Wave-Propagation Management in Indoor Environments Using Micro-Radio-Repeater Systems

Jungsuek Oh, Michael Thiel, and Kamal Sarabandi

Radiation Laboratory, Department of Electrical Engineering & Computer Science
The University of Michigan
3228 EECS Building, 1301 Beal Avenue, Ann Arbor, MI USA 48109-2122
Tel: +1 (734) 764-0500; Fax: +1 (734) 647-2106; E-mail: jungsuek@umich.edu

Abstract

This paper investigates the ability of micro-radio repeaters for managing wave propagation by enhancing signal coverage for the nodes of a mobile ad-hoc network in a complex environment. Such radio repeaters can be considered to be scatterers with a large radar cross section (RCS). Strategically positioning them enables a chain of line-of-sight (LoS) propagation between the transmitter and receiver when the straight signal path is blocked by obstacles such as walls. To specify repeater parameters, wave propagation in various hallway junctions were analyzed using a ray-tracing method that accounted for reflection, penetration, and diffraction. By adding the repeater model to such propagation models, the ability of micro-radio-repeater systems to enhance wave propagation in indoor environments was demonstrated. The results were verified with various measurement examples using a bench-top repeater system at 2.4 GHz. To allow multiple access through a single repeater, a simple repeater structure, composed of two omnidirectional antennas and one amplifier with sufficient gain, was considered. Measurement results indicated that in the chosen various indoor scenarios, a repeater system with an active gain of more than 35 dB with omnidirectional antennas could present scattering larger than typical building diffraction, and thus could enhance signal connectivity at 2.4 GHz.

Keywords: Repeaters; line-of-sight propagation; ad-hoc networks; electromagnetic diffraction; radar cross section

1. Introduction

Wireless connectivity among the nodes of a low-power mobile ad-hoc network in a complex propagation environment is very challenging. This problem is critical when the transceiver nodes are on small wireless platforms operating near the ground, such as tiny mobile robotic platforms deployed in large-scale ad-hoc sensor networks [1, 2]. For such systems, the antenna size must be rather small and close to the ground. The propagation loss for near-ground nodes is much higher than in free space, as the direct signal is almost canceled by the reflected signal from the ground [3]. In order to maintain the network connectivity, either the transmitted power must be increased, or the messages must be routed through the nodes of the network. The latter requires a network protocol that results in low efficiency, latency, and low data rate among the nodes.

An alternative to this approach is to manage the propagation environment. In complex propagation environments such as indoor settings, wave propagation at microwave frequencies is hampered by significant attenuation through walls, multiple reflections among walls, floor, and ceiling, as well as diffraction. Due to significant differences in path length among the rays that reach a receiving point, the signal experiences significant fading due to the absence of the direct line-of-sight contribution [4]. This increased fast-fading phenomena affects the power budget and signal-coverage extent of the wireless network. For example, deep fading causes a drop of the communication link in an indoor environment, even for a short distance between the transmitter and receiver.

Managing the propagation environment entails strategic placement of reflective targets between the transmitter and receiver in the environment to mitigate the effects of intrinsic obstacles and blockages. Reflective targets can be active or passive. Similar to traffic mirrors around sharp bends in a road, passive reflectors can enhance signal connectivity [5-7]. However, such reflectors are bulky, and mainly appropriate for fixed communication nodes. For mobile nodes, passive reflectors that can redirect the signal over a wide angular sector, such as metallic spheres, have a low RCS unless their diameter is very large. This limits the application of passive repeaters to specific conditions. The use of active repeaters has also been successfully demonstrated to enhance signal coverage, for example, from outside of a building to inside, or to enhance wireless communication in a congested urban setting [8, 9]. For active repeaters, the isolation between repeater transmitting (RTx) and receiving antennas (RRx) is achieved by sufficient physical separation, and using antennas with unidirectional radiation. In some cases, additional shielding is accomplished by placing metallic screens between the repeater transmitting and repeater receiving antennas.

Recently, a design for miniaturized low-power radio repeaters with sub-wavelength dimensions and omnidirectional coverage was demonstrated [10]. Due to limitations in size and power, the active gain of such repeaters is moderate. This paper investigates the utility of sub-wavelength micro-radio-repeater systems in an indoor environment. This small active device can be viewed as an equivalent large passive reflector that can boost the signal between a non-line-of-sight transmitter and receiver, creating a new strong propagation path that enables communication. Using physics-based wave-propagation modeling in buildings, the proper placement of such repeaters is theoretically investigated. Strategic positioning of both the repeater and the repeater specifications are studied for wireless-coverage enhancement.

