

Investigation of MAC for a Hierarchical and Heterogeneous Multichannel Ad Hoc Network

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Abstract—We propose a hierarchical and heterogeneous multichannel ad hoc network. The channels employed by this network are nonoverlapping, and each channel differs significantly in its characteristics, such as achievable data rate, communication range, and traffic load. Each terminal is equipped with a frequency-agile radio that has the ability to change its carrier frequency and transmission rate over a wide range of possibilities. These radios communicate using contention-based access and are permitted to utilize multiple channels. A subset of the terminals form a backbone network, and are equipped with a second radio tuned to a traffic channel employing schedule-based access. We consider various hierarchical and heterogeneous multichannel ad hoc network topologies and investigate the backbone networks that increase network-layer performance over scenarios in which too few or too many terminals are selected to form the backbone network.

I. INTRODUCTION

Efficient channel access for large and dense deployments of ad hoc networks is required to support a wide range of emerging applications and to leverage the availability of software-defined radios (SDRs) that can utilize multiple heterogeneous channels. Contention-based protocols work well with low traffic demand, but network performance decreases as traffic demand increases. Schedule-based protocols avoid collisions by scheduling packet transmissions but perform poorly during periods of low contention due to idle or underutilized slots. However, network performance increases as the traffic level increases because slots are more fully utilized. Forming a backbone network within an ad hoc network allows the channel-access problem to be separated into two domains: contention-based, which easily exploits the available heterogeneous channels for individual user traffic, and schedule-based, which is employed to efficiently relay high levels of aggregated traffic across the backbone.

In [1–5], a backbone is formed within an ad hoc network that employs a single channel, and the backbone construction of [6] requires each terminal to have three interfaces with multiple channels. In these works, a backbone is created for topology control, to improve the scalability of the network, reduce routing overhead, or provide a broadcast infrastructure.

Due to the decrease in performance experienced by networks employing multiple channels using contention-based access, [7] and [8] present a schedule-based multichannel MAC protocol for ad hoc networks. These protocols involve

two-dimensional (channel and time slot) negotiation or assignment, which exploits the advantages of multiple channels and schedule-based access.

The cluster-based scheduling algorithms of [9] and [10] combine the concepts of a backbone and schedule-based access. These works consider clustering as a way to introduce structure into an ad hoc network consisting of multiple channels. Each cluster is represented by a cluster head, and these cluster heads form the backbone and are responsible for inter- and intra-cluster schedule-based communication.

We have previously investigated immediate neighbor scheduling (INS) [11], a cross-layer distributed broadcast transmission scheduling protocol that is designed specifically for ad hoc networks employing direct-sequence spread-spectrum (DSSS) modulation. The INS protocol improves spatial reuse and reduces overhead compared to standard schedule-based approaches. The average number of neighbors included in a terminal's schedule has a significant influence on network performance. The benefits of INS are greatest at moderate neighborhood densities in which the terminals have sufficient traffic to maximize utilization of all transmission assignments. Two key problems limit the performance of INS in large and dense networks: poor frequency reuse due to the need to schedule all terminals in a neighborhood and low utilization of the transmission assignments when there is a disproportionate distribution of traffic.

Software-defined radios can take advantage of a heterogeneous and dynamically changing set of communication channels that have a wide range of communication ranges and data rates. We have previously investigated cross-layer contention-based MAC protocols designed specifically for the capabilities of SDRs to utilize heterogeneous channels [12]. Our MAC protocol dynamically measures the characteristics of the channels and improves network-layer performance by selecting the appropriate channel for relaying a packet. The benefits of our MAC approach are particularly evident in dense topologies in which the highly different characteristics of the channels can be fully exploited. However, network performance is ultimately limited due to reliance on contention-based channel access.

