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Abstract

Self-directed movement of radio devices can enable large amounts of power gain since the sources of fluctuations in received signal power due to multipath-induced small-scale fading have highly localized effects. We call the gain achieved by finding a better location the mobility gain. University of Pennsylvania Experimental data for indoor as well as outdoor measurement studies are used to illustrate the potential of this RF-Mobility Gain concept over a wide range of frequencies. An analysis of the RF data reveals that a small amount of energy spent on searching for a better location can pay large dividends in long-term power expenditures for RF transmission. Challenges in building such a system for peer-to-peer links and network applications are discussed along with potential coordination algorithms.

Comments

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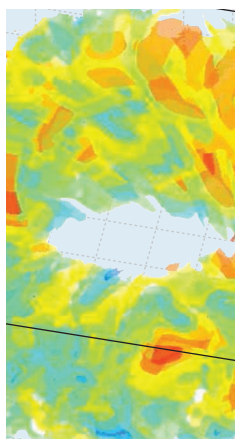
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RF-MOBILITY GAIN: CONCEPT, MEASUREMENT CAMPAIGN, AND EXPLOITATION

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The authors present a 2D and 3D RF fading measurement campaign and an analysis of these results that illustrates the potential benefit of RF-Mobility Gain

ABSTRACT

Self-directed movement of radio devices can enable large amounts of power gain since the sources of fluctuations in received signal power due to multipath-induced small-scale fading have highly localized effects. We call the gain achieved by finding a better location the *mobility gain*. Experimental data for indoor as well as outdoor measurement studies are used to illustrate the potential of this RF-Mobility Gain concept over a wide range of frequencies. An analysis of the RF data reveals that a small amount of energy spent on searching for a better location can pay large dividends in long-term power expenditures for RF transmission. Challenges in building such a system for peer-to-peer links and network applications are discussed along with potential coordination algorithms.

INTRODUCTION

This article presents a 2D and 3D radio frequency (RF) fading measurement campaign and an analysis of these results that illustrates the potential benefit of RF-Mobility Gain (RF-MG). Lockheed-Martin's Advanced Technology Laboratory and the University of Pennsylvania exploit the data set to demonstrate that *motion is a useful degree of freedom* in optimizing communications systems. Examples of strategies are presented to achieve this mobility gain inherent in a setting, using robots or mobile antennae for improved connectivity and persistence. Mobility gain can be multiplicative over a network of relay nodes, and can be combined with other modern radio techniques such as multiple-input multiple-output (MIMO) [1] and antenna diversity techniques [2] to form an ad hoc network of nodes that shares desirable characteristics of both mobile ad hoc networks (MANETs) and fixed infrastructures.

Smith's work began at DARPA and was partially supported by NSF CNS07-39347.

THE CHALLENGE OF COMPLEX RF ENVIRONMENTS

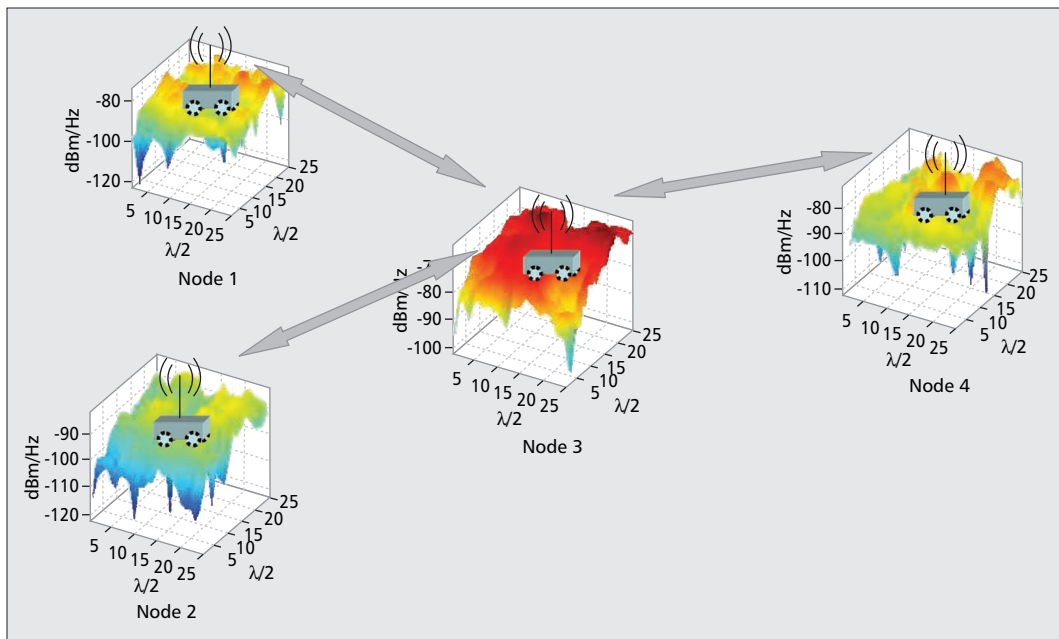
Indoor and urban environments [3] are challenging for communications systems due to the combination of interference from many RF energy sources, the density of users wanting access to the scarce RF spectrum, and the complexity of propagation of RF waves through multiple objects [4–6]. Building materials [7] create attenuation losses, and at the same time may introduce geometric phenomena such as multipath through their surface reflectivity. These losses are affected by both position and frequency, and can have a severe effect on closing the link in a communications system.

