelayCast, we now have m gateways in the destination domain: the packet can be delivered to any one of the m gateways.

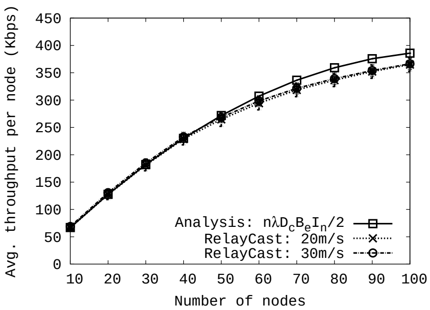

Fig. 5. Average throughput per source

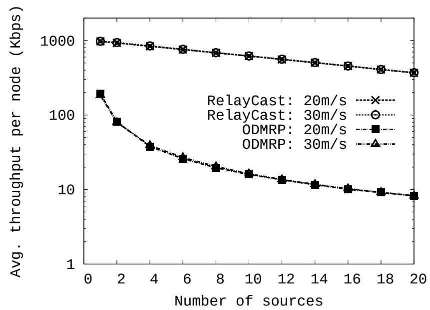

Fig. 6. Average throughput comparison between RelayCast and ODMRP

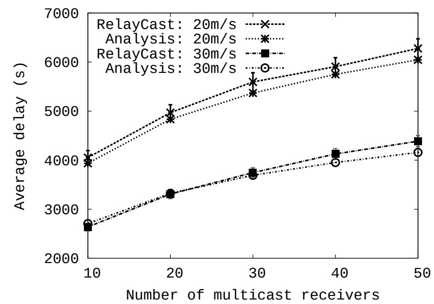

Fig. 7. Average delay of RelayCast

Considering this fact, we use the arguments in Theorem 4 and find $E[D_{P2}] = \frac{n_x}{m\lambda}\sum_{i=1}^{d}\frac{1}{i} = \Theta(\frac{n_x \log n_d}{m\lambda})$. The average delay of Phase 3 is the same as RelayCast, except that the number of conflicting sources is now $n_c = \frac{n_s n_d}{gk}$; i.e., $E[D_{P3}] = \Theta(\max(\frac{\log g_d}{\lambda}, \frac{n_c \log g_d}{\lambda}))$. Since Phase 2 and Phase 3 happen concurrently, for delay calculation we only need to consider the last domain that has received the packet from the source gateway. Thus, the average delay is simply the sum of average delays in three phases as shown in the above theorem. Readers can find details of the proof in [17].

In our inter-domain DTN model, a member node can communicate with other nodes in different domains only via its own gateways. Theorem 6 shows that this restriction requires us to increase the number of gateways per domain proportional to the number of domains as $\Theta(gk)$. If we relax this restriction, we can reduce the number of gateways to $\Theta(g)$, yet still achieve the same scaling behavior. Since a node can access gateways of other domains, the total number of accessible gateways in the network is $\Theta(gk)$. When we have the radio range of $\Theta(1/\sqrt{gk})$, there will be $O(1)$ gateway in the radio range. Thus, we can achieve the same scaling behavior with $\Theta(g)$ gateways per domain. Given that we have limited number of gateways per domain, it is very important to allow members to communicate with other gateways in different domains. In practice, network-wide relaxation may not be feasible due to heterogeneous protocols/devices, security concerns, and policy reasons, but relaxation within an organization hierarchy may be possible, which will greatly help capacity provisioning of the mobile DTN backbone in the coalition environments.

V. SIMULATIONS

We present the throughput and delay of RelayCast using QualNet v3.9.5, a packet level network simulator. We defer the evaluation of inter-domain RelayCast as part of our future work.

A. Simulation Setup

We use the random waypoint mobility model with 0 pause time and constant node speeds at 20m/s and 30m/s in a 5000m $\times$ 5000m region. We use 802.11b with 250m transmission range and 2Mbps transmission rate and use a two-ray ground path-loss propagation model. We use the Multicast Constant Bit Rate (MCBR) traffic in QualNet to measure the maximum throughput. We vary the number of nodes from 10 to 100, and warm up simulations for 10,000s. We implement RelayCast and compare its performance with analytical results. We also compare the results with On-Demand Multicast Routing Protocol (ODMRP), a well-known multi-hop wireless multicast protocol [15]. For ODMRP, we set the refresh interval to be 3 seconds and the forwarder's lifetime to be 9 seconds. For inter-contact time measurement, the duration of a simulation is 100,000 seconds; for RelayCast performance measurement, we run simulation for 40,000 seconds. Reported results are the averages of 50 runs with different random seeds and are presented with the 95% confidence interval.