For this work, each terminal is equipped with a single half-duplex frequency-agile radio that can be tuned to a particular carrier frequency and its associated channel-symbol rate. To achieve efficient channel utilization in large and dense ad hoc

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networks, a hierarchical approach is developed in which a subset of terminals utilize a second transceiver with a fixed carrier frequency and channel-symbol rate to form a backbone that utilizes INS as the channel-access protocol. All other terminals associate with a backbone terminal and employ contention-based channel access that exploits the capabilities of SDRs and the additional available heterogeneous channels. The terminals that participate in the backbone need to be carefully selected so that the transmission schedules can achieve high efficiency through frequency reuse and traffic is funneled to the backbone to maximize utilization of the transmission assignments. Initial investigations have demonstrated that selecting the backbone utilizing the principles of minimizing a connected dominating set, controlling the number of terminals associated with a backbone node, or minimizing number of relays does not lead to good network-layer performance for our proposed hierarchical and heterogeneous multichannel ad hoc network. Utilizing multiple heterogeneous scenarios, we demonstrate that network-layer performance is highly dependent on how many and which terminals are included in the backbone. This work provides initial design insights and guidelines that will direct future research on approaches to initialize and maintain a backbone for heterogeneous multichannel ad hoc networks.

II. SYSTEM MODEL AND CHANNEL-ACCESS PROTOCOLS

A. Physical Layer Model

The radios in our system employ DSSS modulation, and N_{max} is the maximum spreading factor. There are M nonoverlapping channels available to the system. These channels are heterogeneous and characterized by their carrier frequencies and chip rates. Each terminal in our system is equipped with a single frequency-agile radio with a half-duplex transceiver that can be tuned to any one of channels 1 through $M - 1$ at any given time. Each terminal is also equipped with a second half-duplex transceiver, and for the terminals forming the backbone, this transceiver is assigned a particular channel, channel M . All terminals tuned to the same channel use an identical carrier frequency and chip rate. The carrier frequency and chip duration for channel i is f_i and T_{C_i} , respectively. For this system, we assume that channel bandwidth is proportional to carrier frequency. Thus, if $f_i < f_j$, then $T_{C_i} > T_{C_j}$.

For channels 1 through $M - 1$, the spreading factor is fixed and equal to N_{max} . The probability that a packet is successfully acquired and decoded is based on the symbol-energy to interference plus noise ratio (EINR). The details of the acquisition model are explained in [13], and the model for multiple-access interference from partially overlapping transmissions and the calculation of the probability are in [14].

Because transmissions are time-slotted on channel M , a different packet reception model is used. A transmission from terminal A to B is successfully received only if the EINR at terminal B exceeds threshold β . Because interference patterns on channel M tend to recur from one transmission frame to the next, radios on channel M employ transmission rate adaptation to increase the data rate on links with a high EINR. This is achieved by reducing the spreading factor according

TABLE I: ALLOWABLE TRANSMISSION MODES

Outgoing link EINR estimate	Link spreading factor	Maximum packet forwarding rate
$\beta < \hat{\xi}_M(A, B) \leq 4\beta$	N_{max}	1 packet per slot
$4\beta < \hat{\xi}_M(A, B) \leq 8\beta$	$N_{max}/2$	2 packets per slot
$8\beta < \hat{\xi}_M(A, B)$	$N_{max}/4$	4 packets per slot

to the level of the EINR estimate. The transmission modes allowed by this system are listed in Table I, where $\hat{\xi}_M(A, B)$ denotes the EINR estimate for the link from terminal A to B on channel M . The details of transmission rate adaptation and its implementation are further explained in [11].

Because the channels are heterogeneous, the distance for which a packet can be received with a high probability differs among the channels. The *communication range* is the maximum distance between a transmitter and a receiver such that a target EINR of β is achieved in the absence of multiple-access interference. A channel with a faster data rate has a shorter communication range.

B. Contention-Based Protocol

The contention-based protocol of our system is described in [12], and we summarize the key details that affect integration with the hierarchical organization here. Of the M channels available to the system, channels 1 through $M - 1$ are for contention-based access. Channel 1 is the control channel and is used to reserve access to traffic channels 2 through $M - 1$.

Request-to-send (RTS) and clear-to-send (CTS) packets are transmitted on the control channel, and data packets, acknowledgement (ACK) packets, and negative-acknowledgement (NACK) packets are transmitted on the traffic channels. Because RTS, ACK, NACK, and data packets are transmitted using a receiver-directed code, they can only be acquired by their intended recipient. However, CTS packets are transmitted using a common spreading code and can be acquired by any neighbor listening on the control channel.

