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Routing and Power Control in Frequency-Hop Random-Access Ad Hoc Networks

Frederick J. Block and Thomas C. Royster IV
MIT Lincoln Laboratory
Lexington, MA 02420

Abstract—Frequency hopping provides some protection against multiple access interference in random-access ad hoc networks. Power control and the use of short hopping slots can further reduce interference by promoting spatial reuse. If the network is fully connected, frequency hopping and power control alone may be sufficient to allow good throughput without the use of routing. This approach is particularly desirable as avoiding routing can simplify network setup and reduce packet delay. However, if the network is heavily loaded, frequency hopping may no longer sufficiently protect against interference, so including routing may be beneficial. In this paper, we consider application of least interference routing (LIR) to frequency hop random-access networks. The performance of a family of LIR metrics is considered for a variety of networks to determine which cases multi-hop routing should be used, and it is shown that the choice of the optimal metric is sensitive to several network characteristics.

I. INTRODUCTION

It is desirable that tactical ad hoc networks provide robust connectivity, high throughput, and scalability. Applications using these networks also can require information to be exchanged in a timely manner. However, these requirements are often in conflict. In many cases, throughput can be improved by the use of power control and multi-hop forwarding [1], but this comes at a cost of worse delay [2]. Throughput can also be improved through coordination at the channel access layer (e.g., time division multiple access). However, scheduling can also increase delay and complicate the inclusion of additional nodes into the network. Because they can provide simpler network set up, are inherently responsive to changing traffic demands, and do not require a radio needing to send urgent information to wait for its next time slot, random-access techniques such as Aloha are often more suitable for many tactical applications.

Although the use of routing to improve throughput has been considered in random-access networks [3], [4], results are mainly for cases without spread-spectrum modulation. If frequency-hopping (FH) is used, receivers can be robust against strong multiple access interference [5]. In many cases where routing in FH networks has been considered [6], [7], the effect of multiple access interference from radios in the network has been small compared to that of external interference sources. When the offered load in a fully connected FH network is below the level of multiple access interference that the spreading protects against, routing provides no benefit to throughput. Throughput, at best, would be the same as in a network that utilized transmissions directly to the intended destination. There may be benefits in terms of energy consumption, but because multiple transmissions are needed to deliver a packet, delay would necessarily be higher.

However, if there are enough radios present, a FH network can still be overutilized. It is possible to keep the number of packets lost due to collisions reasonably small in networks that do not use forwarding by limiting the rate at which nodes access the channel, for example by backing off as packets are lost [8], and through power control [9]. Still, without forwarding through intermediate radios, there is a limit to the maximum throughput. Higher throughput in busy FH networks should be attainable by using routing along with reduced transmitter power, but because of the overhead caused by routing protocols and increased delay due to forwarding, it is useful to examine the conditions under which multi-hop forwarding can outperform direct transmission.

This paper considers performance of fully connected FH random-access networks where nodes can employ power control and routing. Network throughput, delay, and energy consumption are compared for a family of routing metrics based on the concept of least interference routing [3]. It is shown that the choice of the metric must depend not only on the desired trade-off between throughput, delay, and energy usage, but also on the size of the network, accuracy of the power level adaptation, and wireless propagation characteristics. Furthermore, relatively small changes in the link metrics can significantly affect throughput.

II. NETWORK MODEL

Radios are distributed uniformly over a circle of radius $R$, i.e., the distance of a radio from the center of the circle has distribution

$$f(r) = 2r/R^2, \quad 0 \leq r \leq R$$

and the angular distribution is uniform over $[0, 2\pi)$. Nodes undergo no mobility.

The physical layer is based on the frequency-hop model used in [9]. Each packet is encoded using an $(N, K)$ Reed Solomon (RS) code, with a single code symbol transmitted per hop. There are $M$ frequency channels available. Transmissions are slotted, and each transmitter chooses a random frequency-hopping pattern per slot, with all frequencies chosen for each hop picked uniformly and independently.
A pulse is erased at a receiver if the cumulative interference at the receiver in the same FH channel has power equal to or greater than the desired pulse. The path loss between two radios is modeled as log normal [10] with the mean path loss (in decibels) equal to $20 \log_{10}(d)$, where $d$ is the distance between the two terminals, and standard deviation of $\sigma$ dB. It is assumed here that any fading is flat over the hopping bandwidth. If $\sigma = 0$ dB, path loss is deterministic and based on distance only.

