The Importance of the Multipoint-to-Multipoint Indoor Radio Channel in Ad Hoc Networks

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Abstract--Study of the multipoint-to-multipoint (M2M) radio channel, the physical backbone of wireless ad hoc networks, has direct application in the simulation and design of multi-hop routing protocols. The ad hoc network radio channel differs from the point-to-point or point-to-multipoint channels previously investigated, since each device may communicate with any other device. First, this paper presents a M2M measurement campaign conducted in an open-plan office area at 925 MHz. The measurements are analyzed to demonstrate spatial correlation between neighboring hops in the network. Then, the measurements are used to numerically characterize the effectiveness of a minimum-energy routing scheme. These measurements show that using existing models in the simulation of ad hoc networks can result in inaccurate results. Observations are made about the performance of a minimum-energy routing protocol in a real M2M radio channel. Finally, a channel model is suggested to more accurately represent the M2M radio channel.

I. INTRODUCTION

This paper considers the physical radio channel of a M2M network. Such radio networks have been long considered for military networks because of their 'survivability' characteristics [1]. M2M networks have recently become even more important because of wireless ad hoc network applications. The M2M radio channel is the physical backbone of the multi-hop routing protocols proposed and being evaluated for use in wireless LANs [9], wireless sensor networks [4], and 4G cellular systems.

A log-normal shadowing channel model is given by

$$p_{i,j} = p_0 - 10n\log_{10}\left(\frac{d_{i,j}}{d_0}\right) + X_\sigma \qquad (1)$$

where $p_{i,j}$ is the received power at device i transmitted by device j, p_0 is the received power at a reference distance d_0, n is the path loss exponent, $d_{i,j}$ is the path length, and X_σ is the fading error, a zero mean Gaussian random variable with standard deviation σ_{dB} [11]. This channel model has been used to represent point-to-point and point-to-multipoint indoor channels [6]. However, we know of no multipoint-to-multipoint measurements conducted and reported to verify the model for M2M networking applications.

An accurate M2M channel model would be of value in ad hoc networking research. Researchers have used the physical channel as motivation for having a multi-hop network. Because of the d^{-n} path loss characteristic, it is advantageous from a total radiated power perspective to make multiple short hops rather than a single long transmission. In an environment with a higher n, this advantage is more noticeable. The reduction in transmit power comes at the price of increased receiver energy dissipation. However, as IC advances cause receiver energy consumption to fall, more and more systems will find multi-hop networks to be advantageous.

Several researchers have used radio channel models to evaluate the energy-efficiency of multi-hop routing protocols [3][5][7][8][10]. Typically, researchers have been content to use a d^{-n} channel model without modeling channel fading ($X_\sigma = 0$). Such analysis and simulation is used to get rule-of-thumb system characteristics or proof-of-concept results. But the random nature of the fading channel shouldn't be neglected. When considering several hops in series, the randomness of the channel has more severe effects compared to a single-hop channel. Just one severe fade in along a multi-hop route could cause a packet to be lost. However, when several multi-hop routes in parallel are possible to get a message from source to destination, there is a type of route diversity. Having multiple parallel routes allows minimum-energy routing protocols to choose a low energy route.

Even when researchers model random fading [3], no model exists to address the correlations in X_σ between the channels in a M2M network. In a real environment, an obstruction such as a wall, furniture, tree, or building may cause similar shadowing on several closely located links, causing statistical correlation. A M2M channel model without spatial correlations would ignore the effects of a heterogeneous physical environment. To address these effects, we present M2M channel measurements in Section II. In Section III, we analyze these measurements to show numerically their effects on an ad-hoc network operating in the measured environment. Then, in Section IV, we present a model that can be used to recreate these effects in simulation.

II. MULTIPOINT-TO-MULTIPOINT MEASUREMENTS

Channel measurements are conducted in the Motorola facility in Plantation, Florida. The measurement system consists of a HP 8644A signal generator transmitting a CW signal at 925 MHz at an output level of 0.1 mW and a Berkeley Varitronics Fox receiver. A $\lambda/4$ dipole with Roberts balun resonant at 925 MHz is positioned at a height above the floor of 1 m at both the transmitter and receiver. The antennas are both stationary during each measurement and have an omnidirectional radiation pattern in the horizontal plane and a vertical beamwidth of 30°. The Fox receiver was set to average received power over one second. The campaign is

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conducted during evenings and on weekends to ensure that the channel is mostly static during the measurements.