Here, we describe the basic channel-access protocol, and we explain later how the source and destination terminals select a traffic channel for a data packet transmission. *Source* terminal S initiates a transmission by sending an RTS packet to *destination* terminal D . This RTS packet includes a list of the unblocked channels at S that are available to D . After D acquires and decodes the RTS packet, it checks if at least one of the channels listed in the RTS packet is unblocked at D . If so, D selects one of these channels for the data packet transmission and includes this channel in the CTS packet it transmits to S . Once S acquires and decodes the CTS packet, it transmits the data packet on the traffic channel indicated in the CTS packet. After acquiring the data packet, D transmits an ACK packet to S if the data packet is decoded successfully or a NACK packet if the data packet is not decoded successfully.

An *overheard* CTS packet is a CTS packet that is acquired and decoded by a terminal other than the terminal for which it is intended. For channel-access protocols such as [14], [15], or the DCF mode of the IEEE 802.11 standard, a terminal that acquires and decodes an overheard CTS packet must refrain from using the traffic channel indicated in the CTS packet for an amount of time equivalent to the duration of the data packet and subsequent ACK packet transmissions. The

terminal that received the overheard CTS packet considers this traffic channel *blocked*.

Using the *fastest completion* (FC) channel-access approach, the source and destination terminal select a traffic channel for a data packet transmission based on the expected time to complete a transmission. The *expected completion time* for traffic channel i at terminal L is the amount of time L expects is required to complete a transmission using channel i and is the sum of the transmission time and the delay terminal L may experience before it is able to use channel i .

Consider a transmission attempt between source terminal S and destination terminal D . Terminal S computes the expected completion time of each traffic channel that is available to D . If a blocked channel has the shortest expected completion time, S does not generate an RTS packet and can not initiate a transmission to D until the blocking timer expires. However, if an unblocked traffic channel has the shortest expected completion time, S sends an RTS packet including each unblocked traffic channel with a shorter expected completion time than that of those channels which are blocked. After D acquires and decodes the RTS packet, it computes the expected completion time of each of its traffic channels that are included in the RTS packet. If a blocked traffic channel has the shortest expected completion time, D ignores the RTS packet, and the transmission does not occur. If, however, an unblocked traffic channel has the shortest expected completion time, D selects this traffic channel for the data packet transmission.

Terminals employing the FC approach simply select the channel with the fastest expected completion time, accounting for the blocking times. If the selected channel is unblocked, the transmission is initiated immediately. However, if the channel is blocked, the transmission is deferred until this channel becomes unblocked. As described in [16], the FC approach is modified by weighting the expected completion time of slower unblocked traffic channels when the fastest traffic channel is blocked such that the number of transmission attempts on slower unblocked channels decrease when there is minimal contention for the fastest channel and increase when there is heavy contention for the fastest channel. For this work, the FC approach uses the weighting variation of [17].

C. Schedule-Based Protocol

The INS protocol [11] is employed by the backbone terminals accessing channel M . The *neighborhood* of terminal A is used to schedule transmissions for A and is defined as the set of terminals with which A must share channel M . Lyui's algorithm [18] assigns each terminal a color number that is unique among the terminals in its neighborhood, and used to assign transmission slots. The resulting collision-free transmission schedule is referred to as a frame, and the size of a terminal's transmission schedule, *frame size*, is the smallest power of two no less than the largest color number in the terminal's neighborhood. Each terminal is guaranteed at least one transmission slot per frame, and additional slots may be assigned to a terminal depending on the coloring of other terminals in its neighborhood.

Lyui's algorithm was initially designed to generate collision-free schedules for a graph-based channel model. Like traditional transmission schedules, this algorithm avoids interference by having larger neighborhoods. For Lyui's algorithm, a terminal's neighborhood includes itself, its neighbors, and the neighbors of its neighbors. However, the algorithm can be extended to operate with other channel models such that the size of the neighborhood used for scheduling depends on the level of multiple-access interference permitted. A larger neighborhood decreases multiple-access interference and reduces spatial reuse while a smaller neighborhood increases multiple-access interference and allows terminals to transmit more often.

