Routing in Ad Hoc Networks: A Case for Long Hops

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ABSTRACT

For multihop wireless networks, a fundamental question is whether it is advantageous to route over many short hops (short-hop routing) or over a smaller number of longer hops (long-hop routing). Short-hop routing has gained a lot of support, and its proponents mainly produce two arguments: reduced energy consumption and higher signal-to-interference ratios. Both arguments stem from a simplified analysis based on crude channel models that neglects delay, end-to-end reliability, bias power consumption, the impact of channel coding, mobility, and routing overhead. In this article we shed more light on these issues by listing 18 reasons why short-hop routing is not as beneficial as it seems to be. We also provide experimental evidence to support this claim. The conclusion is that for many networks, long-hop routing is in every aspect a very competitive strategy.

INTRODUCTION

For ad hoc and sensor networks, a fundamental question is whether it is advantageous to route over many short hops (*short-hop routing* or, in the extreme case, *nearest-neighbor routing*) or over a smaller number of longer hops (*long-hop routing* or even *single-hop routing*). Recently, this debate extended to multihop extensions of wireless LANs (WLANs) and multihop cellular networks. Short-hop routing has gained a lot of support, and its proponents mainly produce the following two arguments:

- Lower energy consumption (or higher signal-to-noise ratios [SNRs]). If a long hop of distance d is divided into n hops of distance d/n, the energy or SNR benefit is assumed to be $n^{\alpha-1}$, where α is the path loss exponent.
- Higher throughput (or higher signal-to-interference ratios [SIRs]). The shorter the hops, the higher the received signal strength, whereas the interference is assumed to remain constant. The higher SIR, in turn, results in higher transport capacity in an interference-limited network [1].

The validity of both arguments is rather limited, as discussed in detail in the next sections. The first argument stems from an oversimplified analysis of energy consumption and neglects important issues such as delay, end-to-end reliability, and bias power consumption. The second argument does not consider the total duration of multihop communication and delay, either, and takes advantage of the power attenuation law $d^{-\alpha}$, which becomes unrealistic as d gets small due to the field distribution in the near field of the antenna and the inherent loss in the wireless channel (see the experimental results later for a specific example of how the path loss deviates from the power law at small d).

In this article we shed more light on these issues by listing 18 reasons why short-hop routing is not as beneficial as it seems to be. Some of the reasons have been individually mentioned in other work and/or discussed from a more theoretical perspective in [2]. Here we present a comprehensive collection, with the aim of providing insight rather than detailed theoretical analyses, and we corroborate and illustrate our findings with experimental results using different generations of the Berkeley motes sensor network platform. Small experiments are included with their respective reasons, and a larger experiment with 10 nodes running for 24 h is described and discussed.

NETWORK AND LINK MODEL

Part of our discussion applies to many types and classes of networks and wireless channels. However, to be concrete we often focus on networks with random node distribution and additive white Gaussian noise (AWGN) or Rayleigh fading channels.

Node distribution. Analytical results are often derived for networks whose nodes constitute a Poisson point process in the plane. Note that for infinite networks the Poisson point process corresponds to a uniform distribution, and for large networks the two distributions are equivalent for all practical purposes.

Generic routing. Many different routing algorithms exist for ad hoc and sensor networks, but common to all of them is the fact that at each hop, progress shall be made toward the destination. This generic routing strategy is illustrated in Fig. 1. If the nearest neighbor within a certain sector of the source-destination axis (node S) is

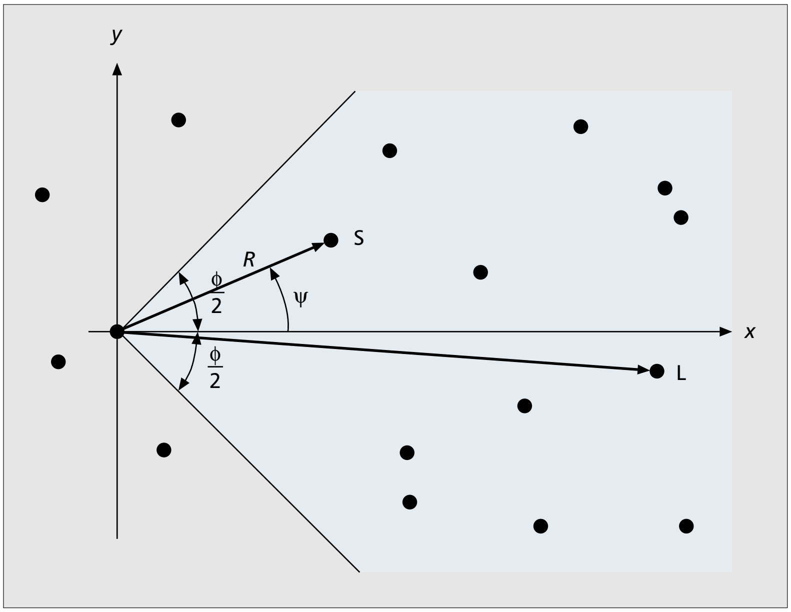

Figure 1. *Part of a random network with the source at the origin and the x-axis pointing toward the destination node.* S *and* L *denote possible first relay nodes in a short- and long-hop scheme, respectively. In this case,* S *is the nearest neighbor within a sector* ϕ *around* x*, at distance* R *and angle* ψ*. Hence (*R*,* ψ*) are the polar coordinates of the nearest neighbor within a sector* ϕ*.*

chosen as the next relay, this is certainly an instance of short-hop routing. If many nearby neighbors are skipped and a node transmits directly to a more distant neighbor (say, node L), we speak of long-hop routing.

Note that the distance to the nth nearest neighbor that lies within the desired sector follows immediately from the Poisson assumption. For $n = 1$ (nearest neighbor), the distance is Rayleigh distributed; for higher n, it follows a generalized gamma distribution [3]. The expected energy consumption for a transmission to the nth neighbor is then given by the αth moment of the distance random variable.