Two meter tall Hayworth partitions and ceiling-height interior walls divide the area into cubicles, lab space, and offices. Four devices are placed in the corners of the 17 m by 14 m area. Forty other locations are scattered throughout the area, which consists of four columns of cubicles and the hallways that separate them. One to three device locations are chosen for each cubicle, and a total of 11 device locations were in the hallways. This density might be expected in a medium density indoor ad hoc networking system, in which each employee in an office area has one or more personal devices operating in the network. Together, there are 44 device locations in a 238 m^2 area, or on average, one device per five square meters.

Fig. 1. Photo of measurement area, looking over cubicle walls

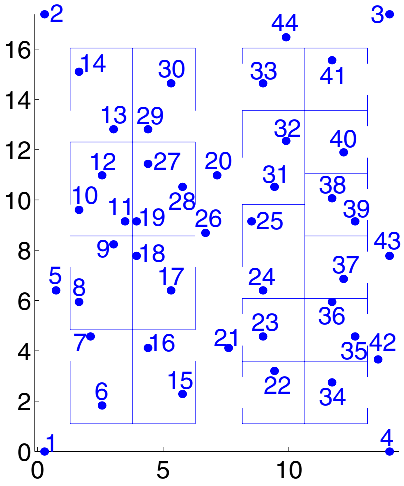

Fig. 2. Map of measurement area showing all 44 device locations.

We measure the channel of all pair-wise links in the 44 device ad-hoc network. First, the transmitter is placed at location 1, and received power readings are taken and recorded at locations 2 through 44. Next, the transmitter is moved to location 2, and power readings are taken at locations 1 and 3 through 44. This process continues until power measurements have been made between each pair of devices, for a total of 1892 RSS measurements. The measured received powers are plotted in Fig. 3.

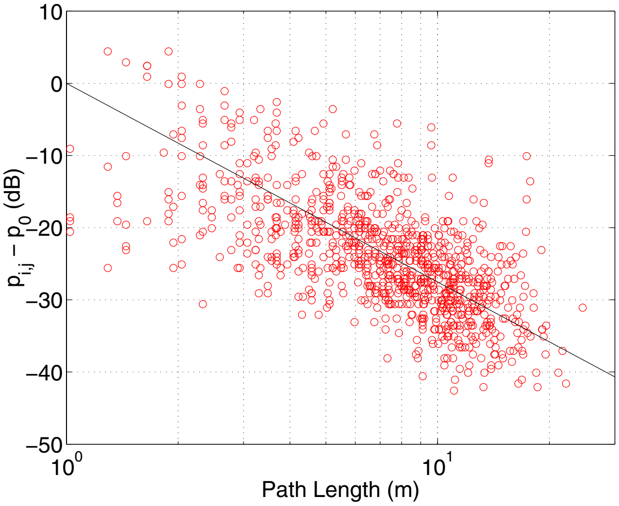

Fig. 3. Measured path loss vs. distance. Linear fit shows channel model of Eq. 1 with $n = 2.75$ and $\sigma_{dB} = 6.4$.

III. MEASUREMENT RESULTS

A. *General Channel Parameters*

Applied to a path loss exponent model, as shown in Fig. 3, the measured data fit the channel model of Eq. 1 with a d_0 of 1 m and n of 2.75. The histogram of X_σ, shown in Fig. 4, appears Gaussian in dB and has a standard deviation of σ_{dB} = 6.4 dB.

We calculate the mean fading error at the i^{th} device, $\overline{X}_\sigma(i)$, by averaging the X_σ for each link connecting to that device. These values are recorded in Table I.

TABLE I
MEASURED MEAN FADING ERRORS AT EACH DEVICE

i	$\overline{X}_\sigma(i)$	i	$\overline{X}_\sigma(i)$	i	$\overline{X}_\sigma(i)$
1	4.63	16	-2.16	31	0.16
2	2.57	17	-0.81	32	0.82
3	4.32	18	-2.68	33	-2.55
4	4.46	19	-0.84	34	-2.62
5	0.37	20	0.97	35	-0.25
6	0.19	21	1.85	36	-2.86
7	-2.92	22	-2.46	37	-1.60
8	-0.53	23	0.70	38	-2.69
9	-5.14	24	0.39	39	-0.51
10	-0.47	25	-3.35	40	-1.83
11	-6.00	26	0.86	41	0.16
12	-2.30	27	-1.54	42	2.48
13	-4.98	28	0.74	43	2.85
14	0.23	29	-2.08	44	1.63
15	-0.69	30	1.01		

We notice that the devices in the hallways average a $\overline{X}_\sigma(i)$ of 2.45 dB, while the devices in the cubicles have an average $\overline{X}_\sigma(i)$ of -1.50 dB. The standard deviation of $\overline{X}_\sigma(i)$ over all devices i is 2.43 dB. This is significantly higher than what would be expected from the log-normal shadowing channel model. In that model, we would expect the mean of 43 different fading errors X_σ to have a standard deviation of $\sigma_{dB} / \sqrt{43} \approx 0.97$ dB. We can say that it is likely that devices at particular locations have a non-zero mean fading error.