The indoor wave-propagation simulation is based on ray tracing, a combination of Geometrical Optics and the Geometrical Theory of Diffraction, which have successfully been used for the analysis of indoor wave propagation over decades [11-13]. The use of ray tracing for validating the feasibility of a repeater system was reported in [14]. On the basis of these theoretical results, specifications and scenarios are given for successful use of repeaters in indoor environments, and the use of the repeater system is validated by measurements.

2. Theoretical Analysis

2.1 The Concept of a Radio Repeater

The radio-repeater system is designed to amplify and transmit a predetermined received signal. A series of repeaters is capable of relaying information in stringent wireless-propagation environments by forming an ad-hoc network. A rudimentary figure of the radio-repeater system is shown in Figure 1. The radio repeater establishes a line-of-sight communication link between the transmitting and receiving stations. To demonstrate the application of such a system, let us imagine a simple propagation scenario where a direct communication link between transmitter and receiver is blocked by the walls of a building, as shown in Figure 2a. In this case, the signal coverage is established via penetration through the walls and diffraction from the edges of the walls, with both signal paths highly attenuated. By utilizing the radio repeater at the appropriate position, a direct communication link is formed, and thus signal coverage can be improved, as depicted in Figure 2b.

2.2 Formulation of Wave Propagation with a Repeater System

As a simplification, the received power at the receiver through the repeater can be computed using the Friis transmission formula, assuming free-space propagation between the repeater and both the transmitter and the receiver. First, the Friis transmission formula is applied once to find the received power at the repeater position. This power is amplified and retransmitted, and the Friis transmission formula is applied a second time to find the received power at the receiver position. The equation below shows this process:

$$\frac{P_{Rx}}{P_{Tx}} = \frac{G_{Tx} G_{RRx} \lambda^2}{(4\pi R_1)^2} G_{Amp} \frac{G_{RTx} G_{Rx} \lambda^2}{(4\pi R_2)^2}$$
$$= (G_{Tx} G_{Rx}) \frac{\lambda^2}{(4\pi R_1)^2} \frac{\lambda^2}{(4\pi R_2)^2} (G_{REP}), \quad (1)$$

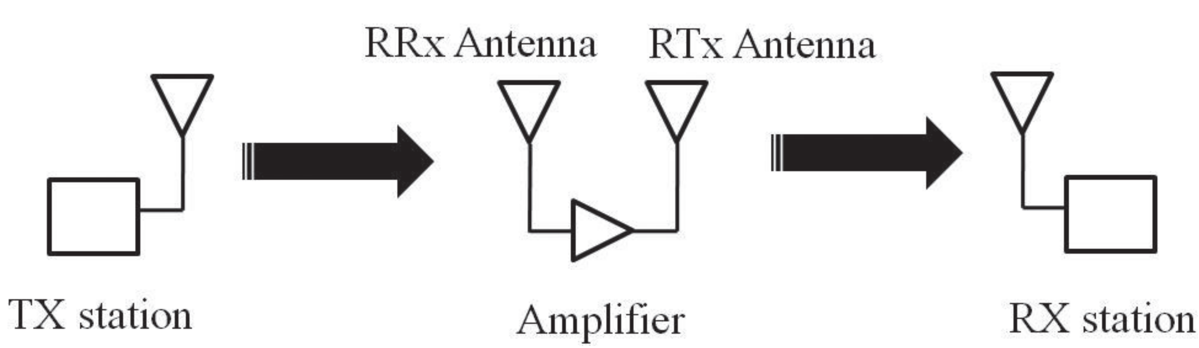


Figure 1. The radio-repeater system configuration.