Link model. Often, a *disk model* (or *protocol model*) [1] is used for the analysis of wireless networks, where a transmission is either 100 percent successful or fails completely, depending on whether the distance is smaller or larger than the so-called transmission radius. More realistic is the *threshold model* (or *physical model*), also considered in [1], where a certain signal-to-interference-and-noise ratio (SINR) is needed for successful transmission. Still, for additive white Gaussian noise (AWGN) channels, the threshold model yields 0 or 100 percent probability unless the Gaussian distribution of the noise is explicitly taken into account and should therefore be used with care, in particular for relatively short packets and/or weak channel codes. Although some of the reasons listed in the next section also apply to the disk model, we mostly use a physical AWGN or Rayleigh block fading channel model. In the Rayleigh fading model, it is assumed that a certain (instantaneous) SINR level Θ is required for successful reception (threshold model). This threshold, together with the noise variance, the *relative* transmitter-receiver distances of the desired transmitter and the interferers, and their relative power levels, determine the reception probability in a Rayleigh fading environment [4].

Hardware. For the experimental part, we used the Mica2 and MicaZ generation of Berkeley motes. The Mica2 motes use a CC1000 (Chipcon) radio at 433 MHz with frequency shift keying (FSK) and a transmit power range from –20 to 10 dBm. The MicaZs are Zigbee (IEEE 802.15.4) compliant, transmitting in the 2.4 GHz industrial, scientific, and medical (ISM) band with orthogonal quaternary phase shift keying (OQPSK)/direct sequence spread spectrum (DSSS) with power levels ranging from –25 to 0 dBm. Both types of motes are powered by standard AA batteries. Detailed information on the motes can be obtained at http://www.xbow.com.

Reasons for Routing over Long Hops

Clearly, the most compelling argument against short-hop routing is the end-to-end delay. However, we do not consider delay in itself an argument for long-hop routing, since energy and delay can be traded off against each other. So, for a fair comparison, we may fix the energy consumption and search for the protocol with the smallest delay, or impose a delay constraint and determine which protocol consumes the least amount of energy.

Interference

According to [5], when comparing short- and long-hop routing, "It is unclear whether more interference is caused by a single transmission at higher power or multiple transmissions at lower power." Indeed, a shorter transmission at higher power (corresponding to a shorter route with longer hops) may permit more efficient reuse of the communication channel. So what matters for the interference are not the transmit power levels but the total radiated *energy*. That is, the products of the power levels and durations of the transmissions. Thus, minimizing the interference equals minimizing the transmit energy. The routing schemes with the least energy consumption will also be those causing the least interference. It is then a matter of designing a clever medium access control (MAC) scheme to take advantage of this reduced interference.

It must not be forgotten that the SIR does not depend on absolute power levels. If all nodes scale their power by the same factor > 1, all the SIR levels remain constant, but the SINR levels increase. Thus, increasing all transmit power levels in the network by the same factor does not have a negative impact on any packet reception probability in the network (on the contrary), in stark contrast to what is predicted by the disk model. This fact and the energy considerations indicate that *long-hop transmission does not inherently cause more interference*. Hence, it is not clear a priori which routing scheme will provide the best throughput.

End-to-End Reliability

Under the disk model, reception probabilities are either 100 or 0 percent. If every receiver is in its desired transmitter's disk, the end-to-end reliability is always 100 percent, which is clearly not realistic, since packet errors or bit errors accumulate — the end-to-end reception probability is the product of the link reception probabilities (assuming no retransmissions). So to achieve a desired end-to-end reliability with short-hop routing, the relay nodes need to transmit at a higher power. This offsets, at least partially, the SNR gain of short-hop routing.

Experimental results. Five Mica2 motes are arranged in a line with internode distance 1.5 m in an indoor environment with some obstacles. 1000 packets of length 240 bits are transmitted and relayed through the network at a rate of 2 packets/s at –15 dBm transmit power. The solid line in Fig. 2 shows how the reliability decreases along the route (solid curve) when all links are highly reliable. The curve follows quite exactly a geometrical progression where at each hop about 0.8 percent of the packets are lost. The other two curves demonstrate the susceptibility of the route to small-scale fading: if any one of the nodes in the route moves by about half a wavelength, it may end up in a bad fading spot, which severely harms the end-to-end reliability. The smaller the number of hops, the less likely this is to happen.

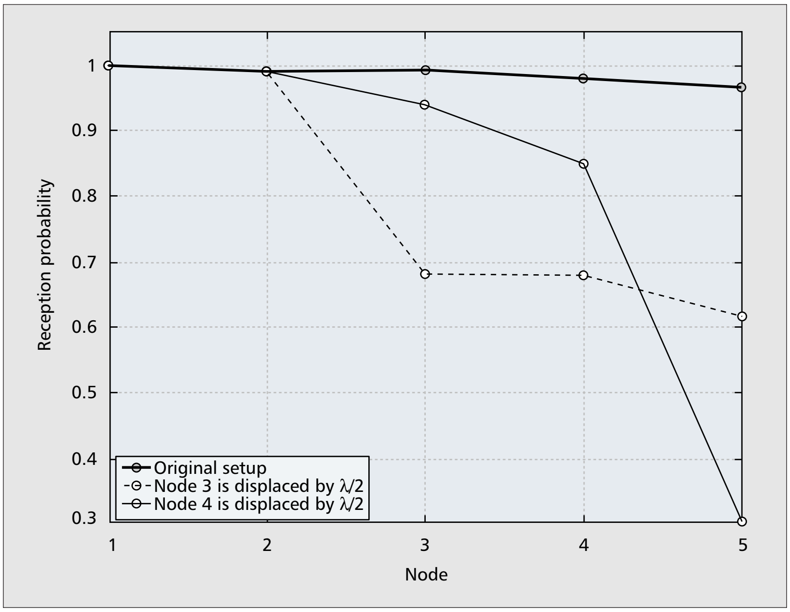

Figure 2. *Reliability of a multihop connection for three different network arrangements. The solid line represents the case where all five Mica2 nodes are exactly in a line; for the other two curves, one of the nodes is displaced by about half a wavelength (35 cm).*

