2015 International Conference on Computing, Networking and Communications (ICNC), Workshop on Computing, Networking and Communications (CNC)

A Method to Improve Signal Quality in Wireless Ad-Hoc Networks with Limited Mobility

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***Abstract*—A wireless ad-hoc network is a collection of nodes that are dynamically and arbitrarily located in such a manner that the interconnections between each node are capable of changing on a continual basis. In this paper, we provide a novel way to improve node interconnects without changing the overall network topology by allowing nodes to have limited mobility. Received signal strength (RSS) measurements are recorded from neighboring nodes as the node makes small changes in position. This allows the node to move out of fades due to multi-path or shadowing, and is a form of selection diversity that requires only a single antenna. This algorithm is tested using a full 3-D ray tracing propagation model as well as physical measurements in an indoor scenario.**

***Keywords*—RSSI, RSS, MANET, wireless, ad-hoc, mobile, positioning, selection diversity**

I. Introduction

Key goals for improving mobile ad-hoc networks include preserving battery life, increase wireless link throughput, improve efficiency of routing algorithms and reduce power consumption while limiting bit error ratio. In this paper we consider the case where nodes have limited mobility and can move at least three or four wavelengths from an initial position. Such systems have been suggested previously, for example in the DARPA Landroid project [1] in which many small limited mobility nodes can be rapidly deployed to establish ad-hoc networks in emergency scenarios such as disaster areas or military operations. When nodes are not in line of sight with each other, reflections and refractions of the transmitted signal cause multi-path interference with fades as deep as 30 to 40 dB. Making small adjustments in each node's position allows the node to escape from deep fades or shadows, resulting in better throughput at lower transmit power. Another potential application is in low-power wireless sensor networks, in which determining node positions for maximum connectivity is difficult. Equipping nodes with inexpensive motors for limited mobility could be a cost-effective way to meet performance goals.

This method is analogous to "selection diversity" [2], [3], [4], [5], [6], where nodes have multiple antennas separated by a fixed interval dx, and the antenna with the highest instantaneous carrier-to-noise ratio is used. Selection diversity is often a good approach for solving fades due to multi-path; however, it is typically limited to 2-4 antennas due to cost and added complexity. The method we propose utilizes a single antenna to sample radio signal strength at multiple locations by repositioning the platform. The result is equivalent to using 5-20 or more antennas in a selection diversity setting.

RSS measurements are made at locations separated by an interval dx. In order to minimize power consumption, dx is chosen to minimize correlation between the received envelopes at x and $x + dx$. This gives the highest probability of avoiding a fade while minimizing the number of test positions.

The proposed method was tested in an indoor environment with many obstacles and no significant line-of-sight paths. In addition to physical radio measurements, the technique was tested using simulated RSS measurements collected using full 3-D ray-tracing models based on Remcom's Wireless InSite™ software suite. Monte-Carlo simulations provided further insight into the method's performance.

Finally, we assume the topology is a wireless mesh network in which nodes are grouped into clusters and all nodes in the cluster are within one-hop distance of each other. Since the algorithm is applied at the cluster level, it can easily be scaled to large networks [7], [8].

The remainder of this paper is organized as follows: Section II describes experimental setup and indoor propagation measurements. Section III shows how the optimal dx value is determined, and gives details of the positioning algorithm. Section IV describes how Monte-Carlo modeling is used to predict system performance. Section V discusses several technical considerations for implementing the technique, and Section VI gives conclusions.

II. Indoor Propagation Modeling and Measurements

The technique was tested on the 5th floor of the University of Wyoming Engineering building. Three node locations were chosen having no line-of-sight paths. The transmitters were operated in the 915 MHz ISM band at a power level of 23.5 dBm using omni-directional whip antennas. The node locations and distances between nodes are shown on the floor plan in Fig. 1.