B. Results

We measure the per-node throughput by increasing the CBR traffic rate (i.e., packets/sec). The size of a packet is 1500B. Heusse et al. showed that the channel utilization of 802.11b with a packet of size 1500B is 70% (denoted as u) [9]. For a given bandwidth B, the effective bandwidth is given as $B_e = Bu$. In Theorem 3, we showed that the throughput per source is $\Theta(n\lambda)$. In other words, a node encounters another node with rate $n\lambda$, which is a renewal process with the mean inter-renewal interval of $\frac{1}{n\lambda}$. For a given contact duration D_c, a node can transfer on average $D_c B_e$. We use a very simple interference model where interference reduces the throughput by a constant factor, and the frequency of interference is proportional to the number of nodes in the network. The average throughput is given as $n\lambda D_c B_e I_n$ where I_n denotes the degree of interference given n nodes. Now we want to know how throughput scales as the number of nodes increases when there is a single source that sends packets to $n-1$ multicast receivers in the network. If a random node is a pure relay node (not a multicast receiver), it can fully utilize its contact period delivering packets to the encounter receiver. However, in our case, every node other than the source is both a relay node as well as a multicast receiver and thus, the bandwidth is fairly shared by incoming and relaying traffic. Thus, the average throughput is given as $n\lambda D_c B_e I_n/2$. In our simulations, the mean inter-contact time is given as 1344.00s and 924.08s for the speed of 20m/s and 30m/s respectively. Figure 5 shows the measured throughput and analytical results. The figure shows that the analytic throughput model matches well with the simulated results, but they slightly deviate from each other as the number of nodes increases. We believe this gap can be reduced by using a more sophisticated interference model such as [21].

We compare the scalability of RelayCast with that of ODMRP. In particular, we evaluate the cases $n_s n_d \leq n$ where RelayCast can achieve the throughput of $\Theta(1)$. We increase the number of sources from 1 to 20 each of which has 5 random destinations. To find the best scenario of ODMRP, we use various MCBR rate ([20,200] pkts/s) with packet sizes of 512B and 1024B, and different area sizes (750m $\times$ 750, 1000m $\times$ 1000m, and 1250m $\times$ 1250m). Our results show that the maximum throughput is attained when a 512B packet is sent at the rate of 200 pkts/s in an area of size 1000m $\times$ 1000m. Figure 6 reports the results. As the number of sources increases, the throughput of RelayCast slowly decreases, but the throughput of ODMRP decreases significantly. For instance, when the number of sources has increased from 1 to 2, the throughput of ODMRP is decreased from 183.6Kbps to 79.7Kbps, whereas that of RelayCast is reduced from 975.6Kbps to 926.8Kbps. This result confirms that RelayCast is a more scalable solution for multicast in DTN environments.

Finally, we investigate the average delay of RelayCast. We show how the average delay of RelayCast changes as the number of destinations increases. In order to measure the delay incurred by the protocol, we throttle down the sending rate at the source so that we can minimize the impact of queueing delay. This result is reported in Figure 7 along with analytic results from Theorem 4. The graph shows that our analytic results matches with simulation results fairly well. In general, the average delay increases, as the number of destinations increases.

VI. Conclusion and Future Work

We investigated the throughput and delay scaling properties of multicasting in DTNs. We analyzed the maximum throughput bound of DTN multicast. We then proposed RelayCast, a routing scheme that extends the Grossglauser and Tse's two-hop relay algorithm and showed that RelayCast achieves the maximum throughput of $\Theta(\min(n\lambda, \frac{n^2\lambda}{n_s n_d}))$ where n_s is the number of sources and n_d is the number of receivers associated with each source. We compared throughput and delay properties of RelayCast with those of conventional wireless multicast schemes and showed that RelayCast is much more scalable. Moreover, we extended RelayCast to delay tolerant coalition networks where multiple domains exist, and nodes communicate with other nodes in different domains via gateways due to security concerns and policy reasons. We found the throughput and delay scaling properties of inter-domain RelayCast and showed that there exists an optimal inter-domain networking configuration that achieves the same scaling behavior as single domain multicast.

There are several directions of future work. First, we will consider DTNs where the inter-contact behavior of an arbitrary pair of nodes can be described by a generalized two-phase distribution (i.e., a power-law head with an exponential tail) [1]. Recent experiments have confirmed that the two-phase distribution is the most realistic model for vehicular and pedestrian scenarios, where the specific shape of the distribution depends on the degree of correlation among mobile traces [12]. Also, we will consider group mobility patterns such as Reference Point Group Mobility (RPGM) [10]. Second, we will analyze the impact of various network parameters and routing strategies (such as buffer constraints and replication) on the capacity/delay scaling properties of delay tolerant coalition networks.

References

[1] H. Cai and D. Y. Eun. Crossing Over the Bounded Domain: From Exponential To Power-law Inter-meeting Time in MANET. In *MobiCom'07*, Montréal, QC, Canada, Sept. 2007.

[2] C.-K. Chau, J. Crowcroft, K.-W. Lee, and S. H. Wong. Inter-Domain Routing for Mobile Ad Hoc Networks. In *MobiArch'08*, Seattle, Washington, Aug. 1999.

[3] D.-Z. Du and F. K.-M. Hwang. A Proof of the Gilbert-Pollak Conjecture on the Steiner Ratio. *Algorithmica*, 7(2-3):121–135, 1992.