Shannon Capacity

Assume that a certain distance in a network is covered by an n-hop route for some small n, say $1 \leq n \leq 5$. In this case spatial reuse is not possible (maybe the first and last link could be used simultaneously, but even this is not certain), so a simple time-division multiple access (TDMA) MAC scheme will perform optimally. Dividing the distance into n hops increases the SNR at each hop by n^{α}. On the other hand, the end-to-end rate is decreased by a factor of n. So the n-hop scheme needs to transmit at an n times higher per-hop rate to achieve the same end-to-end throughput.

Since the rate loss is linear while the gain from the increased SNR is only proportional to $\ln n$, there exists an optimum n for each end-to-end rate. Focusing on the case of one vs. two hops, for example, it can be shown that single-hop outperforms two-hop routing as soon as the desired bandwidth-normalized rate (spectral efficiency) is larger than the path loss exponent α. A detailed analysis and comparison of Shannon capacity in n-hop line networks is presented in [6].

Channel Coding

If practical channel codes are taken into account, multihop is further penalized due to the necessary encoding and decoding at each hop. In particular, for near-capacity coding strategies such as turbo and low-density parity-check (LDPC) codes, the decoding delay may be significant due to the iterative decoding schemes employed. More important, under the same delay constraints, short-hop schemes have to resort to shorter block lengths, which implies a larger gap to capacity than for long-hop schemes.

Total Energy Consumption

It is often assumed that a reduction of the transmit (or radiated) energy yields a proportional reduction of total energy consumption. Even without taking into account receive energy, this is not true for any practical power amplifier. In particular, in low-power transceivers, the local oscillators and bias circuitry will dominate the energy consumption, so that short-hop routing does not yield any substantial energy benefit if a more distant relay node can be reached with sufficient reliability [7]. For random networks, relatively high peak power levels are necessary to keep the network connected [8], and short-hop routing would require a substantial backoff on the average, resulting in poor power efficiency at the power amplifier.

Experimental result. The measurement in Fig. 3 shows that for the MicaZ and Mica2 hardware, the total power consumption is almost independent of the transmit power. The fraction of power actually transmitted ranges from less than 0.1 percent at the lowest power setting to 1.4 percent for MicaZ and 14 percent for Mica2 at their respective highest output power levels. Clearly, reducing the output power does very little to save energy, and the receive power consumption is as high as the transmit power consumption.

Path Efficiency

Routes in random networks cannot follow straight lines. The path efficiency, defined as the ratio of Euclidean distance of the end nodes and the actually traveled distance, is higher if longer hops are used. Consider the generic routing strategy in Fig. 1. For nearest-neighbor routing in a sector ϕ the expected path efficiency for a long connection is $E[\cos\Psi]$. If long hops are permitted, the routing algorithm can find nodes that are closer to the source-destination axis, resulting in smaller angles Ψ. In the extreme case of single-hop routing, the path efficiency is trivially one. For regular networks, nearest-neighbor routes may also be inefficient. For a square lat-

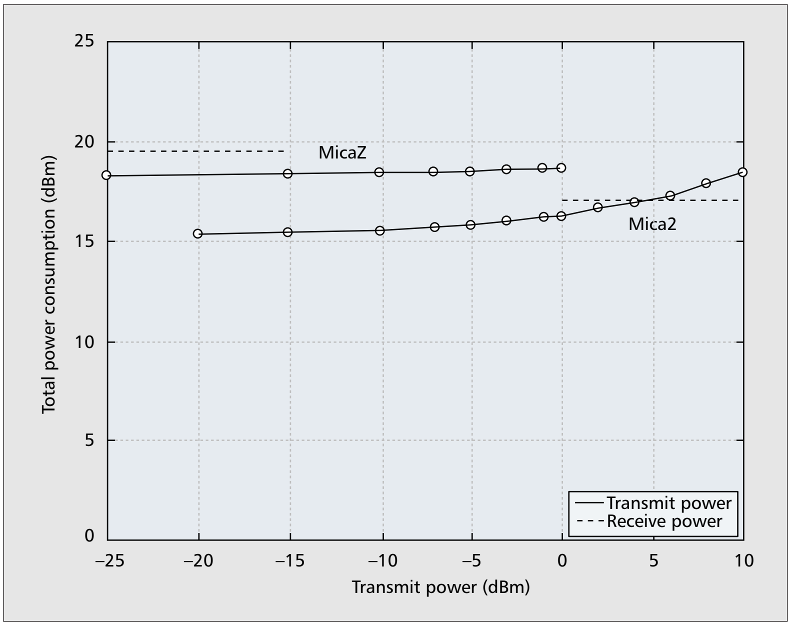

Figure 3. *Total power consumption vs. transmit power and receive power.*

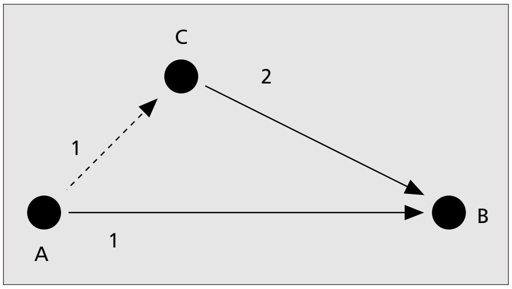

Figure 4. *Simple cooperative scheme. A first transmits to B, and in the second time slot the cooperating node C retransmits the information it received when overhearing A's transmission.*

tice network, for example, with source and destination at opposite corners, the path efficiency is only $1/\sqrt{2}$ if nearest-neighbor routing is employed.