Each radio is assumed to know the path loss to every other receiver, and the power level of each transmission is adapted accordingly. All radios can transmit with enough power to close links to all other radios in the network. Power adaptation using both $\delta$ dB steps and perfect adaptation (i.e., power can be set precisely to the ideal level) is considered. The power level chosen is assumed to include enough margin that thermal noise is negligible. Radios are also allowed, with probability $p$, to increase the power of a particular frequency hop by $\mu$ dB, as described in [9]. This gives additional margin on certain hops, making it more likely that they are not erased. Because this also increases interference to other radios, $p$ should not be too large. A packet is lost if more than $N - K$ pulses are erased. Acknowledgments for each intermediate transmission along the path are assumed (but not modeled), and if a packet is not received, the transmitter re-enqueues it and attempts retransmission on a later slot. Full duplex transmission is assumed. A transmitting node interferes with its own reception on only those symbols where the two signals occupy the same channel.

Each radio in the network uniformly chooses one other node as its intended receiver. Furthermore, every radio has a separate queue for each source / destination flow. Packets are generated according to a two state Markov model. In the “off” state, no packets are generated. When in the “on” state, a node generates a new packet if its queue corresponding to this flow is empty. State transitions can occur on slot boundaries with either probability $p_{o1}$ (off to on) or $p_{10}$ (on to off). Per hop flow control is also used to ensure that the queues of relay nodes remain at manageable levels. A radio cannot relay a packet from a flow (i.e., it is blocked) to the next hop in the path unless the next hop has fewer than $\phi$ packets in the corresponding queue. For the cases considered here, $\phi = 1$.

A variant of slotted Aloha is used for channel access. It is assumed that nodes are perfectly synchronized and that propagation delays and slot guard times are negligible. At the beginning of a slot, each node chooses one of its unblocked queues. The queues can be chosen in a round-robin manner (i.e., all unblocked flows get equal service). However, in the cases considered here, weighted fair queuing is used [12], [13]. At each node, the weight for each queue is determined by the amount of interference a transmission from that queue will cause. (Recall that power is adapted to the minimum needed to close the link to the desired receiver, so the interference level varies per queue.) For example, if a transmission intended for a particular receiver must be transmitted at a power level such that $c_i$ other receivers (including the transmitter) are in range, the weight for the corresponding queue is $w_i = 1/c_i$. If perfect adaptation is used and $\sigma = 0$, $c_i$ is the number of radios that are equidistant or closer to the transmitter than the intended receiver. If $\delta$ dB steps are used for power adaptation or fading is present, nodes at greater distances than the intended receiver may also be counted.

To simplify the decision, the choice of a particular queue is made randomly using probabilities calculated from the weights. The probability that queue $i$ is selected is

$$P(i) = \frac{w_i}{\sum_{k \in \text{unblocked queues}} w_k}.$$ 

Flows that are less likely to cause interference are more likely to be selected.

Once a particular queue is selected, the radio makes a decision to transmit the packet based on interference levels at neighboring nodes. Here, each receiver is assumed to know the number of potential transmissions (i.e., both actual transmissions and transmissions deferred to channel access limitations) for each previous slot that would be strong enough to cause interference. The number of potential transmissions is designated $s_{i,k}$ for slot $i$ at receiver $k$. If $i+1$ is the current slot, each node $k$ calculates

$$S_{i,k} = (1 - \beta)s_{i,k} + \beta S_{i-1,k}.$$ 

Let $U_i$ denote the mean value of $S_{i,k}$ from set of receivers that node $\ell$ can cause interference to if it transmits from the selected queue. As $U_i$ increases, the radios in range of node $\ell$ are potentially subjected to greater levels of multiple access interference, so to keep interference levels reasonable, the probability that $\ell$ transmits should decrease. The probability that node $\ell$ will transmit in slot $i+1$ is

$$Pr(\ell) = \min(1, \gamma/U_i)$$

where $\gamma$ is a network-wide constant. A larger value of $\gamma$ increases the probability of transmission. Variations include setting $U_i$ to the maximum of the $S_{i,k}$, and using actual transmissions (not potential transmissions) to determine the interference level.

### III. ROUTING METRICS

Because all radios are in range of each other, routing is not strictly necessary here. However, by routing to intermediate hops, nodes can reduce transmission power and potentially cause less interference to other radios.