DEFINITION OF RF-MG

We define *mobility gain* as the RF gain achieved by moving from an inferior position (the baseline to which the gain is referenced) to a superior position. Figures 1, 2, and 3 illustrate this potential gain in the large power variations experienced over small areas in indoor and urban environments. Noticeable features are the spatial correlation patterns, and the combinations of RF fading peaks and troughs with 30 dB variations. With proper coordination and mobility strategy, a network of mobile radio nodes can achieve significant mobility gain, as shown later.

RF-MG EXPLOITATION

Spatial diversity and multiple antenna systems are already in use for optimizing wireless channel capacities, but, as of now, the degree of spatial diversity they offer can be thought of as a discrete and limited sampling (subset) of the full RF map. Mobility gain greatly expands the sample space, targeting the full capacity offered by the channel, because the sampling of the RF fading map can be made continuous. Systems used to implement RF-MG must exploit the continuum of the RF environmental conditions; thus, the key is how the sampling is performed in RF-MG systems, and how the network of RF-MG radios is coordinated/controlled to maximize the potential gain.



■ **Figure 1.** Network level perspective of RF-Mobility Gain enabled ad hoc network.

The most attractive RF-MG strategy is to attempt to control the impact of small-scale fading experienced on the link. Several measurements performed in urban environments and indoor environments indicate that the power fluctuations due to small-scale fading decorrelate rapidly over less than half of a wavelength [8]. Small moves can create large gains. Of course, the relative fading experienced by two ends of a link can be adjusted by moving the antennas without moving the radio.

The goal of RF-MG is to provide a mobility-based solution to optimize the link quality for either capacity improvement or power savings; any power saved by minimizing path loss on the RF link reduces the depletion rate of the participating nodes' energy stores while maintaining the same baud rate. Optimizing position to limit shadowing is another approach, but it requires site-specific approaches that require costly sampling strategies, whereas optimization of small-scale fading only requires local sampling of the fades to find the Rician fading distribution. On average, small-scale fading optimization for RF-MG will outperform shadow fading mitigation strategies.

COORDINATION AND NETWORK ROUTING UNDER AN RF-MG SCENARIO

OPTIMIZATION VIA COORDINATION

Global optimization of the ad hoc topology demands at least local cooperation, where a node uses its own local RF sensing capability and its multihop network connection to non-neighboring nodes to optimize the RF mesh for the "common good." This is driven by the fact that the RF fading maps are constant only if the other node is fixed, as shown in Fig. 2.