Sleep Modes

If nearby neighbors are not used as relays, they can be put into very low-power sleep modes, whereas short-hop routes require many nodes to be awake frequently. Sleep modes provide substantial energy savings, particularly for sensor networks. For the mote platforms, the energy consumption in sleep mode is typically 30 dB smaller than in receive or transmit mode and about 27 dB smaller than in idle mode. Thus, in periods of low activity, it is desirable to have only a few nodes awake as sentries, which requires long hops to keep them connected. Generally, in ad hoc networks, if a given source-destination pair is exchanging bursty traffic, it is often impossible to use sleep modes at the relay nodes due to the limited accuracy of the sleep schedules and the uncertainty in the traffic and wireless channel. Also, the energy consumption at wakeup may be substantial compared to the benefit of a short sleep period, so long hops are preferable to reduce the number of active nodes.

Experimental result. See "A 10-Node Experiment" later.

Cooperation

Cooperation between nodes has received considerable attention in the information theory and networking communities [9, 10]. Especially for fading channels, the cooperative diversity gains can be substantial. The situation that is typically studied is a three-node arrangement (Fig. 4), where cooperating node C, overhearing the transmission of source A, relays the information to destination B, so B receives two versions that can be combined beneficially. A very simple form of cooperation would be to have C retransmit a packet if an acknowledgment is not received from B, rather than having A itself retransmit. Nearest-neighbor routing foregoes most types of cooperation.

Routing Overhead and Route Maintenance

In [5] it is pointed out that (when we replace a larger number of short hops by a smaller number of long hops) "It is far from clear what happens to the overall transmission energy, since to implement a nearest-neighbor policy, significantly augmented overhead control traffic will be required to coordinate the establishment of the routing paths and access control protocols across the entire network."

In a first order approximation, the control traffic for routing and route maintenance is proportional to the number of nodes in the route. Also, the probability of a route break due to energy depletion and node failure clearly increases with the number of nodes involved, as well as the memory requirements for the routing tables. In addition, energy consumption cannot be balanced efficiently among nodes if it is required that all nearest neighbors participate in routing. Long-hop schemes have a drastic advantage when it comes to avoiding low-energy nodes as relays.

Experimental results. See "A 10-Node Experiment."

Link Longevity in Mobile Environments

The SNR of short-hop routes is more quickly affected by moving nodes. For example, if a node at distance 1 moves away by 1 unit, the SNR change is 2^{α}, which causes the link to break[1] (unless an unreasonably high SNR margin is applied when the route is initially established). On the other hand, if a relay node is 3 units away and moves by the same distance, the SNR change is only $(4/3)^{\alpha}$, which can probably be tolerated. Figure 5 illustrates this scenario for $\alpha = 2$ and an SNR margin of 3 dB; that is, the transmit power is set such that the SNR at the receiver's initial position is 3 dB above the threshold Θ. As can be seen, node L can move in an arbitrary direction in a substantially larger area without causing a link break. If the mobility pattern is linear, the lifetime of a link is roughly proportional to its (original) length. For more local random patterns such as Brownian motion

[1] *Here we consider a link to be broken if it cannot anymore provide a certain reception probability.*

or other random walks, the gain in lifetime may be much more significant. So longer hops are less susceptible to link breaks than short hops.

The arguments above are based solely on large-scale path loss. Small-scale fading can have an even more harmful effect on short-hop routes, as shown in Fig. 2.

Experimental results. Using MicaZ motes, we compare the packet loss probabilities at d_s and $2d_s$ with those for d_l and $d_l + d_s$. The transmit power is adjusted such that the loss is about the same at the initial distances d_s and d_l. The results are presented in Table 1. As can be seen in the ratio column, the short links suffer significantly more if the link length is increased by the same amount.

TRAFFIC ACCUMULATION AND ENERGY BALANCING

For sensor networks or multihop cellular networks, traffic accumulation around a base station (BS) or access point can pose a formidable problem. With strict short-hop routing, the relaying burden cannot be distributed among a high enough number of nodes, leading to a critical area around the BS whose nodes suffer from a short lifetime. If long hops are permitted, more nodes can reach the BS directly, and the relay traffic can be distributed more evenly.

Also, if all nodes in a chain are constantly used as relays, the energy consumption cannot be balanced among them. Only if longer hops are available can some low-energy nodes be put to sleep.

Experimental results. See "A 10-Node Experiment."

VARIANCE IN HOP LENGTH IN RANDOM NETWORKS

Consider a random network with nearest-neighbor routing and a power control scheme that adapts the transmit power to the large-scale path loss d^α to maintain a certain link quality. In this case the variance of the hop length d [3] leads to increased variability in energy consumption. The expected maximum link energy consumption in an n-hop route grows as $\ln(n)^{\alpha/2}$ [2]. So the route lifetime decreases at least with $1/\ln n$.

If longer hops are permitted, the distances and thus the power consumption can be better equalized among the nodes in a route. The farther a node can transmit, the smaller the variance in the hop distances can be made by choosing the furthest node within a certain maximum distance.