As an example, the indoor propagation path between Nodes 2 and 3 was measured by having Node 3 continually broadcast "hello" messages while the receiver (Node 2) was moved in

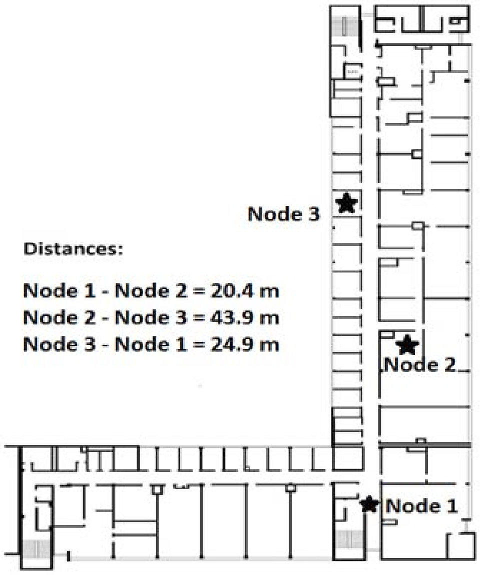

Fig. 1. The engineering floor plan with node locations.

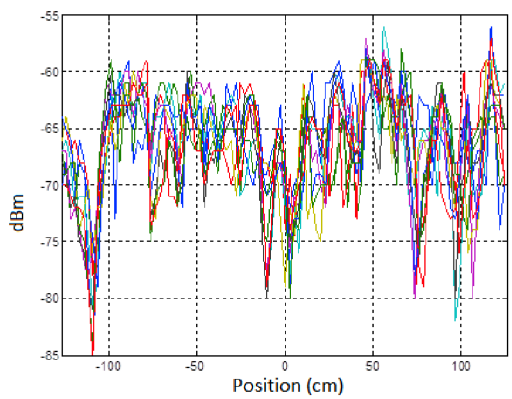

Fig. 2. Ten realizations of RSS measurement experiment showing the effects of fading and RF noise.

a straight line in 2.5 cm intervals. A total of 100 locations were tested, and the process was repeated ten times at the same locations to verify that multi-path fading were present. Resulting RSS values shown in Fig. 2 reveal that fades occur at approximately 12 to 25 cm intervals. Thus, on average moving about 12 cm will usually move this node out of a deep fade. Similar fades are observed in the 3-D ray tracing results shown in Fig. 3. The corresponding heat map in Fig. 4 shows received signal strength over a 3 x 3.6 m office area, where ripples illustrate the spatial distribution of multi-path fading.

Fig. 5 shows the Rayleigh distribution plotted along with the histogram of empirical RSS data. A goodness-of-fit test further verified the Rayleigh fading assumption, which is used in the Monte-Carlo simulation tests described in Section IV.

The biased autocorrelation $r_k(m)$ for the k$^{\text{th}}$ dataset, as well as the autocorrelation ensemble average were computed using (1) and (2).

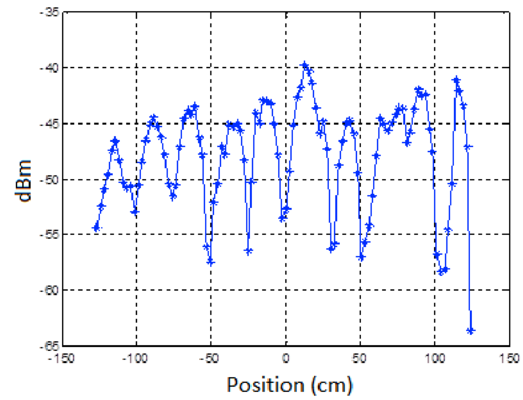

Fig. 3. RSS measurements based on the ray-tracing simulation.

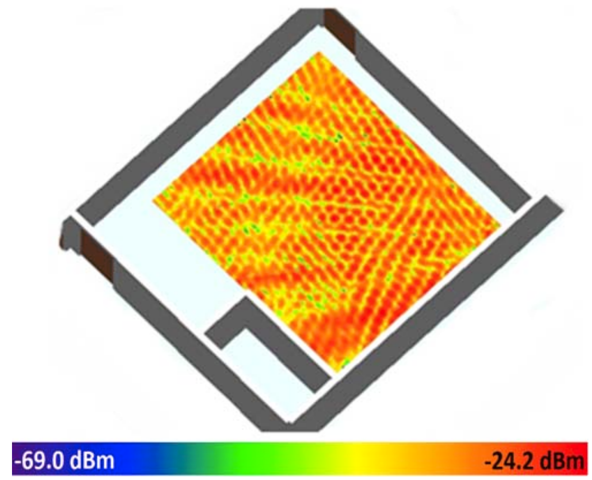

Fig. 4. RSS values showing the spatial distribution of fading in a small office.