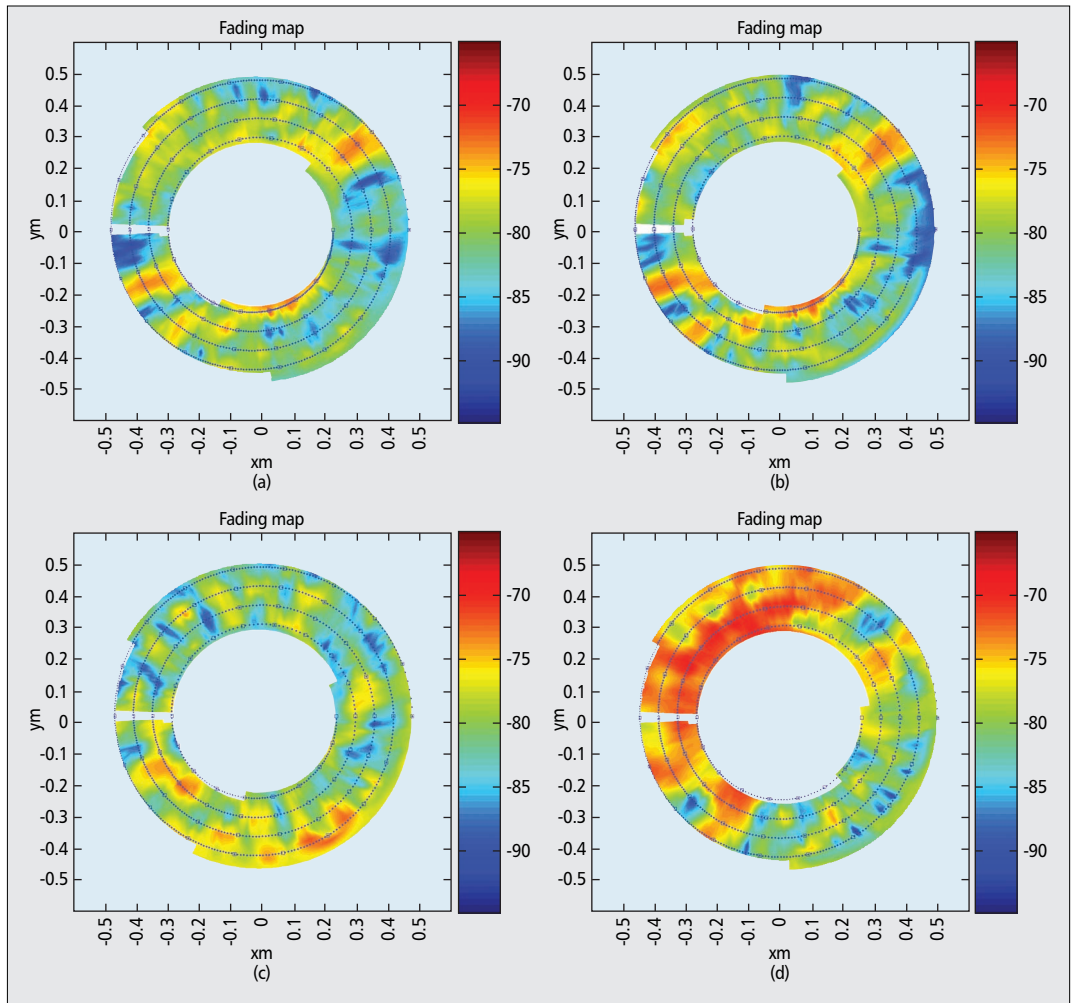
Communication among the robots provides the opportunity for coordinating and optimizing

the search strategy. The shared knowledge among cooperating nodes is used to prevent a "solitary" node from improving its mobility gain at the expense of other nodes. The distributed control algorithms necessary to build a scalable robotic mesh of nodes with a network-wide improvement in mobility gain are a major research challenge, requiring novel strategies. There are many possible strategies to exploit RF-MG. One strategy is "get out of the dips," which requires little movement from either the transmitter or receiver to significantly improve the peer-to-peer link, as seen in Fig. 4. This is a simplistic 1D search for a single peer-to-peer link.

Another basic strategy is to optimize the link quality over multiple point-to-multipoint radio links that form a network topology. One example of this strategy is From-Trunk-To-Leaves (FTTL), where the *inertial* weight for a node is proportional to its number of single-hop neighbors. Therefore, the node with the most single-hop neighbors or the node that participates in the most multihop routes has the lowest probability of moving since it is firmly established as a hub node in the network. This maximally connected node is referred to as the *trunk* in this algorithm. As the number of neighboring nodes is reduced, the node is more likely to engage in exploration toward optimization of the MG with the node with the most weight (i.e., the new trunk). This tree analogy is carried forward to the leaf nodes that have the highest degree of edge mobility. The optimization radiates outward from the trunk to branches to leaves. This type of strategy is currently under investigation, and the results will be reported separately.

A second optimization example is Altruistic Power, Equalization, and Exploration (APEX), where the routes established by the network are weighted with respect to usage and power consumption over the hops. This measure of Watt-hour or route pure energy cost (RPEC) to the network is based on requirements combining

Global optimization of the ad hoc topology demands at least local cooperation, where a node uses its own local RF sensing capability and its multihop network connection to non-neighboring nodes to optimize the RF mesh for the "common good."



■ **Figure 2.** 2.44 GHz fading samples for: a) original transmit location; b) 10 minutes later; c) 24 hours later; and d) transmitter is immediately moved by one wavelength (map is 1 m²).

duty cycle of the route, quality of service (QoS), and aggregated transmit power over the hops. RPEC is a weighted linear or nonlinear combination of these parameters. Once the routes are weighted across the network, the algorithm optimizes the routes with the highest energy need while maintaining the QoS using the same principles as FTTL. After each move, the relative weighting of the routes is reassessed and the algorithm repeats.