Routes are chosen based on the concept of least interference routing (LIR) [3]. In [3], LIR was considered extensively for random-access networks without spreading. Routes with links that cause little interference to other radios are preferred. Calculating link costs requires knowledge from the physical layer of the power level needed to reach the desired receiver and the effect a transmission at this power has on other nodes in the network.

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1 Because of the use of FH signaling, results using this model are expected to be similar to those from an unslotted random-access system [11].
In the formulation used here, the cost of a particular path (designated \( n \)) from radio \( i \) to \( k \) is

\[
C_{i,k,n} = \sum_{\ell \in \text{Path}(i,k,n)} c^\alpha_{\ell}
\]

where \( \alpha \) is a nonnegative constant, and \( c_{\ell} \) is the number of radios that can hear the transmission from node \( \ell \). Let \( \Psi \) denote the set of all possible routes from node \( i \) to destination \( k \). Path \( m \) is chosen between \( i \) and \( k \) if

\[
C_{i,k,m} = \min_{n \in \Psi} C_{i,k,n}.
\]

The parameter \( \alpha \) can be tuned based on the degree to which potential interference should be avoided. If \( \alpha = 0 \), the path cost is equal to hop count. Because the network is modeled as a fully connected mesh here, each radio will transmit directly to its intended destination. By increasing the value of \( \alpha \), routes with links causing high levels of interference are less likely to be selected. Instead, links with lower power levels are preferred, and the hop count of the path is likely to increase. Note that in general, routes are not symmetric, i.e., the path from \( k \) to \( i \) is not simply the reverse of the path from \( i \) to \( k \). Because node locations and hence potential interference levels do not change in this model, routes are calculated only at network formation.

Other possibilities for routing metrics include least resistance routing (LRR) [6] and minimum power routing. Link costs using minimum power routing are based on the power level used, e.g., \( p^\gamma_{\ell} \), where \( p_{\ell} \) is the transmitter power used by node \( \ell \). To understand why this might perform worse than LRR, consider the case where a node can transmit using a high power without causing much interference (perhaps because it is located in a sparsely populated area of the network). Minimum power routing would give a path using this link a high cost. However, because this link causes little interference and also because it covers a substantial distance (reducing hop count), the corresponding route may work well.

LRR metrics are based on actual interference experienced by the receivers on the path, i.e., the routing algorithm tries to avoid paths whose receivers are subjected to high levels of interference. It has previously been considered for non-fully connected networks subjected to partial band interference [6]. For the fully connected network considered here, the LRR technique would never use intermediate nodes to transmit to the intended destination. (Because costs are additive, the resistance of the final destination is always in the cost.) A variation on LRR incorporates energy consumption to discourage routes using links that have little interference but require high power [7], which would encourage multi-hop routes for the cases considered here. In networks where interference predominantly comes from external sources (e.g., a jammer), LRR techniques should work well. However, unlike LIR, LRR does not necessarily reduce the level of multiple access interference, which is under the control of the network.

\[\text{IV. SIMULATION RESULTS}\]

Network sizes ranging from four to 300 radios are considered for three cases using LIR with various values of \( \alpha \). In the first case, transmitter power levels can be adapted perfectly, and transmissions undergo free-space path loss (i.e., \( \sigma = 0 \) dB). In the second case, there is free-space path loss, and transmitter power levels can be adjusted in \( \delta = 6 \) dB steps. Finally, perfect power adaptation and log-normal fading with \( \sigma = 6 \) dB are considered in the third case. In all cases, \( \beta = 0.8 \) is used when calculating the potential interference estimates needed to determine transmission probabilities. A (32, 16) extended RS code is used for forward error correction. In cases where the transmitter is allowed to randomly vary its power level on a pulse-by-pulse basis (indicated with the tag “random” in the results), power increases by \( \mu = 6 \) dB with probability \( p = 0.4 \). The transition probabilities for the packet generation states are \( p_{01} = p_{10} = 0.2 \), i.e., the generating application is expected to stay in a particular state for five slots and is in the “on” state an average of 50% of the time.

Results were averaged over 50 network runs each consisting of 1000 time slots. Performance metrics of interest include throughput, delay, normalized energy consumption, throughput efficiency, and transmission success probability. Throughput is measured as the average number of packets reaching their final destinations per slot, and delay is the average number of slots between packet creation and final delivery. Throughput efficiency is a measure of the number of packets delivered relative to overall energy usage.