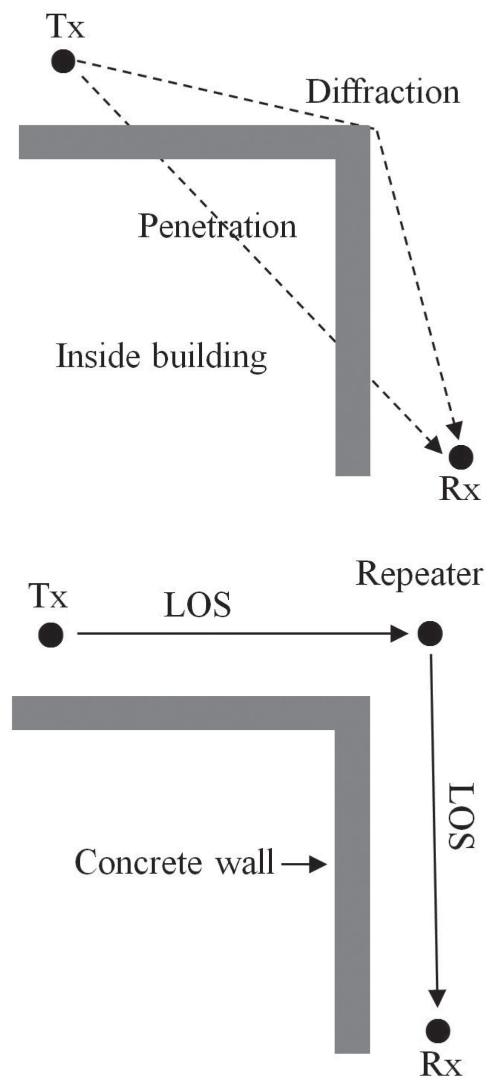


Figure 2. The concept of radio repeater placement: wave propagation (a) without and (b) with the repeater.

where P_{Tx} and P_{Rx} are the transmitted and received powers; G_{Tx} and G_{Rx} are the gains of the transmitter/receiver antennas; G_{RRx}, G_{RTx}, and G_{Amp} are the gains of the repeater receiving/repeater transmitting antennas and of the amplifier in the repeater; $G_{REP} = G_{RRx} G_{RTx} G_{Amp}$ is the total gain of the repeater; R_1 is the distance between the transmitter and the repeater; and R_2 is the distance between the repeater and the receiver.

It is assumed that the repeater consists of transmitter and receiver antennas, and one amplifier in between the two antennas. It should be noted that when wave propagation goes through the repeater, the attenuation due to $\lambda^2 / (4\pi)^2$ as well as the gain due to G_{REP} occur. The direct path loss and the path loss with the repeater system can now be compared:

1) Direct link:

$$\frac{P_{Rx}}{P_{Tx}} = G_{Tx} G_{Rx} PL_{Tx \to Rx} , \tag{2}$$

2) Through repeater:

$$\frac{P_{Rx}}{P_{Tx}} = G_{Tx} G_{Rx} G_{REP} PL_{Tx \to REP} PL_{REP \to Rx} , \tag{3}$$

where $PL_{Tx \to Rx}$ is $\lambda^2 / \left[4\pi \left(R_1 + R_2 \right) \right]^2$, the path loss from the transmitter to the receiver; $PL_{Tx \to REP}$ is $\lambda^2 / \left(4\pi R_1 \right)^2$, the path loss from the transmitter to the repeater; and $PL_{REP \to Rx}$ is $\lambda^2 / \left(4\pi R_2 \right)^2$, the path loss from the repeater to the receiver.

Consequently, in order to enhance the signal coverage with the repeater, the following equation has to be met:

$$G_{REP} PL_{Tx \to REP} PL_{REP \to Rx} > PL_{Tx \to Rx} . \tag{4}$$

From Equations (2) and (3), Equation (4) can be rewritten as

$$G_{REP} > \frac{1}{\left(\dfrac{\lambda}{4\pi R_1} + \dfrac{\lambda}{4\pi R_2} \right)^2} . \tag{5}$$

To simplify Equation (5), let R_1 and R_2 be same as R, and then Equation (5) becomes

$$G_{REP} > \left(\frac{2\pi R}{\lambda} \right)^2 . \tag{6}$$

Suppose that multiple radio repeaters are positioned on a straight line, as shown in Figure 3. Considering the simplest scenario using only one repeater, the minimum required repeater gain (MRRG) to establish the same path loss as the case without the repeater is given by $G_{REP} = \left[(2\pi R) / \lambda \right]^2$ from Equation (6). Figure 4 shows the MRRG as a function of the distance R, normalized by a wavelength. Case A represented a case when the actual repeater gain (20 dB) was lower than the MRRG, while Case B with 40 dB repeater gain, did the reverse. For both cases, repeaters were positioned at every 5λ. Figure 5 shows the path loss using the cascaded repeaters as a function of R/λ for the two cases. As expected, the path loss at $R = 30\lambda$ in Case A was much higher than the path loss without a repeater, while in Case B, the use of the repeater had a significant advantage over the case without a repeater.