IMPACT OF RF-MG OPTIMIZATION ON NETWORK ROUTING PROTOCOLS

It is possible to use a traditional ad hoc routing protocol as the network layer in an RF-MG enhanced radio network, although the degree of global mobility gain may be reduced. Figure 4 depicts the physical laydown and topology of four nodes that form an ad hoc network. The nodes are shown superimposed over their 2D RF fading maps. If the links are all non-line of sight (NLOS), and the central node moves at least a half wavelength, it is possible that the depicted RF fading surfaces for the other three nodes will completely decorrelate and become unknown. The arrows that connect the nodes are the current topology of the ad hoc network and indicate

the existing next-hop routes. This network topology has converged to a star network where the central node is the root of the tree and would benefit from the FTTL coordination behavior discussed in the previous section. The varying levels of interaction and communication between the RF-MG coordinator and the network routing protocol give rise to some interesting situations. If an RF-MG coordination controller service is aware of the routing topology, it could use the route information to modify its strategy to move nodes relative to each other while minimizing damage to links that are part of currently utilized routes. Conversely, if the routing algorithm is aware of the strategy and capabilities of the RF-MG coordination controller, it may select certain routes based on cross-layer information like the Rician K -factor of each single-hop link, the probability of improving each link based on the observed fading map, and other relevant physical layer attributes.

IMPACT OF MG ON THE AODV AND OLSR AD HOC ROUTING ALGORITHMS

Ad Hoc On Demand Vector (AODV) and Optimum Link State Routing (OLSR) are two well-known wireless ad hoc routing protocols that are

based on reactive and proactive routing protocols, respectively. A reactive routing protocol does not maintain its routes and needs to flood the network with discovery packets when transmitting information to a node that is more than one hop away. As the RF-MG coordination behavior executes to establish, reinforce, or erase one-hop links, the routes have to dynamically adapt to these changes. Unless the RF-MG controller is aware of the current utilization of each of its single-hop links, it may inadvertently break some of its single-hop links while it moves a node through an RF fading surface, thereby forcing the ad hoc routing protocol to dynamically find a new route through the collection of connected nodes. Under this scenario, it is apparent that a proactive routing protocol like OLSR will be at a disadvantage because it continuously burns power to maintain routes by periodically transmitting routing control messages. These carefully maintained routes are then possibly broken by the RF-MG coordinator as it runs its per-link optimization behavior. Avoiding this destructive cycle is a good motivation for establishing cross-layer/cross-protocol communication between the RF-MG coordinator and any ad hoc routing protocol.

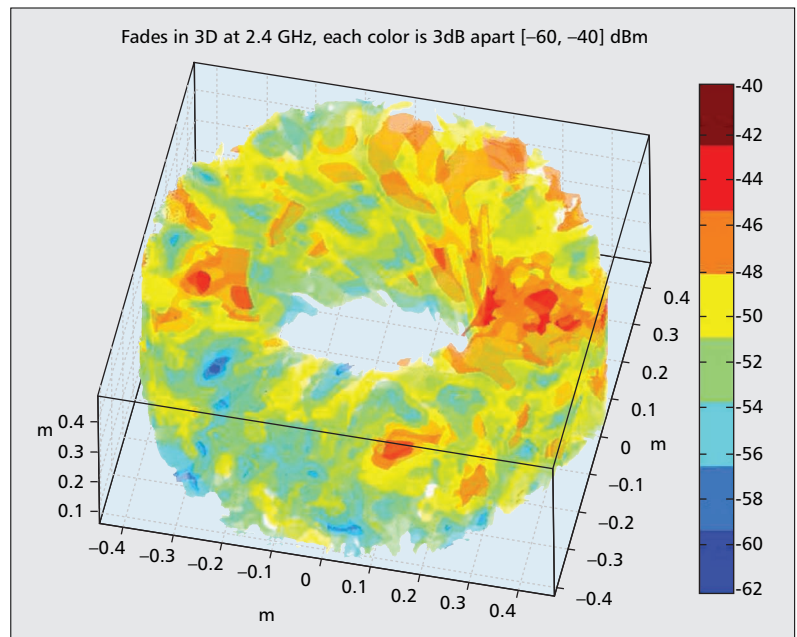
2D MEASUREMENTS

Tests were performed outdoors to capture the effect of NLOS propagation with many multipath components to measure the stability of the 2D fading map over time and location. A transmitter-receiver radio pair was set up under NLOS conditions by placing them on opposite sides of a corner of a six-story office building surrounded by a parking lot full of automobiles. The map was obtained by allowing a robot equipped with a radio to wind itself in a tight spiral pattern with a highly reproducible 1/10-wavelength accuracy to create a repeatable spatial 2D sampling of RF space on the ground. The position of the robot was tracked using infrared (IR) sensor detection markings along the spiral track. The transmitter placed on the other side of the building spanned several locations, including an origin location used for all test frequencies and another frequency-dependent location placed one wavelength further along the side of the building and away from the corner separating the radios. Several measurements were performed at carrier frequencies of 2440, 420, 120, and 60 MHz spanning 20 MHz channel bandwidths.