BOUNDED ATTENUATION

As pointed out in the introduction, a path loss model with a singularity at distance $d = 0$ is not realistic for networks with high density. Clearly, the transmit power is a natural bound on the received power, but due to the inherent losses in the wireless link, there is a much lower bound, say bP_t, where P_t is the transmit power and $b \ll 1$. So a more realistic path loss model is $\min\{b, cd^{-\alpha}\}$, where c depends on the antenna gains, wavelength, and circuit losses. In this case there is no benefit of using shorter hops than

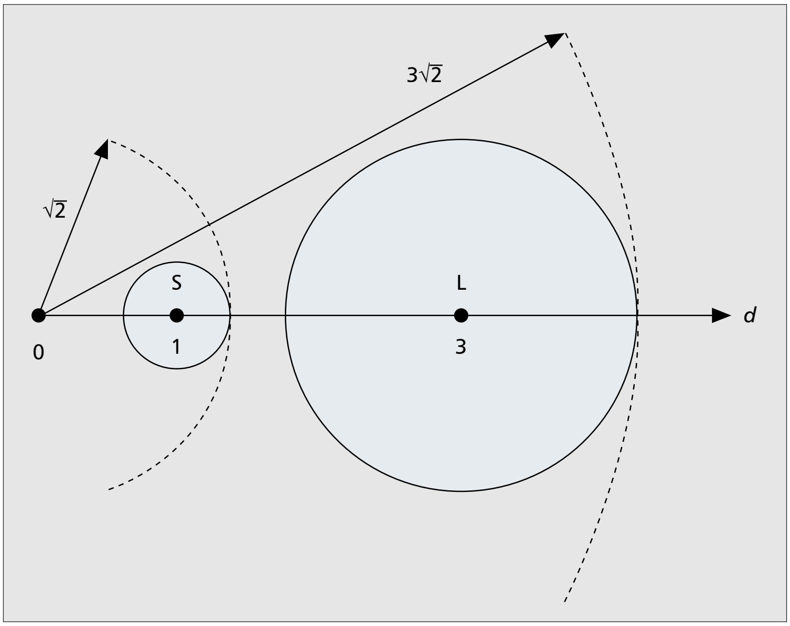

Figure 5. *Comparison of short- and long-hop routing in a mobile environment. The distance to the short- and long-hop relays is $d_s = 1$ and $d_l = 3$, and a link margin of 3 dB and a path loss exponent of 2 are assumed. The shaded ball is the largest ball in which the nodes can move in any direction without breaking the link. The area of L's ball is $(d_l/d_s)2$ times larger than that of S's ball.*

Distances (m)	Transmit power (dBm)	Loss probabilities	Ratio
d_s = 0.6,1.2	–25	2%, 9%	4.5
d_l = 2.4,3.0	–15	2%, 4%	2.0
d_s = 1.0,2.0	–25	6%, 22%	3.7
d_l = 5.0,6.0	–10	5%, 13%	2.6

Table 1. *Packet loss probabilities at different distances and power levels for MicaZ.*

$d_{\min} := (b/c)^{-1/\alpha}$, since the received power does not increase if the distance is decreased further. Thus, each hop should have length $d_{\min}$ at least, no matter how many nodes are closer than that.

Experimental result. Figure 6 shows measurement results using Mica2 motes. The signal strength starts to flatten out at distances smaller than about 2 m. At shorter distance, the path loss curve deviates significantly from the power law $5 \cdot 10^{-5} d^{-3}$. The cap on the received signal strength is at about –53 dBm, so we have $b \approx 10^{-5.3}$ and thus obtain $d_{\min} \approx 2.1$m (for $\alpha = 3$), which, at a wavelength of $\lambda = 0.69$ m, is quite exactly 3 wavelengths. Hence, hops shorter than a few wavelengths should be avoided.

OPPORTUNISTIC TRANSMISSION

In a fading environment with little or no node mobility, links to nearby neighbors may suffer continuously from bad fading states, whereas links to more distance neighbors may benefit from constructive fading. Hence, more distant nodes may be reachable at no additional energy

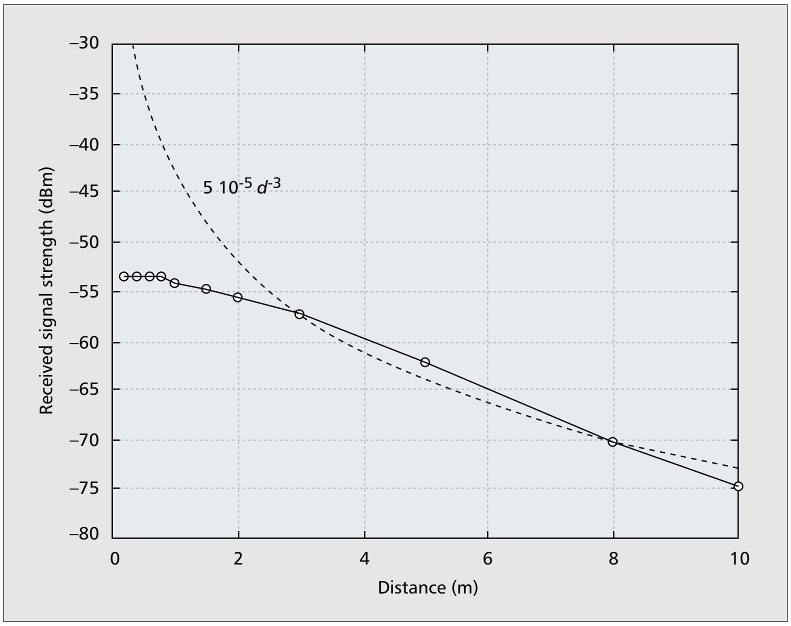

Figure 6. *Signal strength as a function of distance for Mica2 motes for a transmit power of 0 dBm measured in a laboratory environment. To avoid the problem of fading, a large motorized turntable is used to average out the fading component. The dashed line shows a power law curve whose parameters were found by curve fitting.*

expenditure if long hops are permitted. With mobility, a long-hop scheme can continuously select the best relay among a large number of neighbors.

Experimental result. See "A 10-Node Experiment."