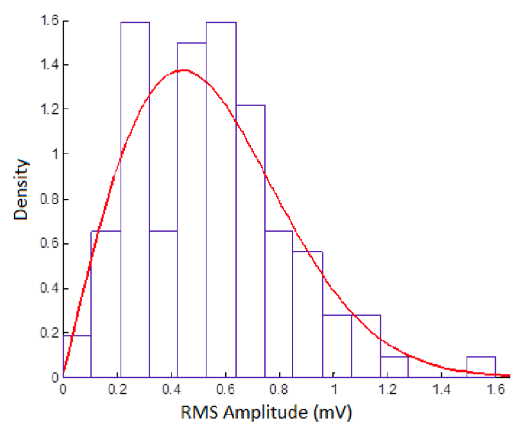

Fig. 5. Rayleigh distribution and histogram of RSS measurements.

$$r_k(m) = \frac{1}{N} \sum_{n=0}^{N-m-1} x(n)x(n+m) \tag{1}$$

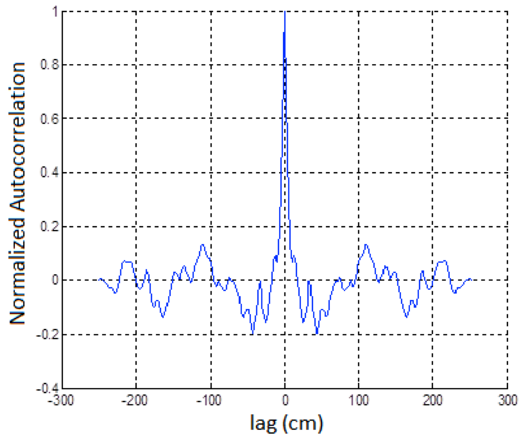

Fig. 6. Autocorrelation of measured RSS values vs. lag in cm.

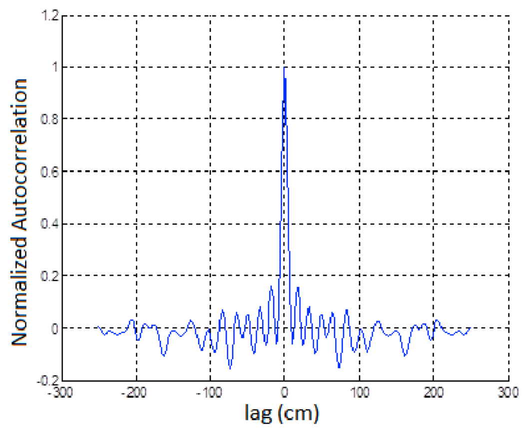

Fig. 7. Autocorrelation of simulated RSS values vs. lag in cm.

$$r(m) = \frac{1}{10}\sum_{k=1}^{10} r_k(m) \qquad (2)$$

The normalized autocorrelations (after removing the mean) of the ten sets of empirical data shown in Fig. 2 and simulated data in Fig. 3 are now shown in Figs. 6 and 7, respectively. Ideally the motion increment dx is chosen so that adjacent measurements are uncorrelated and fewer RSS measurements are necessary to obtain the desired level of selection diversity. The lag required for zero autocorrelation is $dx = 12.7$ cm (Fig. 6) and $dx = 10.2$ cm (Fig. 7), which is consistent with fade characteristics observed in Figs. 2 and 3. This is approximately $1/3$ of a wavelength at 900 MHz, thus we set $dx \cong \lambda/3 = 10.9$ cm.