Frequency measurements were performed four times, as follows:

- 1 Perform a full spiral sampling for the frequency of interest.
- 2 Wait 10 min and perform another full spiral sampling with no change in the transmitter or receiver location.
- 3 Move the transmitter one wavelength away from its original position and keep the receiver assembly at the same location.
- 4 Repeat measurements one day later with transmitter at its original location.

The results in Fig. 2 at 2.44 GHz show that the small-scale fading maps are repeatable over a timeframe of minutes, meaning that the



■ **Figure 3.** Indoor 3D NLOS fading map at 2.44 GHz.

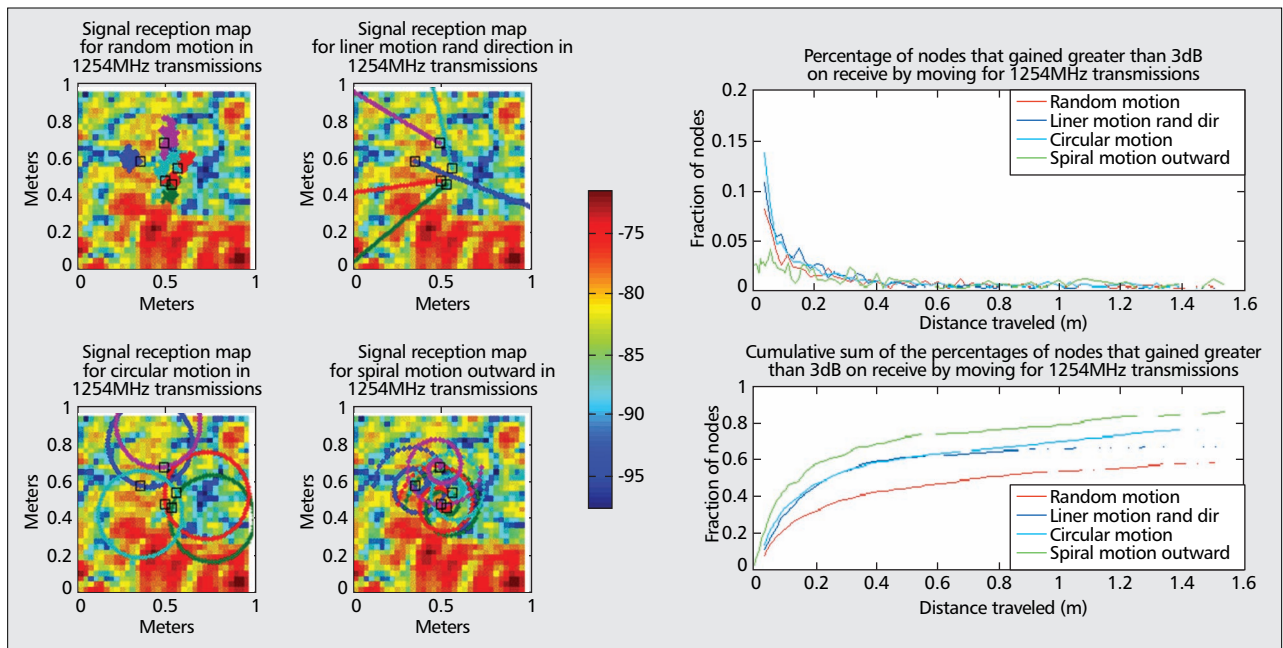
dynamics of the process that drives the changes in the multipath is slower than tens of minutes. Over 24 hours, the map shows a large decorrelation indicating that the spatial multipath distribution has changed as the car positions in the parking lot change.

Analysis of the 20 MHz wide channels spanning 60 MHz to 2.44 GHz showed that it is often better to select a new carrier frequency at low carrier frequencies (in the case of relatively short channels and the resulting frequency selective fading) rather than relying on mobility to decrease fading since physically moving the node to a better fading regime at low wavelengths expends more energy than negotiating a new unoccupied frequency. The network coordination required for this dynamic tuning is similar to the coordination used to obtain mobility gain, and one technique for dynamic spectral tuning is presented. However, at frequencies above 400 MHz the maps are largely spatially decorrelated, and significant gains can be achieved via small moves.