PERCOLATION AND CONNECTIVITY IN RANDOM NETWORKS

As discussed in [11], long hops substantially improve the connectivity of a random network, even at the cost of losing some short ones. The percolation threshold, that is, the critical node degree above which an unbounded connected component exists (in an infinite network), is a good indicator for connectivity. Below the percolation threshold, the network is certainly disconnected, whereas above the threshold, two randomly chosen nodes are connected with positive probability.[2] If only hops shorter than a certain length are used (disk connection model), the average node degree must be at least 4.51. On the other hand, if long hops are allowed with a certain probability (random connection model), the average node degree can be lowered to 1. For a fair comparison, the area of the so-called connectivity function is the same in both cases, which implies that permitting long hops comes at the cost of making short hops less reliable. Nonetheless, there is a significant benefit if long hops are allowed.

DELAY VARIANCE

Until now, we have only discussed and compared the *mean* delay incurred in short-hop and long-hop routing. If the network offers delay guarantees, (at least) second-order statistics have to be taken into account as well. For purposes of illustration, assume that the delays at each hop are iid exponentially distributed with mean 1 and thus variance 1. In this case both mean and variance increase linearly with the number of hops in a route, and the cumulated delay is gamma distributed. Figure 7 shows the (cumulated) delay that can be guaranteed with probabilities p_D = 90 percent and p_D = 99 percent in an n-hop route. It can be seen that this minimum guaranteed delay grows faster than proportional to n. This is also true if the per-hop delay were normally distributed with mean μ and variance σ^2; in this case we would expect the delay guarantee to grow like $n + \sqrt{\sigma^2}$. The curve $n + \sqrt{n}$ (corresponding to an 84 percent delay guarantee for normally distributed delays) is shown for comparison in Fig. 7. It can be seen that it is a good approximation for the exponential case.

In practice, the per-hop delay may not be exponential or Gaussian, and the iid assumption may not hold. For example, if traffic is heavy and there is a backlog at the nodes' queues, the queuing delays in the resulting tandem queue system will be negatively correlated (i.e., a long delay at hop i will likely lead to a shorter delay at node $i + 1$, since the backlog at node $i + 1$ will be reduced while this node is waiting for the next packet from node i). Nonetheless, due to the uncertainty in the wireless channel, the variance will still increase along the route, leading to an overproportional increase of the guaranteed delay. On the other hand, if the traffic is light, most of the delay will be due to retransmissions of lost packets (service time). In this case the delay incurred by an automatic repeat request (ARQ) scheme will be iid geometrically distributed with parameter p_r. Since the geometrical distribution is the discrete counterpart of the exponential distribution, we can expect similar behavior to that shown in Fig. 7. For other distributions, similar conclusions can be drawn by considering delay variances and invoking Chebyshev-type inequalities.

So, while a mean delay constraint can simply be broken down to individual links, the superlinear growth of the guaranteed delay with the number of hops in the case of hard delay constraints enforces the use of fewer (i.e., longer) hops.

MULTIPATH ROUTING

Routing over multiple path simultaneously has gained momentum in recent years in the routing community. To ensure that the routes are not only node-disjoint but also cause minimum inter-route interference, they need to be spread out as quickly as possible from the source and destination nodes. One way to achieve this is to define individual routing sectors for each multipath branch in the sense of Fig. 1. For sufficient separation, one may want to define the angle ϕ for each branch in such a way that the sectors are separated by 2ϕ, while avoiding routing backwards. In doing so, for n-branch multipath routing, we obtain $\phi = \pi/(3n - 2)$. The case $n = 3$ is illustrated in Fig. 8. The multipath routing algorithm now needs to identify suitable relay nodes in each sector. Even if nearest-neighbor routing is used, the resulting hops will be longer than in the single-route case due to the smaller ϕ. In a

[2] *Note that no finite node degree is sufficient for strict connectivity.*

random network of density 1, the expected distance to the nearest neighbor in a sector ϕ is

$$\sqrt{\pi/(2\phi)},$$

so with n-branch multipath routing this distance becomes

$$\sqrt{3n/2-1}.$$

The required maximum hop length (transmission range) that guarantees that a node can be found in a sector $\phi(n)$ is also increasing with $\sqrt{n}$. This shows that close to the source and destination, multipath routing requires longer hops.

It is also desirable that the multipath routes have approximately the same number of hops to avoid large differential delays or packet reordering. So the variance of the number of hops in each route should be small. Assume the mean hop length is $\bar{h}$ and the "straight part" of the routes has length D (Fig. 8). If these straight parts were one-dimensional networks with Poisson distributed nodes, the hop numbers themselves would be Poisson random variables with mean and variance $D/\bar{h}$. If the routes are two-dimensional, the hop numbers are not Poisson, but their variance is still inversely proportional to $\bar{h}$, which shows that only long-hop multipath routing leads to routes of comparable length.

Multicast Advantage

So far, we have only addressed unicast routing. For multicast, other trade-offs between short-hop and long-hop routing exist. In particular, as discussed in [5], it is advantageous for a source to transmit at high power levels to reach a maximum number of nodes in the multicast group, thereby reducing the total delay significantly. This advantage is also apparent in multipath routing (Fig. 8): if the same information is sent over all routes, the n first relay nodes form a multicast group, and the transmit power should be chosen such that all of them can be reached with sufficient reliability.