However, it must be noted that the condition for the repeater to be advantageous was unrealistic in the straight-line wave-propagation scenario. For example, when a repeater with

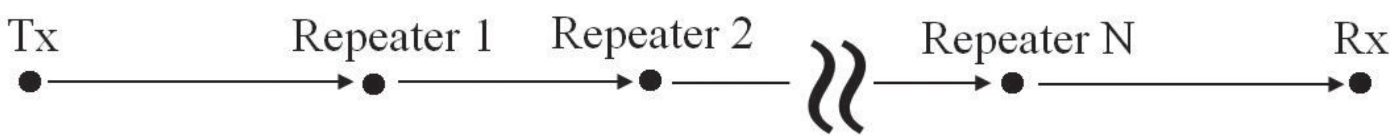


Figure 3. Radio repeaters on a straight-line path.

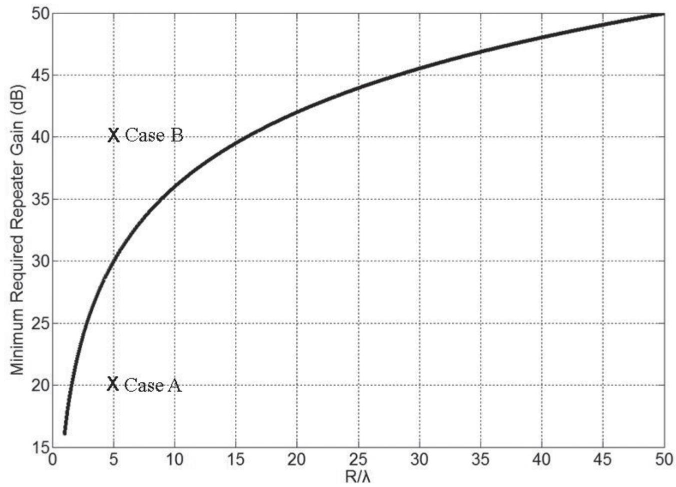


Figure 4. The minimum required repeater gain to make the path loss with a repeater the same as the path loss without a repeater, as a function of R/λ .

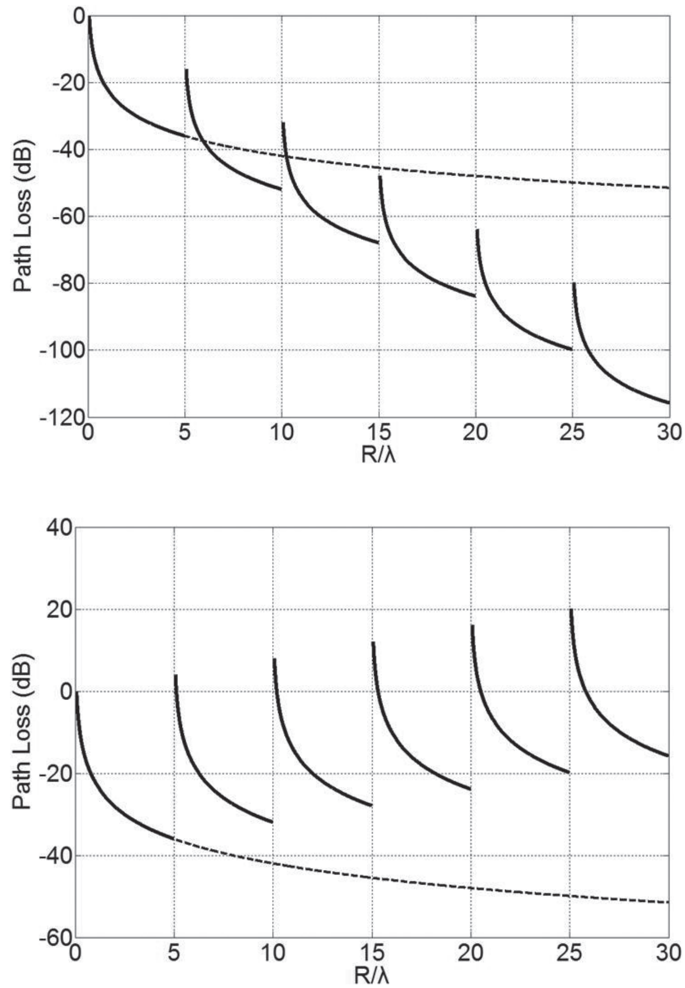


Figure 5. The path loss corresponding to Cases A and B in Figure 4.