III. Node Positioning Using Mini-Max

Next, the proposed technique is tested using the simple three-node scenario. We assume that all nodes are required to communicate with all other nodes in the cluster. In this case, a reasonable network goal would be to maximize the worst case link performance, which allows all nodes to use the lowest transmit power while accommodating the node in the weakest radio location. The technique is implemented using the following algorithm:

1) Node 3 moves a distance dx while Nodes 1 and 2 hold their positions fixed. For each Node 3 position, Nodes 1 and 2 transmit a "hello" packet, and Node 3 records the RSS. This is repeated for M different positions and the two sets of measurement, from Nodes 1 and 2, are shown in Fig. 8.
2) Node 3 then moves to the position x that satisfies the mini-max criterion:

$$final\ x = arg\ max_x\{min_{node} RSS(x, node)\} \qquad (3)$$

where node $\in \{1, 2\}$. In other words, we first find the weakest received signal at each position, and then move the node to the position giving the best reception of the weakest signal.

Finally, the above steps are repeated using the same mini-max criteria to reposition Nodes 1 and 2. The algorithm may be repeated for several iterations. However, this was not done since it is unlikely that any performance gains would justify significantly increased time delay and power usage.

As an example, Fig. 8 shows measured Node 3 RSS values for signals transmitted from Nodes 1 and 2. As expected, there is substantial variation in RSS as we move Node 3 about its initial position due to multi-path fading. We can also observe that the initial position (Position 0) of Node 3 is not optimal.

The next step is to find the combined minimum values of both RSS curves and then find the maximum point on that plot. The combined minimum RSS and resulting maximum is shown in Fig. 9. The maximum RSS occurs at position $x = 22.5$ cm and represents a significant improvement between Nodes 1 and 3 as well as Nodes 2 and 3.

A summary of RSS improvements due to the algorithm can be found in Table I. The same experiment was repeated using the 3-D ray tracing values and the simulated results are listed in Table II. In these tables, columns represent transmitter

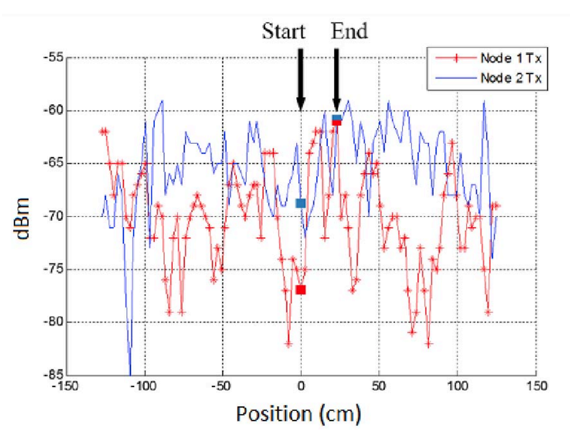

Fig. 8. The empirical RSS collected by Node 3 when Nodes 1 and 2 are transmitting. Start and End positions are indicated by the arrows and red and blue squares.

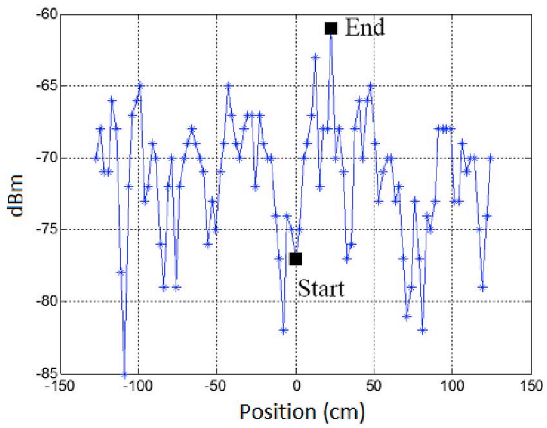

Fig. 9. Minimum of measured RSS when Nodes 1 and 2 are transmitting. The optimum "mini-max" location is indicated by the black square labeled "End".

TABLE I. RSS IMPROVEMENTS (dB) FOR EMPIRICAL DATA

	Node 1 Rx.	Node 2 Rx.	Node 3 Rx.
Node 1 Tx.	-	12	16
Node 2 Tx.	5	-	8
Node 3 Tx.	13	10	-

TABLE II. RSS IMPROVEMENTS (dB) FOR SIMULATED DATA

	Node 1 Rx.	Node 2 Rx.	Node 3 Rx.
Node 1 Tx.	-	22	18
Node 2 Tx.	10	-	9
Node 3 Tx.	22	11	-

nodes, while rows represent receiver nodes. A glance at both tables shows substantial improvement in signal strength, which can greatly impact a routing cost table for a mobile network. We can also observe that the signal strength improvement measured from Node A to Node B is not necessarily equal to that of Node B to Node A, where A and B can be any two nodes in the network. This is due to the non-reciprocal nature of the mini-max solution. The simulation results in Table II are slightly better than the empirical results in Table I, which is likely due to modeling errors (e.g., tables, chairs, book cases, etc. were not included in the computer model).