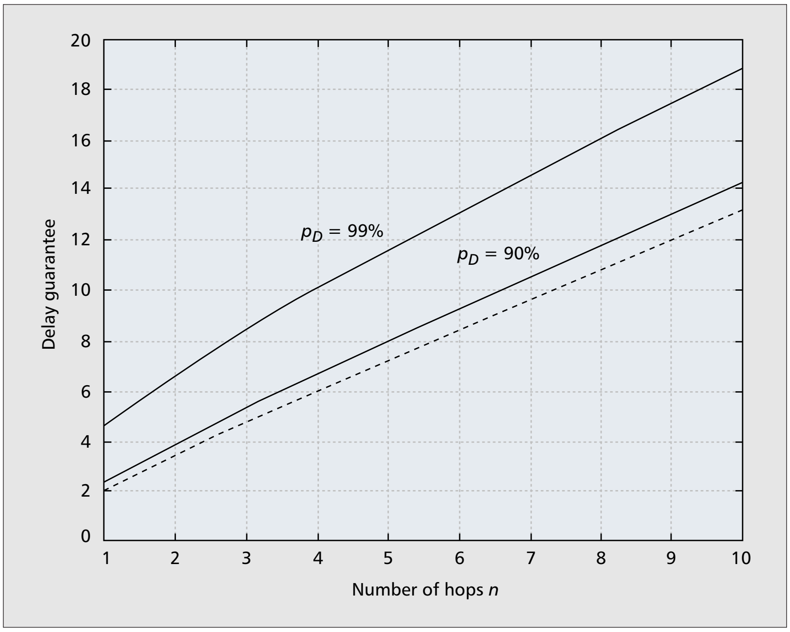

Figure 7. *The minimum delay that can be guaranteed with probabilities p_D = 90 percent and p_D = 99 percent in a route if the per-hop delays are iid exponential with mean 1. The value for $n = 1$ is $-\ln p_D$. The dashed line, for comparison, is $n + \sqrt{n}$, which is the delay that can be guaranteed with 84 percent reliability for normally distributed delays with mean and variance 1.*

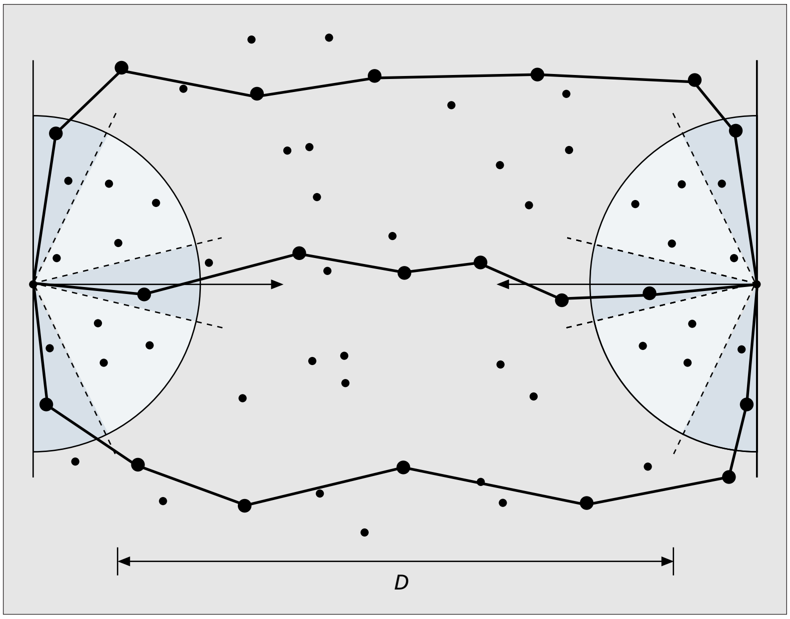

Figure 8. *Example for multipath routing with n = 3 branches. The angle of the routing sector for each branch is $\pi/7$ (shaded sectors), while the sectors in between are twice as wide.*

A 10-Node Experiment

The goal of this larger experiment is the validation of several of the reasons mentioned in the previous section and, consequently, the demonstration of the superiority of long-hop routes in this particular case.

Setup and Routing Algorithm

We placed 10 MicaZ motes in a laboratory environment in an arrangement shown in Fig. 9. This network is to deliver a continuous stream of packets at a rate of about 40 packets/min from node 1 to node 10 over a duration of 24 h. Although the nodes themselves are static, people moving in the laboratory cause a certain amount of fading.

Description of routing algorithm. A metric is calculated at every node for each possible route consisting of a weighted sum of the minimum link quality (quality of the weakest link), the minimum node battery voltage, and the inverse of the number of hops in the route. Every node selects the downstream neighbor with the maximum metric. This process is repeated on all the awake nodes every 5 s. If a node is not used for routing at least seven times in a 30 s period, it goes to sleep for 60 s.

The metric used to establish the route from node 1 to 10 favors energy balancing and long hops, as it penalizes large hop numbers and avoids nodes whose batteries are low.

Fresh batteries were used, the transmit power is –15 dBm for both control and application traffic, the MAC scheme is standard carrier sense

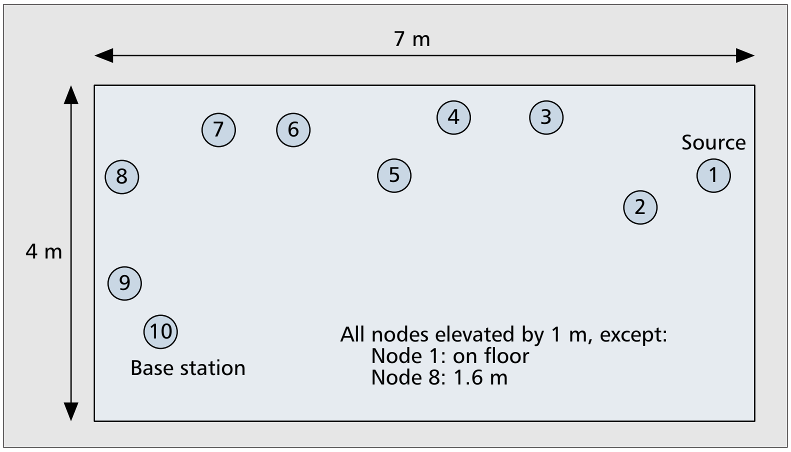

Figure 9. *Setup of the 10-node experiment in an indoor environment.*

multiple access with collision avoidance (CSMA/CA), and no acknowledgments are used to make links reliable. A packet containing the current battery voltage is transmitted to the BS by each node at full power (0 dBm), and the motes' LEDs are used for monitoring purposes.