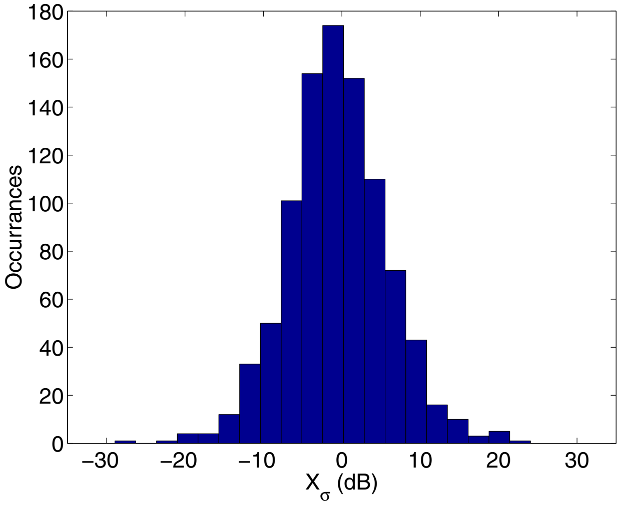

Fig. 4. Histogram of measured fading error using the model in Eq. 1.

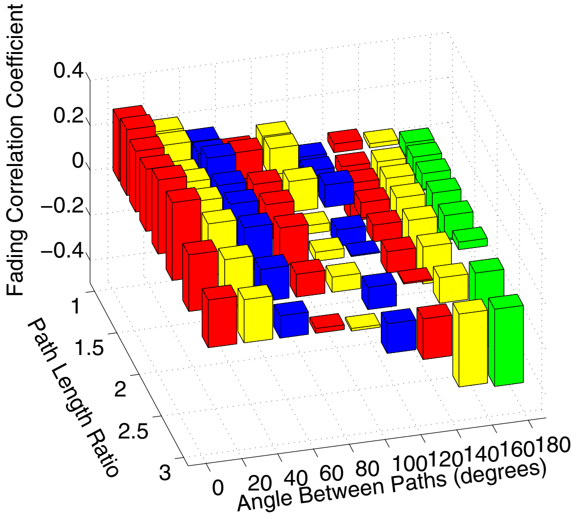

Fig. 5. Correlation coefficients of fading error between the links *i-j* and *j-k*, plotted as a function of angle $\alpha_{i,j,k}$ and path length ratio *l(i,j,k)*.

B. *Partition-based Model*

We can also use a partition-based path loss model to attempt to reduce the variance of the model. The endpoints of the cubicle walls are entered into the computer and are used to count how many partitions the line between each transmitter-receiver pair has crossed. Using the method presented in [2], we find a partition loss of 1.9 dB, path loss exponent of 2.1, and standard deviation of 5.9 dB. The calculated partition attenuation is statistical, not physical. It indicates that the measured data more closely fits the model in the least-squares sense if the 1.9 dB attenuation is included in the model. In this case, the addition of the additional degree-of-freedom in the channel model only reduces the standard deviation of channel model error by half of a dB, indicating that the partition-based model explains only a little of what is happening in this particular environment. Other obstructions and over-the-cubicle-partition propagation, neither of which are directly considered in the partition-based model, may be dominant in this environment.

C. *Channel Spatial Correlations*

We also consider the correlations between two adjacent hops in a multi-hop route. Essentially, what we want to do is to check the fading errors, X_σ, of our existing channel model to see if there are spatial features not modeled. One question is, if a message is passing from device *i* to device *k* and arbitrarily chooses an intermediate node *j*, is the fading on the link *i-j*, $X_\sigma(i,j)$, correlated with the fading on the neighboring link *j-k*, $X_\sigma(j,k)$? To answer, we consider each triplet *i-j-k* in the network, a total of about 40,000 combinations. The data are separated into bins based on angle $\alpha_{i,j,k}$ and by a path length ratio variable:

$$l(i,j,k)=\begin{cases} d_{i,j}/d_{j,k} & \text{if } d_{i,j}>d_{j,k} \\ d_{j,k}/d_{i,j} & \text{if } d_{i,j}\le d_{j,k} \end{cases} \qquad (2)$$

If the chosen intermediate device *j* is very close to either *i* or *k*, then the ratio variable *l* will be high. Conversely, if device *j* is equidistant from *j* and *k*, then ratio variable *l* will be one.