With DSSS modulation and transmitter-oriented spreading sequences, transmissions can be received in the presence of interference from other terminals, which allows the INS protocol to use smaller neighborhoods to schedule transmissions. This results in increased spatial reuse and less control overhead. The routing protocol for INS computes link costs based on the link rate, slot utilization, and link EINR.

III. INTEGRATION OF CONTENTION-BASED AND SCHEDULE-BASED PROTOCOLS

Co-site interference is eliminated by selecting the carrier frequency of the schedule-based traffic channel to be far enough away from the carrier frequencies of the other channels. Thus, the contention-based and schedule-based traffic channels can be used independently. Backbone and nonbackbone terminals communicate using contention-based access on channels 2 through $M - 1$, and backbone terminals communicate with one another using schedule-based access on channel M . Each nonbackbone terminal associates with the backbone terminal with the largest EINR. The EINR values are estimated from network-layer control packets periodically transmitted on the channels employing contention-based access. A packet generated at a nonbackbone terminal is forwarded to its associated backbone terminal. This packet is then forwarded through the backbone to the backbone terminal associated with the packet's destination. If the packet's destination is a nonbackbone terminal, the backbone terminal forwards the packet directly to its destination. Direct communication is not permitted between nonbackbone terminals.

In selecting the terminals forming the backbone, traditional connected dominating set (CDS) algorithms such as those in [19–21] are not suitable due to the complex nature of our system. Factors that affect the selection of backbone terminals include the characteristics of channel M , the links in the backbone, and the links between nonbackbone and backbone terminals. Below, we describe these factors and explain how each contributes to backbone-terminal selection.

Due to transmission rate adaptation, backbone terminals communicate with one another using one of three packet forwarding rates. Links with higher packet forwarding rates are advantageous because they lead to more packet transmissions in a slot, and increased frequency reuse (due to a smaller communication range). These links have a greater probability

TABLE II: CHANNEL ATTRIBUTES

Channel 2			Channel 3			Channel 4		
f_i	D_i	Δ_i	f_i	D_i	Δ_i	f_i	D_i	Δ_i
(GHz)	(kbps)	(m)	(GHz)	(kbps)	(m)	(GHz)	(kbps)	(m)
1	250	1626	1.5	750	752	2	2250	396

of being used because INS assigns a lower cost to links with a higher packet forwarding rate. Selecting backbone terminals such that the distance between neighboring terminals is within the communication range corresponding to the highest possible packet forwarding rate, increases the probability that a link with a high packet forwarding rate will exist between the terminals. Thus, in addition to forming a connected backbone, we select terminals that increase the number of links in the backbone with a high packet forwarding rate.

In addition to considering the characteristics of the links in the backbone, we also consider the links between nonbackbone and backbone terminals. A backbone terminal communicates with its associated nonbackbone terminals on up to $M - 2$ traffic channels, each of which has a different communication range. These heterogeneous links give greater flexibility in the selection of backbone terminals. Backbone terminals are selected such that each nonbackbone terminal can access the backbone using at least one of the $M - 2$ traffic channels available. In addition, these terminals are selected such that the number of nonbackbone-terminal associations is closely balanced among the backbone terminals (or not excessive for any particular backbone terminal).

Too few terminals in the backbone causes network performance to suffer due to contention among nonbackbone terminals. However, too many terminals in the backbone results in idle or underutilized transmission slots; these could otherwise be assigned to congested backbone terminals to increase capacity. INS utilizes frame sizes that are powers of two. Thus, in addition to the guidelines above, the number of backbone terminals chosen for the *initial* backbone is a power of two. We examine the performance of the initial backbone, and modify the selection of backbone terminals to increase network-layer performance.

IV. SIMULATION MODEL AND RESULTS

We consider a network with three heterogeneous traffic channels and one control channel for contention-based access. The attributes of these channels are listed in Table II, where D_i is the data rate and Δ_i is the communication range for channel i and are calculated as in [12]. The control channel has the same attributes as channel 2, and the channel employing schedule-based access, channel 5, has the same characteristics as that of channel 3. The carrier frequencies of the control channel and channel 2 and of channels 3 and 5 differ by a small amount to ensure that these channels are nonoverlapping. Because the spreading factor is adapted on channel 5, D_3 is the minimum data rate for channel 5, and Δ_3 is the maximum communication range for channel 5.