Results

In the 24 h experiment, 59,040 packets were transmitted (41/min on average), and 50,864 were successfully received at the BS, corresponding to a packet loss of about 14 percent. Given that there were no retransmissions at all and the transmit power was relatively small, this loss is quite acceptable.

Among all the routes found, 9.4 percent were single-hop, 87.7 percent were two-hop, 2.5 percent three-hop, and 0.4 percent four-hop (or more). The *mean* path loss over a distance of about 8 m prevents packets from being received at a transmit power of –15 dBm. So the fact that single-hop routes exist indicates that the algorithm exploits positive fading states (i.e., is opportunistic), thereby allowing all relay nodes to sleep for some period.

Figure 10 shows that some nodes are used as relays much more frequently than others (e.g., nodes 4 and 5 in the left plot), while the depletion curves look quite similar (thanks to the energy balancing component in the routing metric), so the battery drainage is not uniform, although all nodes use the same transmit power. Node 5 is relaying quite exactly 10 times more packets than node 4, indicating that it operates more efficiently and/or has a stronger battery.

Comparison with Short-Hop Routing

Comparing our discharge curves with the ones provided in the battery data sheet,[3] we can conclude that the source node has consumed about 2 kJ and the relay nodes roughly 1 kJ in the 24 h period, corresponding to average power levels of 23 mW and 11.5 mW, respectively. This 50 percent gain at the relays is in good agreement with the 2/3 sleep period of unused nodes. With short-hop routing, the discharge curves of the nodes would all be lower than for the source node in Fig. 10b, since all the relays would not only transmit each packet but also receive each packet, and the receive energy is substantial (Fig. 3).

If the individual nodes are considered, the situation may be substantially worse for short-hop routing. Consider node 4, whose battery is depleted to the same level as the other relay nodes', although it only relayed 1323 packets. Extrapolating, this node may die after only about 4000 packets, which would cause the (strict) short-hop route to break. Clearly, relying on every node in the chain may drastically reduce the lifetime, by much more than just a factor of two compared with the long-hop algorithm. Also, the use of sleep modes is certainly not aggressive in the algorithm used. By increasing the length of the sleeping periods, even higher gains can be expected.

So, in summary, the key advantages of the proposed long-hop scheme are that packets reach the BS about four times faster, and the network lives at least twice as long, most likely much longer. This significant gain is achieved by an algorithm that exploits sleep modes, favors long hops with favorable fading state, and aims at energy balancing. The long hops also require less maintenance and are more robust to node

[3] *See the data sheet for the EN91 batteries at http://www.utilitysafeguard.com/s.nl/sc.23/category.2564/.f*

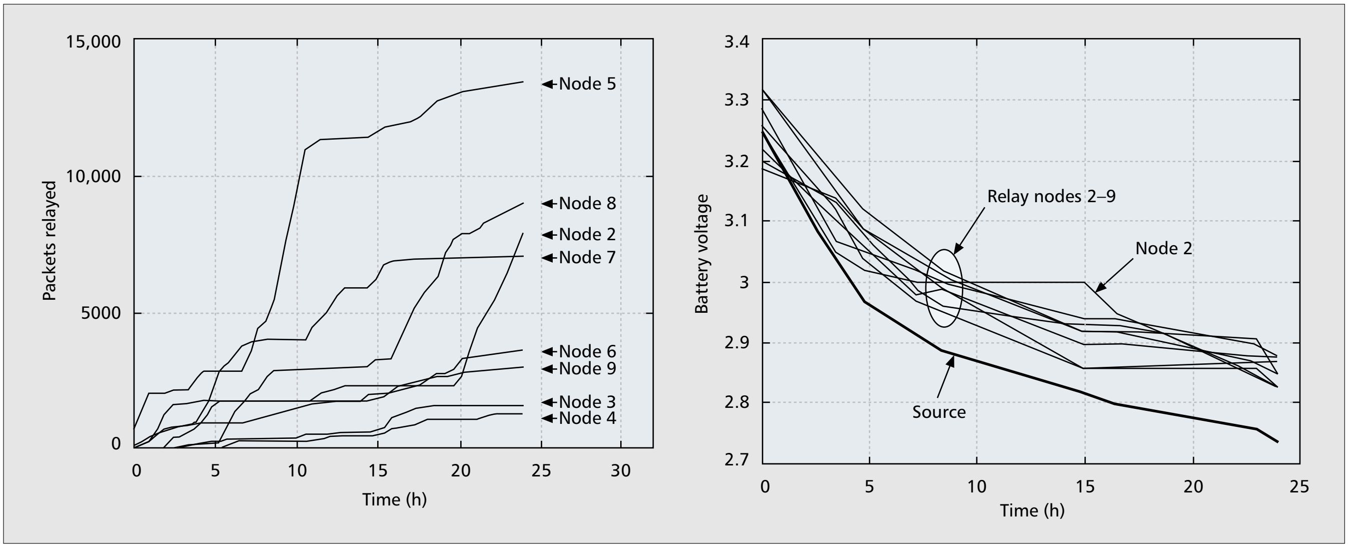

Figure 10. *Measurements for the 24 hour experiment.*

failures, and, in a multisource setting, would alleviate the problem of traffic accumulation around the BS.

CONCLUSION

We have listed 18 reasons why the trade-off between routing over many short hops and routing over fewer longer hops is not as clearcut as is often assumed. Many of these reasons are also verified and illustrated experimentally on sensor networking hardware. Not all reasons apply to all types of networks, of course, but several of them will be relevant for most networks. The conclusion is that *routing as far as possible is a very competitive strategy* in many cases. Conversely, from a design perspective, the peak transmit power should be chosen such that a node can reach well beyond nearest neighbors.

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