As shown in Fig. 2, RF noise substantially affects RSS measurements. At our location we measured RSS standard deviation to be $\sigma_{RSS} = 4.7$ dBm. Note that values in Table I represent a difference of independent RSS measurements and thus have variance $\sigma^2 = 2\sigma^2_{RSS}$ with standard deviation $\sigma = \sqrt{2}\sigma_{RSS} = 6.7$ dB. Hence, the table values can be interpreted as having error bars of approximately ± 6.7 dB.

IV. MONTE-CARLO SIMULATIONS

Additional insight is possible using Monte Carlo simulation. We assume that nodes are approximately equidistant from each other and fading is well modeled by the Rayleigh distribution. Furthermore, it is assumed that the motion interval dx gives uncorrelated RSS measurements. It is of interest to determine how much diversity gain can be achieved by moving a node to n different locations. Here, diversity gain is defined as:

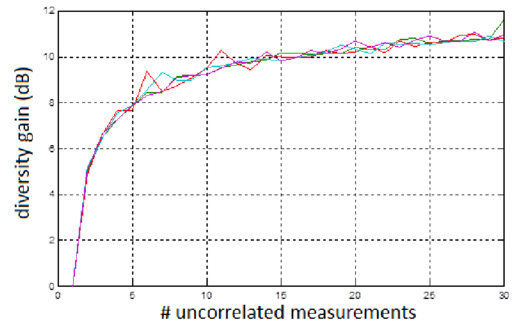

Fig. 10. Monte Carlo simulation showing the diversity gain relative to single receive position. Results for 2, 3, 4, and 5 nodes virtually overlap.

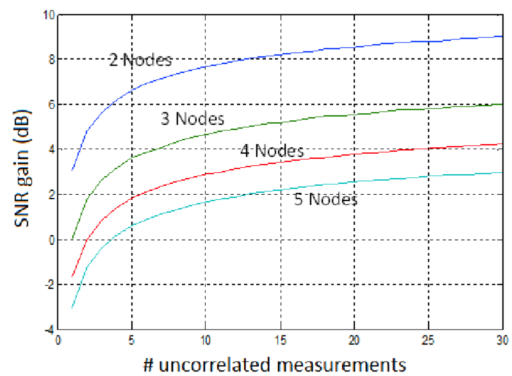

Fig. 11. SNR gain assuming unit noise variance.

$$G_D = E\left\{10\log_{10}\left[\frac{RSS_n}{RSS_1}\right]\right\} \quad (4)$$

where E{} is expectation, RSS_1 is the RSS value for a single node position without any diversity gain, and RSS_n is the mini-max RSS value when n measurement positions are used. The effect of different numbers of nodes is also simulated for the cases N_{node} = 2, 3, 4, and 5.

Fig. 10 shows diversity gain vs. the number of test positions n based on 10,000 random trials. For $n \approx 10$, gain begins to level off at about $G_D \cong 9$ dB, and appears to be independent of the number of nodes. For example, at 915 MHz and using $dx = \lambda/3$ as discussed above this implies the node would have to move a total distance of about $10\lambda/3 = 1.1$ m to achieve 9 dB diversity gain on average.