We consider the five network topologies of Table III such that the terminals for the grid topologies are arranged in a five-by-five grid, and the terminals in the random topologies are placed randomly with a uniform distribution. For each

TABLE III: TOPOLOGY ATTRIBUTES

Topology	Number of Terminals	Deployment Area
small-scale grid	25	600 m x 600 m
large-scale grid	25	~1000 m x 1000 m
cluster	25	See Fig. 1
small-scale random	50	1000 m x 1000 m
large-scale random	50	3000 m x 3000 m

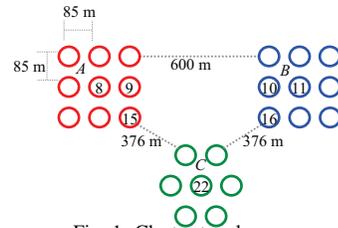


Fig. 1: Cluster topology.

topology, we begin with an initial backbone (described in Section III), and variations are determined based on its performance. For each variation, we ensure that the backbone is connected, and that each nonbackbone terminal is able to access the backbone.

Initially, we utilize the simulation program described in [11] to calculate the INS transmission schedules, forwarding tables, and link EINRs for all backbone terminals. These results are utilized by our OPNET simulation to investigate the network-layer performance of our hierarchical and heterogeneous multichannel ad hoc network. The OPNET simulation includes detailed physical-, link-, and network-layer models. For our experiments, $N_{max} = 16$, $\beta = 5$ dB, and we adopt the simulation parameters used in [12] except there are now five channels, the queue size for the backbone terminals using INS is 20 packets, and all forwarding attempts from a nonbackbone terminal are to its associated backbone terminal only.

Traffic is generated for each terminal in the network by a Poisson generator. The destination of each packet is determined randomly with a uniform distribution among the other terminals in the network. The performance of our protocol is measured using the end-to-end success probability, which is the fraction of packets that reach their destinations. Specifically, we analyze the *performance threshold*, which is the largest generation rate for which the end-to-end success probability is greater than 90%.

The results for the cluster topology are depicted in Fig. 2. The best performance is achieved when three terminals are selected for the backbone. The performance threshold decreases by 45%, 36%, and 72% when the number of backbone terminals is doubled, halved (and rounded to the nearest integer), and includes all terminals, respectively. Communication between backbone terminals in the same cluster can occur using a maximum packet forwarding rate of 4 pkts/slot. Communication between backbone terminals in clusters A and C and clusters B and C can occur using a maximum packet forwarding rate of 2 pkts/slot, and communication between backbone terminals in clusters A and B occurs using a packet forwarding rate of 1 pkt/slot. The three terminals selected that provide the best performance are terminals 15, 16 and 22. For this scenario, terminals 15 and 16 do not communicate directly but relay their traffic to one another through terminal 22 using links with a rate of 2 pkts/slot. The performance for selecting

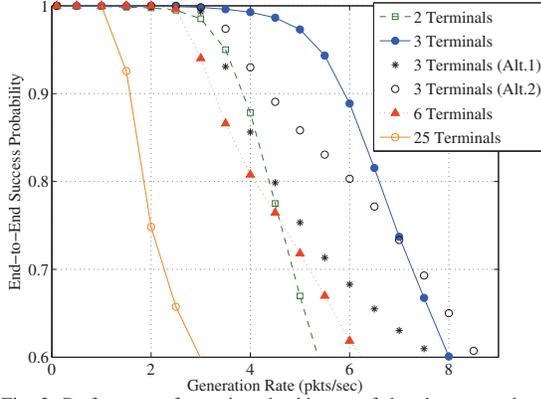


Fig. 2: Performance for various backbones of the cluster topology.

backbone terminals 8, 11, and 22 (Alt. 1) results in a 36% decrease in the performance threshold since the link between terminals 8 and 22 and terminals 11 and 22 has a reduced rate of 1 pkt/slot. As a final example, the backbone terminals are 9, 10, and 22 (Alt. 2). The links between terminals 9 and 22 and terminals 10 and 22 have a rate of 1 pkt/slot, but terminals 9 and 10 can also communicate directly using a rate of 1 pkt/slot. However, this selection of backbone terminals results in a 27% performance decrease over the best selection. Thus, performance depends on the number of backbone terminals as well as the EINR and resultant packet forwarding rate that is achieved between them.