INDOOR 3D MEASUREMENTS

We next performed extensive tests and measurements to demonstrate that small antenna movements can achieve large gains in power saving for radio operation due to the low spatial correlation of NLOS wireless channels.

Multiple measurement campaigns were conducted to capture the RF fading for typical indoor and outdoor urban wireless channels. The measurements were conducted using a National Instruments 5600 software defined radio (SDR) to transmit and receive a 20 MHz wideband waveform. The received power is arithmetically averaged across the receiver's band for each location and is considered representative of the integrated received power experienced by an IEEE 802.11 radio. Figure 3 is a 3D depiction of the received signal strength in a



■ **Figure 4.** a) Measured 2D indoor NLOS RF power reception map; b) simulated RF-MG results for various paths through the 2D fading map.

NLOS channel obtained in a cluttered laboratory at various heights. Each color change represents a 3 dB relative difference in received power with its neighboring power levels. This shows that within a small cylindrical volume of 1 m diameter and 0.5 m height, there are several RF hot spots with potential gains up to 20 dB. For this measurement the wireless channel is time dispersive due to the presence of nearby metal desks, chairs, and cabinets.

The Rician probability density function (PDF) of the signal amplitude was estimated at four heights above floor level using a 3D version of the 2D spiral measurement rig. The Rician PDF's K -factor was found to be -5.4 , -2 , -1.2 , and 1.3 dB for 6, 15.5, 25.5, and 35.5 cm heights, respectively. This result matches the well-known concept of spatial correlation as a function of height evident when one end of an RF link is located above ground-level scattering objects (e.g., a cellular antenna on a mast in an urban environment). In our case all measurement points experience some degree of NLOS, but the strength of the specular path generally increases as the height of the antenna increases.

THE USE OF MOTION TO OBTAIN MOBILITY GAIN

MOBILITY GAIN PRINCIPLE

Urban cell phone users are familiar with trying to find a good location for communications. This is an example of the search process discussed previously, and the boundaries of the search might be given by walls or user intangibles such as patience. A typical search method is moving and observing signal strength indications such as the number of “bars” in the cell phone display. Once an acceptable location is found (where a

call can be placed or received), the user stays in this position and the “search” terminates.

Let us first consider the case of optimizing link quality via motion for a simple peer-to-peer case where two RF-MG radio nodes can do the following: communicate, collaborate, transmit on demand, and receive/measure that transmission while keeping track of its current location. At least one of the two nodes is capable of mobility or its antenna can move. Even though the variations in RF strength are stochastic, the model parameters can easily be derived based on a Rician PDF using the second and fourth order moments of the received signal amplitude. The radio can search its surrounding space for a more benign fading condition at the cost of coordination, channel sounding, and processing. For example, a gain of 10 dB on the link (moving from a blue area to a red area in Fig. 2) results in an equivalent capacity gain. The improvement may be traded for reduced transmit power or increased throughput, depending on the application, while maintaining the same level of QoS.

MOBILITY STRATEGIES

Automation of the mobility gain principle would consist of a search strategy, a search goal, and a termination criterion. Example strategies might include random walks, bounded linear motions, and spirals. A strategy can be evaluated by the amount of motion required to locate the “goal” of improved mobility gain. The search will be bounded by the travel required to apply the search strategy in a constrained area. The distance traveled in the strategy can also serve as a bound, in which case the efficiency with which the search of the volume can be achieved is important.

To illustrate this, a mobility strategy study was performed on a 2D fading map collected at 1.2 GHz obtained under NLOS conditions in an

office building. Figure 4a shows the RF fading map for the CW at 1.254 GHz along with four mobility strategies used to sample the map.

There is a large dB variation over the map (in excess of 20 dB — the color map is over a 30 dB dynamic range), and the fading statistics are Rayleigh. In these maps we also show a series of mobility strategies: random walk, linear motion, circular motion and spiral motion of the mobile antenna. In this study a node is allowed to move across the map while the transmit node stays fixed using any one of the four motion types. A Monte Carlo study was performed for each motion type, randomizing the start position in the map and the direction of motion. All motions use the same speed. The measure of the fraction of nodes reaching 3 dB improvement on the link is shown in Fig. 4b's top panel. The bottom panel of Fig. 4b shows the cumulative density function of the mobility gain and shows that for the spiral mobility, 50 percent of the nodes reach 3 dB or better in less than 0.2 m motion distance along the spiral path. It is interesting to note that the random walk performs poorly, and the circular and linear motions are comparable to each other. This optimization approach only works for a single peer-to-peer link.