The correlation values plotted in Fig. 5 show a clear trend versus angle and path length ratio. The results tend to indicate that fading errors are positively correlated when the angle $\alpha_{i,j,k}$ is very low. Fading errors are negatively correlated when the angle is high and the ratio of the path lengths *l(i,j,k)* is very great. The maximum correlation coefficient for a bin is 0.35 and the minimum is -0.34. The values of correlation indicate that other random effects dominate the measured channels, however, spatial effects cause a noticeable spatial correlation in the network.

D. *Minimum-Energy Two-Hop Routing*

With the measured data we can also consider the effectiveness of a minimum-energy routing scheme. As above, consider a route between devices *i* and *k*. Instead of choosing an arbitrary intermediate device, choose the device that minimizes the total transmit power. In this paper, this device j is called the *best-hop device*. We use the measured *linear* received powers, $\hat{p}_{i,j}$ and $\hat{p}_{j,k}$ for all *j*, to determine the best-hop device between devices *i* and *k*. For the direct route between devices *i* and *k*, the required linear transmit power $PT_{i,k}$(min) is

$$PT_{i,k}(\min)=\frac{A}{\hat{p}_{i,k}} \qquad (3)$$

where *A* is a proportionality constant, which is independent of device because of two factors. First, in the measurements, we used a constant transmit power. Second, we assume that the minimum received power is the same for each device. With two hops, we add the linear powers, and

$$PT_{i,j,k}(\min)=\frac{A}{\hat{p}_{i,k}}+\frac{A}{\hat{p}_{j,k}} \qquad (4)$$

The best hop device is the device *j* which minimizes $PT_{i,j,k}$(min). The multi-hop gain, $G_{i,j,k}$(dB), is the dB ratio of the two transmit powers,

$$g_{i,j,k}(\mathrm{dB})=10\log_{10}\left(\frac{1/p_{i,k}}{1/p_{i,j}+1/p_{j,k}}\right) \qquad (5)$$

Because each pair-wise link in our M2M network has a best-hop device, we have a total of 946 best-hop devices. Using the measurements, we show in Fig. 6 how many times a device was found to be the best hop device. It is observed that some devices are much more commonly found to be best-hop devices. The devices in the hallways, that is, device numbers 1-5, 20, 21, 26, and 42-44, are very often chosen as a best-hop device. These devices were chosen 44.5% of the time, even though they are only 25% of all devices. Plus, several of the hallway devices are located on the edges of the rectangular area, where one wouldn't expect to have a best-hop device very often.

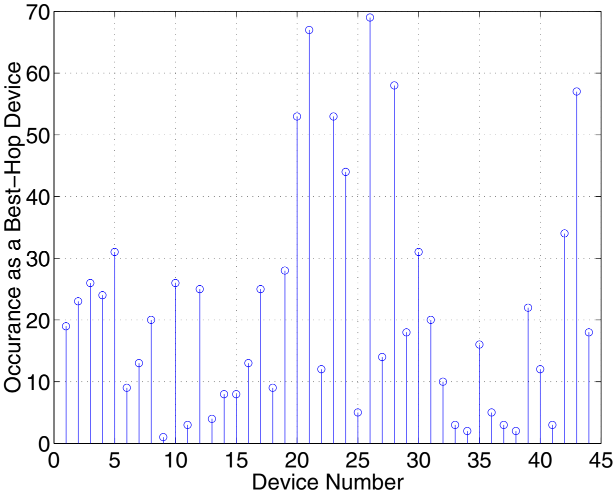

Fig. 6. The number of times that each device is chosen as a best hop device in the network

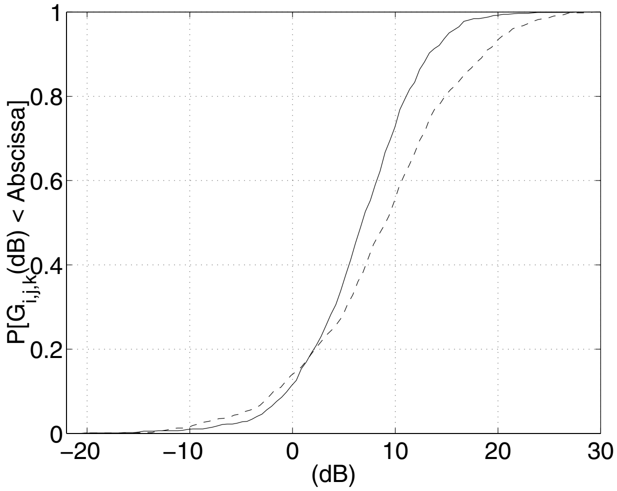

Fig. 7. CDF of $G_{i,j,k}$(dB) when I is the best hop device based on measurements (——) and simulation (- - - -) using the model in Eq. 1.