The performance of different backbones for the grid topologies is shown in Fig. 3. For the small-scale grid topology, a backbone consisting of eight terminals results in the best performance. As depicted in Fig. 3a, this backbone results in a 46%, 175%, and 175% improvement in the performance threshold over a backbone consisting of half as many, twice as many, and all terminals, respectively. As depicted in Fig. 3b, the four- and eight-terminal backbones of the large-scale grid topology result in similar performance. Each terminal of the eight-terminal backbone is assigned a single transmission slot every eight slots, and a large number of packets are dropped due to queue overflow (or congestion) at some of the backbone terminals. At the performance threshold, the utilization factor is above 90% for half of the terminals, and below 61% for the other half. The four-terminal backbone consists of the four congested terminals, and they receive twice as many transmission slots as they do in the eight-terminal backbone. However, the performance of the four-terminal backbone suffers from heavy contention as nonbackbone terminals attempt to access the backbone. These backbones outperform the two-terminal, 16-terminal, and 25-terminal backbones. In fact, due to contention using the two-terminal backbone, and congestion using the 16-terminal backbone, the all-INS backbone results in better performance even though it uses a single channel. High EINR links are selected for the backbone to achieve high packet forwarding rates. For the grid topologies, each link in the forwarding table of the scenario resulting in the best performance has a rate of 4 pkts/slot. For the eight-terminal backbone of the small-scale grid topology, except for one pair

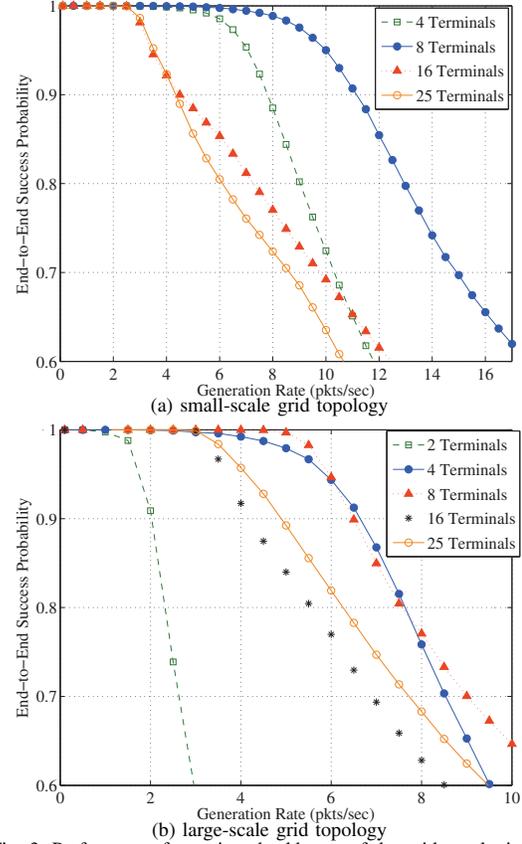


Fig. 3: Performance for various backbones of the grid topologies.

of terminals, there exists a direct link in the forwarding table between every pair of backbone terminals. This is not possible for the large-scale grid topology due to increased spacing between nearest terminals.