Exploitation of the relative spatial RF fading variations is challenging because first, the peer-to-peer maps are only valid while one of the nodes stays in a fixed position. This implies that mobility must be coordinated between participating nodes, which makes optimization of multiple links in a network a challenging problem. The signal space exploration can, however, be guided via statistical means since the distribution of RF fading may be estimated, and used to rate the quality and the probability of getting a better link. As a result, the mobile radio nodes are able to dynamically navigate inside the signal map while intelligently trading power spent on locomotion for potential radio link gain.

Another important aspect of small-scale fading optimization is that, as seen in the measurements, there is no preferred orientation since the map is random. Therefore, what matters is not *where* to move, but *to* move and *register*. This move/register strategy can yield good returns, as seen next.

QUANTIFYING MOBILITY GAIN

To illustrate the mobility gain for a single- or multiple-antenna system, a Monte Carlo analysis of the combination of a MIMO antenna system and an RF-MG enabled radio node was performed to compare and illustrate the mutual benefit of using these techniques. In this simulation radio nodes are placed in an NLOS environment with Rayleigh fading (Rician K -factor is $-\infty$ dB). Spatially diverse antennas (case b) are assumed to be at least $1/2$ wavelength apart so that each antenna experiences independent fading. Beamforming array antennas (cases d and e) are less than a $1/2$ wavelength apart to avoid spatial aliasing. Five cases are considered:

- A single-element antenna (single-input single-output [SISO] baseline case without RF-MG).
- A four-element antenna array with a 4×1 selection diversity switch connected to a single receiver chain (discrete sampling of the fading

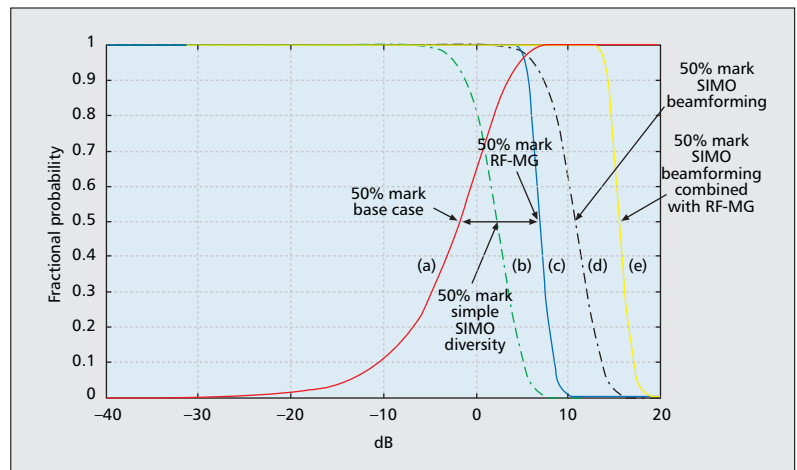


Figure 5. RF-MG analysis for various numbers of antennas.

map at only four points and selecting the antenna with the lowest amount of small-scale fading, SISO case without RF-MG).

- A single-element *mobile* antenna moving over 100 independent samples of a Rayleigh distributed fading process and able to choose the best location that minimizes loss due to small-scale fading (SISO baseline case with RF-MG).
- A four-element antenna array with four coherent receiver chains able to perform beamforming for gain. (This requires a more complex receiving architecture like that used in MIMO systems, SISO without RF-MG.)
- A four-element mobile array with four coherent receiver chains able to perform beamforming for gain while moving over 100 independent samples of a Rayleigh distributed fading process and able to select the best location (SISO with RF-MG).

A Monte Carlo study is performed across 1000 trials for each antenna configuration. Each trial has up to 100 possible locations for mobility and up to four independent antenna fades. The mobile radio nodes are assumed to store the fading observed at each of the 100 locations and have the ability to return back to the optimal location.

Figure 5 shows the results for the five cases. The leftmost red curve (a) is the baseline case and shows the cumulative distribution function of typical Rayleigh fading in an NLOS environment where the radio node cannot move or beamform. This curve shows the statistical probability of having a certain loss at the start of each run. For example, it shows that 10 percent of the fades have a loss of 10 dB or more, and 50 percent have a loss of -1.7 dB or more.