To confirm that this is unusual, a test is conducted using the same device locations as the measurements but with randomly generated received powers. The received powers in the test network are generated between each device based on the channel model in Eq. 1 with $d_0 = 1.0$ m, $n = 2.75$, and $\sigma_{dB} = 6.4$ dB, as calculated in Section III.A. The fading on each link, X_σ, is generated independently. The best-hop devices in the test network are then found. In this test, 16% of the best-hop devices are found to be hallway devices. The channel model of Eq. 1 does not predict this effect.

However, this effect has direct impact in the design of a multi-hop network. These few devices would consistently be chosen as intermediate nodes in a multi-hop network. Unless the network is designed properly, these may become routing bottlenecks as a large fraction of traffic must be routed through them. Also they will see more power drain and shorter battery life than the other devices.

We also studied the two-hop transmit power gain, $G_{i,j,k}$(dB). In Fig. 7, the CDF of the measured $G_{i,j,k}$(dB) is shown as a solid line. The distribution looks Gaussian with mean of 6.8 dB and a standard deviation of 5.7 dB. In 88% of the cases, the best-hop device reduces the total transmit power.

Next, we used our test network to determine what the existing channel model would predict for $G_{i,j,k}$(dB). The results, shown as the dashed line in Fig. 7, are significantly different. The distribution of $G_{i,j,k}$(dB) is still Gaussian, but the mean and standard deviation are both higher, at 8.8 dB and 7.8 dB, respectively. The existing channel model is much more optimistic than our measurements. The channel model predicts 19.5% of the multi-hop gains will be above 15 dB, while the measurements show only 5.5% of values above 15 dB.

IV. MULTIPOINT-TO-MULTIPOINT CHANNEL MODEL

In order to model the M2M channel more effectively, we should consider that the mean fading error for a device is non-zero. For this new M2M model, consider that X_σ for the channel between device i and device j has a mean of $\gamma_i + \gamma_j$ and a variance σ'_{dB}. The variable γ_i is called the *device mean fading error* and expresses the average difference between the received power and what is predicted by the original channel model in Eq. 1. We suggest two methods to determine γ_i:

Statistical: Generate γ_i randomly from a zero-mean Gaussian distribution with standard deviation σ_γ. For the measured environment, $\sigma_\gamma = 1.72$ dB.

Site-Specific: Use a map of an area to delineate different environments depending on the types and degree of obstructions in the area. Each environment has a γ determined by measurements.

In the site-specific method the σ'_{dB} would be determined from measurements, while in the statistical method, σ'_{dB} would be given by

$$\sigma'_{dB} = \sqrt{\sigma^2_{dB} - \sigma^2_{\gamma}} \qquad (6)$$

Both methods would address the higher variance of $\overline{X}_\sigma(i)$ compared to what is predicted by original model. They would help recreate the effects of having particular devices singled out as best-hop devices in a minimum-energy routing protocol. However, only the site-specific method would introduce spatial correlation into the links of the M2M channel model. Two devices which are neighbors are likely to have the same mean fading error, which is a spatial correlation not introduced in the statistical model. This spatial correlation will help recreate the correlation between two links that we observed in Section III.C. More work must be done to verify the performance of this model in a variety of environments.

V. CONCLUSIONS

The results of this paper show that incomplete consideration of the multipoint-to-multipoint radio channel can lead to significant inaccuracies in simulation results. The measurements show a higher variance of $\overline{X}_{\sigma}(i)$ and in particular, mean fading errors that vary based on whether the device was in a hallway or cubicle. The results show that there exist spatial correlations between two links in a M2M channel based on the angle between them and the ratio of the path lengths. Finally, a minimum energy routing protocol experiences differences in a real environment than would be predicted by the existing channel model. In particular, measurements show that a small number of devices bear a disproportionate share of the burden of the routing. In addition, the traditional model can overestimate the radiated energy savings possible in a multi-hop routing network. Since the radiated energy savings must be balanced by the additional energy costs in the network, accurate characterization of $G_{i,j,k}$(dB) is essential. In order to better model these effects, this paper has suggested assigning a non-zero mean fading error to each device, either randomly, or based on site-specific information. We believe that more accurate modeling of the multipoint-to-multipoint channel will allow simulations to show more clearly and more reliably the actual performance of ad-hoc networks.

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