Figs. 1-5 show the performance of the network with perfect power adaptation and free-space path loss. Simulations were run to examine the performance of different values of the channel access parameter \( \gamma \). It was found that \( \gamma = 11 \) gave good performance in all cases except when random transmission power levels were used. When the power level changes randomly from pulse to pulse, \( \gamma = 12 \) was used instead. Fig. 1 shows throughput, and delay is presented in Fig. 2. For small networks with little traffic, the use of FH transmission provides adequate protection from multiple access interference. In these cases, no routing (\( \alpha = 0 \)) gives the highest throughput and lowest delay. When the network size increases to approximately 30 nodes, the channel access protocol begins to throttle the transmission rates of the non-routing networks, and throughput quickly flattens out. With no routing, the use of randomized power levels gives throughput about one packet per slot higher than deterministic power.

Of the networks using routing, the LIR metrics with \( \alpha \leq 0.6 \) give the highest throughputs for small networks. Throughput when using \( \alpha = 0.5 \) is nearly indistinguishable from that when \( \alpha = 0 \), and delay is only slightly higher. This suggests that with values of \( \alpha \leq 0.5 \), packets are rarely forwarded by intermediate nodes. Using \( \alpha = 0.6 \) is slightly worse for small networks. However, as the network size increases, throughput with \( \alpha = 0.6 \) continues to slowly grow and is noticeably higher than both of the non-routing techniques for the 100 node network.
Use of the LIR with $\alpha \geq 0.65$ gives significantly lower throughput than the other metrics for small networks. However, throughput continues to increase approximately proportionally to the square root of the number of nodes. The choice of $\alpha = 0.65$ gives particularly good performance. This gives the highest throughput and lowest delay of all schemes considered for $\alpha \geq 0.65$ and has throughput reasonably close to $\alpha = 0$ for smaller networks. As $\alpha$ increases beyond 0.65, throughput and delay worsen noticeably. These results indicate that the network throughput can be particularly sensitive to the choice of the routing metric.

Simulation results for use of random power levels with routing showed little benefit when the two techniques are combined and are not presented. Because the LIR routing metrics tend to reduce transmitter power levels, the interference experienced by most receivers is small. Thus, occasionally increasing the transmit power is not necessary to overcome interference and in fact causes additional interference to the network since many radios will not hear the transmissions at the base power levels.

Total energy consumption and throughput efficiency are considered in Figs. 3 and 4, respectively. The highest energy consumption and, thus, lowest throughput efficiency, occurs when randomly increasing power to mitigate multiple access interference while not relaying through intermediate nodes. Energy consumption is reduced, but is still relatively poor, for deterministic power and $0 < \alpha \leq 0.6$. Further increases in $\alpha$ reduce energy consumption by larger amounts. Typically, with large $\alpha$, radios will select routes consisting of several short range, low power hops because of the high costs from the interference caused by high power transmissions. For $\alpha = 0.65$ and $\alpha = 0.7$, energy consumption actually drops significantly as the number of nodes increases despite an increased number of transmissions. Throughput efficiency is small and relatively flat for $\alpha \leq 0.6$, but it grows as $\alpha$ increases, particularly as the number of nodes increases. Networks using large values of $\alpha$ have the highest throughput efficiency, despite their relatively lower throughput than networks employing smaller $\alpha$. This demonstrates that energy constrained networks should forgo some throughput in order to extend the useful lifetime of the network.
Fig. 5 shows the average probability that a packet transmission is received. Good throughput performance is achieved for networks with $\alpha \leq 0.6$ with over 20% of packet transmissions failing. However, throughput would decrease if the error rate increased further, so it is important that the random-access protocol limit the number of attempts. For $\alpha \geq 0.7$, the interference reductions from LIR are clearly demonstrated as nearly all transmissions are successfully received for all network sizes. The design of the random-access protocol and the choice of $\gamma$ is not as important here. Even if radios were allowed to transmit without any channel access constraints, the low interference levels would make packet errors unlikely. Finally, with $\alpha = 0.65$, the probability of packet success is noticeably lower than with larger $\alpha$ but approaches 1 in the limit as network size increases. The fact that $\alpha = 0.65$ gives better throughput and delay performance shows that designing to minimize the packet error rate can be suboptimal.