Although the number of nodes has no effect on diversity gain, it does impact performance in other ways. For example, each additional node included in the mini-max calculation reduces the worst case RSS. From (3) we see

$$RSS_{min}(x) = min_{node}RSS(x, node) \quad (5)$$

As more nodes are added, the minimum value keeps dropping, which necessarily reduces the final received signal strength $RSS_{minmax} = max_x\{RSS_{min}(x)\}$. This results in lower signal to noise ration (SNR) at the receiver. Fig. 11 shows the effect on SNR, which is defined as $SNR =$

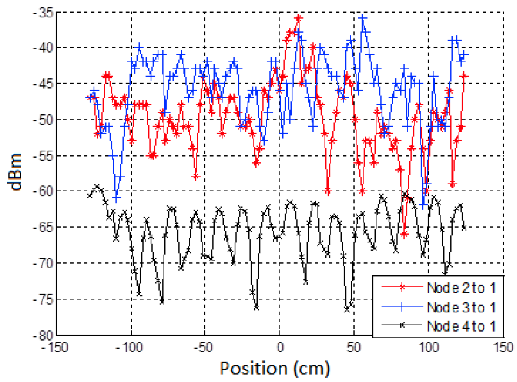

Fig. 12. Case where Node 4 is in a poor RF location.

$10\log_{10}\{E[RSS_{minmax}]/\sigma^2_{Noise}\}$. The noise power is arbitrarily set at $\sigma^2_{Noise} = 1$.

In Fig. 11 it is clear that increasing the number of nodes decreases overall SNR. For example, changing from 2 to 3 nodes reduces SNR by nearly 3 dB thus reducing robustness to noise and interference. But as shown in Fig. 10 protection against fading does not decrease with increasing number of nodes.

V. Considerations

A further disadvantage of including more nodes is increased setup costs, since for N_{node} nodes the number of links to be evaluated is $N_{node}(N_{node} - 1)$. However, if nodes are only required to communicate with the cluster head and not with each other, overhead grows only linearly and the problem is much more tractable.

From an energy viewpoint, this method has high initial cost due to node movement and the need to exchange RSS information, but once the network is established increased diversity gain gives significant energy savings. Thus the best use for the proposed approach is for networks that are relatively static such as sensor networks or an emergency ad-hoc network with one-time setup. Other sources of variation are less easy to control, including noise levels and fade characteristics that may change throughout the day. Therefore, the algorithm could be restarted if network performance experiences a sustained drop in performance.

The mini-max approach works best when internode distances are comparable and RSS values are within 5 to 10 dB of each other. In practice, if one node is more distant or located in an RF shadow, its relatively low RSS can severely impact mini-max performance. Fig. 12 , for example, shows RSS when one node has significantly poorer RSS than the other nodes. Now RSS_{min} is completely controlled by Node 4 and the mini-max solution is blind to the condition of other node links, possibly leading to very suboptimal results.

One simple modification would be to compute mini-max RSS both with and without the weak node being included. If including a node decreases performance by more than a set threshold, the node would be excluded. Investigating the efficacy of this proposed solutions and others is an interesting area for future research.

VI. Conclusions

Our results show that the proposed method can substantially improve RSS in a wireless ad-hoc network subject to multi-path fading. The method implements a form of selection diversity, where multiple antennas are replaced by a single antenna on a platform with limited mobility. A key advantage is that a much larger number of positions can be tested as compared to the number of antennas in most diversity systems, which is usually constrained to 2-4 antennas. Results in Figs. 8 and 9, as well as Table I represent a single experimental test of the algorithm. These results are corroborated by 3-D ray tracing simulations (Fig. 7 and Table II) as well as Monte-Carlo outcomes in Figs. 10 and 11. The Monte Carlo indicates that only 10 measurement positions with uncorrelated RSS values are needed to identify a nearly optimal final node location.

Monte-Carlo simulations were used to predict overall performance of the algorithm in a generic multi-path environment. Thus, the results should be applicable in a range of physical settings. Experiments were also conducted at a single indoor location in order to further validate these results. In future research, physical experiments at other locations would be useful to better understand network performance gains as well as to measure setup times to establish node positions. Increasing the number of nodes in a cluster however has several disadvantages including higher overhead and reduced SNR. Preliminary experiments suggest a setup time of approximately three minutes for three nodes, so if larger clusters are required, the algorithm must be modified to address overhead concerns. For example, testing a subset of the pairwise connection strengths instead of all the nodes should minimize the number of test positions and RSS status transmissions. This idea, and others like it for scaling our approach to much larger networks, are also interesting avenues for future research.

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