The green dot-dash curve (case b) shows using four antennas with selection diversity. The curve is the complementary cumulative distribution function (CCDF) of the process when the radio selects the best antenna out of the four. In this case 50 percent of the time, the RF-MG is 2.8 dB for 50 percent of the nodes in an NLOS environment, where the RF-MG is found by taking the difference between the CCDF of (b) and the CDF of the baseline case (a) at 50 percent probability.

Integrating radios with robotics to achieve mobility gain is a promising direction for future networking research. The RF-MG enabled radio nodes that participate in a cooperative network will demonstrate a never-before seen level of social behavior that literally approaches social networking as seen between humans.

The blue solid curve (case c) shows the CCDF for the same RF fading process, but the SISO radio node can now move and sample 100 discrete locations on the fading map and picks the best location. In this case, 50 percent of the time, the RF-MG is 8.76 dB for 50 percent of the points.

The black dot-dash curve is for beamforming on a four-element antenna array for architecture (d). The solid yellow curve (case e) is the combination of four-element antenna array beamforming and RF-MG over 100 independent samples of the fading map. For case (d) with fixed location beamforming, the gain 50 percent of the time is 11.4 dB for 50 percent of the points. For case (e) with SIMO beamforming and RF-MG, the gain 50 percent of the time is 17.3 dB for 50 percent of the locations.

Another scenario of interest is to evaluate RF-MG when the radio node experiences deeper fades. For example, on the baseline CDF curve, 10 percent of the time, a fixed location SISO radio can have fades of -10 dB or more. Now, for case (c) with an RF-MG SISO radio, 50 percent of the time the radio can improve the 10 percent deeply faded locations to at least 8.8 dB. In this case 50 percent of the time, the RF-MG is 18.8 dB for 10 percent of the locations in the NLOS environment. Hence, node mobility provides substantial gain if we compare a SISO RF-MG node against a fixed location SISO node that is experiencing deep fades.

A conservative interpretation of these curves could be that for 90 percent of the time the improvement is 5.7 dB for the SISO RF-MG, case (c). So for 50 percent of the locations for the baseline case (fades are -1.7 dB or worse), a SISO RF-MG system has a gain of 7.4 dB over 90 percent of the time. This is significant gain on the radio link that would typically require trading bandwidth or throughput for error correction coding or spread spectrum communications.

CONCLUSIONS

Mobility gain provides a new design option for radio systems by exploiting spatial motion. Obtaining a many-dB improvement translates to power saving for endurance or increased capacity. Increasing a link budget by only 3 dB is a significant achievement. Today the best decoding of data sources using turbo decoders and concatenated codes strive to reach gains of 0.5 or 1.5 dB. The cost is substantial in processing, data manipulation, and framing. The RF-MG concept and coordination algorithms allow the RF link to be systematically improved by several dB with little or no a priori knowledge of the environment.

Integrating radios with robotics to achieve mobility gain is an extremely promising direction for future networking research and development.

The RF-MG enabled radio nodes that participate in a cooperative network will demonstrate a never before seen level of social behavior that literally approaches social networking as seen between humans.

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BIOGRAPHIES

JONATHAN M. SMITH [F] is the Olga and Alberico Pompa Professor of Engineering and Applied Science and a professor of computer and information science at the University of Pennsylvania. He served as a program manager at DARPA (2004–2006) and was awarded the OSD Medal for Exceptional Public Service in 2006. His current research interests range from programmable network infrastructures and cognitive radios to disinformation theory and architectures for computer augmented immune response.

MARC P. OLIVIERI is a technology manager at Lockheed Martin ATL with over 16 years of experience in research and development for various advanced sensor and wireless communications programs in both large and small business and university research. He directed technology research for various DoD programs involving dynamic and covert waveforms for signaling and sensing techniques. He received his B.S.M.E. from Université de Technologie de Compiègne, France, and his M.S.O.E. and Ph.D. O.E./minor E.E. from Florida Atlantic University.

ALEX LACKPOUR (alex.lackpour@lmco.com) is a senior member of engineering staff at Lockheed Martin ATL. For the DARPA Landroids program he conducted measurement campaigns that classified the wireless channel in indoor environments from VHF to 3 GHz. For the DARPA XG program he simulated a distributed control protocol that dynamically assigns channel resources between frequency agile radios. He has led research in developing novel SDR technologies and wideband fractal antennas. He received his B.S.E.E. from the College of New Jersey and his M.S.E.E. from Pennsylvania State University.

NICK HINNERSCHITZ is an associate member of engineering staff at Lockheed Martin ATL working in the Wireless and Signal Processing group. He received a B.Sc. degree in computer engineering from Lehigh University in 2008 and is currently pursuing an M.S.E.E. from Drexel University with a focus on signal processing.