Results for the network in which nodes adapt power in $\delta = 6$ dB steps are shown in Figs. 6-8. Here, a radio chooses the lowest of six discrete power levels that can close the link to its intended receivers. The second highest power level is sufficiently large that a transmitter can communicate with a receiver up to $2R$ m away (i.e., the maximum possible separation between radios). The highest power level is used only in the case where a node can decide to increase transmission power on a particular hop with probability $p$. Because radios are unable to reduce power to precisely the level needed to reach a particular destination, radios cause some additional interference to other receivers in the network. However, there is also typically some excess margin available, so receivers can sometimes tolerate the increased interference. It was found that good performance could be often be obtained using a larger random-access parameter $\gamma$ than that used in the network with perfect power adaptation.

Throughput with 6 dB power adaptation is shown in Fig. 6. With $\alpha = 0$, good performance can be achieved using $\gamma = 13$ when power levels are deterministic and $\gamma = 14$ when they are allowed to vary randomly. Without forwarding, the peak throughput is slightly lower than that achievable with perfect power adaptation. When forwarding does occur, the parameter $\alpha$ generally must be larger than the value used in the case with perfect adaptation in order to achieve equivalent throughput. The highest throughput was achieved for large network sizes when $\alpha = 0.8$ here versus $\alpha = 0.65$ in the previous network. For very large networks with $\alpha = 0.8$ and $\gamma = 13$, nodes did start becoming interference limited. Reducing the number of allowable transmissions by setting $\gamma = 10$ improves the throughput slightly.

As before, delay (shown in Fig. 7), increases with $\alpha$. Delay is also somewhat lower than when perfect adaptation is used. Because nodes can adjust their power only coarsely, there is often no reduction in interference if the routing algorithm chooses a next hop that is moderately closer. Thus, more distance is generally covered per hop and fewer intermediate nodes are needed.

The probability of successful transmission is shown in Fig. 8. Note for large networks with $\alpha = 0.8$, the packet success probability begins to decline. This, along with the throughput results, further indicates that while $\alpha = 0.8$ gives
good overall performance, the network is still becoming interference dominated as the number of nodes increases. Better performance could possibly be achieved with a somewhat larger value of $\alpha$. However, the fact that there is a minimum transmission power, and hence range, suggests the potential for poor performance in very large networks. With perfect adaptation, radios can continue to reduce power and rely on more forwarding nodes to keep interference manageable.

The average hop count of the paths selected by the routing protocol for LIR with several values of $\alpha$ are shown in Fig. 9 for perfect power adaptation and adaptation with 6 dB steps. As demonstrated in the simulation results, $\alpha \leq 0.5$ is essentially equivalent to minimum hop routing (i.e., $\alpha = 0$) for these fully connected networks. However, hop count generally increases with $\alpha$ and as the number of nodes increases. With more nodes, there is greater opportunity to cause interference, so transmitter power must be reduced to minimize the routing cost. For a fixed $\alpha$, hop count is larger with perfect power adaptation.

Finally, results for the log normal channel are shown in Fig. 10 and Fig. 11. While throughput (Fig. 10) without routing is approximately the same as that in the other cases considered, throughput with routing is significantly higher. Throughput is also maximized with much lower values of $\alpha$, with values of $\alpha$ near 0.5 giving very good performance. The delay characteristics of the network with log normal fading are also significantly different (Fig. 11). Moderately large values of $\alpha$ now give lower delay than $\alpha = 0$. The performance improvements with routing are due to a “wormhole” effect whereby many nodes can be reached by forwarding through a small number of intermediate radios that have favorable channel loss characteristics. If no routing is used, transmitters may have to use significant power to reach their destinations.

V. CONCLUSIONS

Performance of random-access ad hoc networks utilizing frequency-hop transmission and least interference routing has been considered. For small or lightly loaded networks, the protection offered by FH transmission combined with power control and transmission control at the physical layer will give good network performance without requiring that packets be forwarded through intermediate nodes. In many cases, tactical networks may contain relatively few nodes, and if
the network is fully connected (or nearly so), it may be best to minimize forwarding and the overhead from searching for routes. However, as networks grow in size, these techniques are not sufficient to maximize throughput without forwarding, and the choice of routing metric becomes more important. It has been shown that LIR can perform well in these networks if its metric is chosen appropriately. Generally, the choice of the optimal LIR metric will depend on network size, load, topology, propagation characteristics, channel access parameters, and the accuracy of transmitter power adaptation. Because it is unlikely that these parameters can be known a priori, development of adaptive routing metrics may be necessary. Also, to achieve the potential gains from forwarding, development of routing protocols with low overhead is needed. Finally, development of code rate adaptation techniques to reduce the effect of interference and their integration with power adaptation and routing techniques should continue.

REFERENCES