[4] A. E. Gamal, J. Mammen, B. Prabhakar, and D. Shah. Throughput-Delay Trade-Off in Wireless Networks. In *INFOCOM'04*, Hong-Kong, Mar. 2004.

[5] R. Groenevelt, P. Nain, and G. Koole. The Message Delay in Mobile Ad Hoc Networks. In *Performance'05*, Juan-les-Pins, France, Oct. 2005.

[6] M. Grossglauser and D. N. C. Tse. Mobility Increases the Capacity of Ad Hoc Wireless Networks. *IEEE Transactions on Networking*, 10(4), Aug. 2002.

[7] P. Gupta and P. R. Kumar. The Capacity of Wireless Networks. *IEEE Transactions on Information Theory*, 46(2), 2000.

[8] J. D. Herdtner and E. K. P. Chong. Throughput-Storage Tradeoff in Ad Hoc Networks. In *INFOCOM'05*, Miami, FL, Mar. 2005.

[9] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda. Performance Anomaly of 802.11b. In *INFOCOM'03*, San Francisco, CA, May 2003.

[10] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang. A Group Mobility Model for Ad Hoc Wireless Networks. In *MSWiM'99*, Seattle, Washington, Aug. 1999.

[11] S. Jain, K. Fall, and R. Patra. Routing in a Delay Tolerant Networking. In *SIGCOMM'04*, Portland, OR, Aug.-Sep. 2004.

[12] T. Karagiannis, J.-Y. L. Boudec, and M. Vojnovic. Power Law and Exponential Decay of Inter Contact Times Between Mobile Devices. In *MobiCom'07*, Montréal, QC, Canada, Sept. 2007.

[13] A. Keshavarz-Haddad, V. Ribeiro, and R. Riedi. Broadcast Capacity in Multihop Wireless Networks. In *Mobicom'06*, Los Angeles, CA, Sept. 2006.

[14] S. R. Kulkarni and P. Viswanath. A Deterministic Approach to Throughput Scaling in Wireless Networks. *IEEE Transactions on Information Theory*, 50(6):1041–1049, 2004.

[15] S.-J. Lee, M. Gerla, and C.-C. Chiang. On-Demand Multicast Routing Protocol. In *WCNC'99*, New Orleans, LA, Sep. 1999.

[16] U. Lee, S. Y. Oh, K.-W. Lee, and M. Gerla. RelayCast: Scalable Multicast Routing in Delay Tolerant Networks. In *ICNP'08*, Orlando, FL, Oct. 2008.

[17] U. Lee, S. Y. Oh, K.-W. Lee, and M. Gerla. RelayCast: Scalable Multicast Routing in Delay Tolerant Coalition Networks. Technical Report `http://www.cs.ucla.edu/~uclee/relaycasttr09.pdf`, UCLA CSD, 2009.

[18] X.-Y. Li, S.-J. Tang, and O. Frieder. The Multicast Capacity of Large Multihop Wireless Networks. In *MobiCom'07*, Montréal, QC, Canada, Sept. 2007.

[19] A. Lindgren, A. Doria, and O. Schelén. PROPHET: Probabilistic Routing in Intermittently Connected Networks. In *SAPIR'04*, Fortaleza, Brazil, Aug. 2004.

[20] M. J. Neely and E. Modiano. Capacity and Delay Tradeoffs for Ad-Hoc Mobile Networks. *IEEE Transactions on Information Theory*, 46(2), June 2005.

[21] L. Qiu, Y. Zhang, F. Wang, M. K. Han, and R. Mahajan. A General Model of Wireless Interference. In *MobiCom'07*, Montréal, QC, Canada, Sept. 2007.

[22] S. Shakkottai, X. Liu, and R. Srikant. The Multicast Capacity of Large Multihop Wireless Networks. In *MobiHoc'07*, Montréal, QC, Canada, Sept. 2007.

[23] G. Sharma, R. Mazumdar, and N. Shroff. Delay and Capacity Trade-offs in Mobile Ad Hoc Networks: A Global Perspective. In *INFOCOM'06*, Barcelona, Spain, Apr. 2006.

[24] T. Small and Z. J. Haas. Resource and Performance Tradeoffs in Delay-Tolerant Wireless Networks. In *CHANTS'05*, Philadelphia, PA, Aug. 2005.

[25] Z. Wang, H. R. Sadjadpour, and J. Garcia-Luna-Aceves. A Unifying Perspective on the Capacity of Wireless Ad Hoc Networks. In *INFOCOM'08*, Phonex, AZ, Apr. 2008.

[26] Q. Ye, L. Cheng, M. C. Chuah, and B. D. Davison. OS-multicast: On-demand Situation-aware Multicasting in Disruption Tolerant Networks. In *VTC'06*, Melbourne, Australia, May 2006.

[27] W. Zhao, M. Ammar, and E. Zegura. Multicasting in Delay Tolerant Networks: Semantic Models and Routing Algorithms. In *CHANTS'05*, Philadelphia, PA, Aug. 2005.