Fig. 4 depicts the network-level performance of various backbones for the random topologies. As shown in Fig. 4a, the six-terminal backbone results in the best performance threshold for the small-scale random topology and outperforms scenarios in which the backbone consists of half as many, twice as many, and all terminals by 26%, 32%, and 105%, respectively. Each link in the forwarding table of the six-terminal backbone has a rate of 4 pkts/slot. As depicted in Fig. 4b, the seven-terminal backbone results in the best performance for the large-scale random topology. However, performance suffers from packets dropped at backbone terminals due to congestion. For this scenario, four terminals are congested, and the other three are underutilized. By removing the three underutilized terminals, we obtain the four-terminal backbone. Although these terminals now receive additional transmission slots, there are too few terminals in the backbone, and performance suffers due to contention as nonbackbone terminals attempt to access the backbone. Adding additional backbone terminals near congested backbone terminals is another method for relieving congestion in the backbone. The 14-terminal backbone is comprised of the terminals in the seven-terminal backbone and seven additional terminals. Adding these terminals relieves congestion at two of the four previously-congested backbone

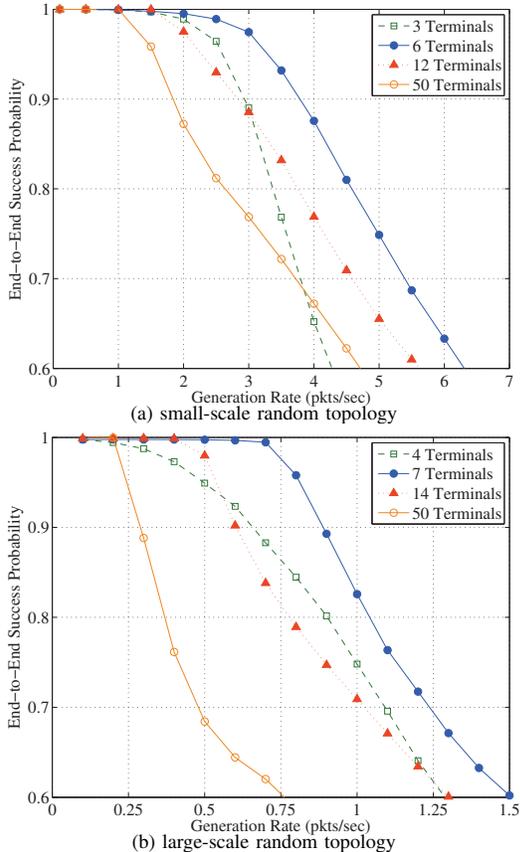


Fig. 4: Performance for various backbones of the random topologies.

terminals. However, due to the sparse connectivity of the network, no additional links exist to relieve congestion at the links formed by the remaining congested terminals. Also, doubling the number of backbone terminals halves the number of transmission slots these congested terminals receive. Thus, the performance threshold of the 14-terminal backbone is worse than that of the seven-terminal backbone by 25%. In contrast to the small-scale random topology, the large-scale random topology has sparser connectivity and backbone links need to span larger distances. Thus, each link in the forwarding table of the seven-terminal backbone has a rate of 1 pkt/slot.

In analyzing the network-layer performance using various backbones, we find that an excessive number of packets dropped due to too many failed forwarding attempts or queue overflow at a nonbackbone terminal implies that there is heavy contention as nonbackbone terminals attempt to access the backbone. We attempt to reduce contention by increasing the number of backbone terminals (particularly around backbone terminals with a large number of associations). However, an excessive number of packets dropped due to queue overflow at backbone terminals, implies that at least one of the backbone terminals is congested. By examining the utilization factor of the backbone terminals, we replace the underutilized backbone terminals with more backbone terminals near the backbone terminals that are congested or remove them so that the congested terminals receive additional transmission slots.

V. CONCLUSION

The backbone terminals for a hierarchical and heterogeneous ad hoc network must be carefully selected. These terminals must form a connected network, and the network must be accessible by nonbackbone terminals. Too few terminals in the backbone leads to inefficient contention as nonbackbone terminals attempt to access the backbone. However, too many backbone terminals leads to underutilization at some terminals and congestion at others. In addition, due to transmission rate adaptation, the terminals should be selected such that the links in the forwarding table have a high packet forwarding rate (although connectivity may require some links to have a low rate). We show that by carefully selecting the backbone terminals for a hierarchical and heterogeneous ad hoc network, network-layer performance increases over scenarios in which there are too few or too many terminals in the backbone and scenarios in which the backbone terminals are poorly selected. Future work entails developing an algorithm that selects the terminals for the backbone that results in maximum network-layer performance.

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