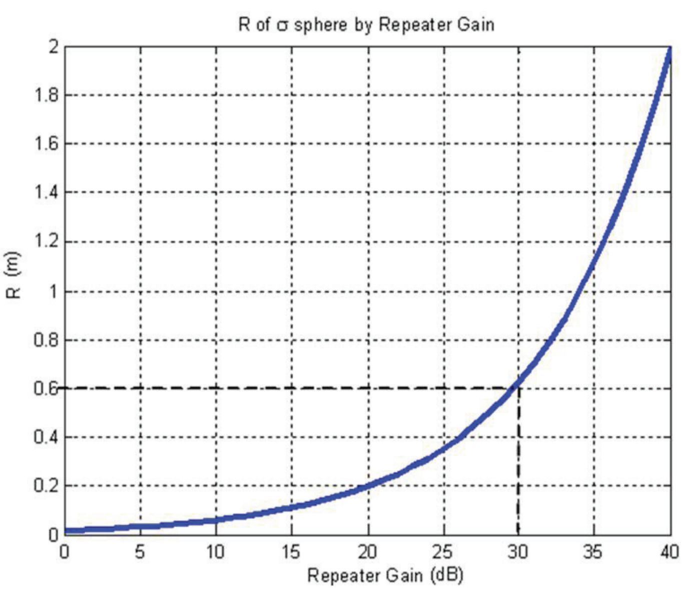


Figure 6. The equivalent sphere's RCS by the variation of a radio repeater gain.

25 dB at 2.4 GHz was used, in order to be advantageous, the repeater had to be positioned within 0.3 m from the transmitter. In this paper, it is therefore assumed that only in the environments where the direct signal path between the transmitter and receiver is highly attenuated, such as complex indoor environments, can the radio repeater contribute to a practical signal-coverage enhancement. In such indoor environments, the $PL_{Tx \to Rx}$, $PL_{Tx \to REP}$, and $PL_{REP \to Rx}$ values must be derived from the actually measured or computed path loss (PL), considering multipath effects.

2.3 The Monostatic Radar Cross Section (RCS) of the Radio Repeater

The measurement of the overall gain of the repeater system cannot be done using a network analyzer, as the connecting cables and the instrument can perturb the near fields, and establish additional couplings between the repeater's receiving and transmitting antennas. Since the radio repeater simply acts as a transponder, its behavior can also be assessed in terms of its monostatic RCS. To calculate the RCS of the repeater, the relationship between an incident power density at the repeater location and the scattered power density at an observation point is required. This can be easily accomplished using the effective aperture of the receiving antennas, $\left(G_{RRx}\lambda^2\right)/(4\pi)$, as shown below:

$$\frac{|E_i|^2}{\eta}\frac{G_{RRx}\lambda^2}{4\pi}G_{Amp}\frac{G_{RTx}}{4\pi R^2}=\frac{|E_s|^2}{\eta}. \tag{7}$$

Using Equation (7), the RCS of the repeater (σ_{REP}) is given by

$$\begin{aligned}\sigma_{REP} &= 4\pi R^2\frac{|E_s|^2}{|E_i|^2}\\ &= \frac{G_{RRx}G_{RTx}G_{Amp}\lambda^2}{4\pi}\\ &= \frac{G_{REP}\lambda^2}{4\pi}.\end{aligned} \tag{8}$$

Since omnidirectional antennas are considered for repeater systems, the closest passive target that can be compared to the repeater system is a metallic sphere. Comparing Equation (8) to the RCS of a metallic sphere ($\sigma_{sphere}=\pi R^2$) the radius of which is large compared to the wavelength allows the calculation of an equivalent passive sphere with the identical RCS. Such a comparison yields an equivalent sphere radius of

$$R=\sqrt{\frac{G_{REP}\lambda^2}{4\pi^2}}. \tag{9}$$

It was found that a repeater with G_{REP} of approximately 30 dB is equivalent to a sphere with a diameter of 1.2 m, as shown in Figure 6.

3. Simulation of Repeater in Indoor Scenarios

As introduced in Section 2.1, the use of a repeater is most effective when the direct path between the transmitter and receiver is blocked. Therefore, simple indoor scenarios were studied to quantitatively determine the level of path loss and the specifications of a repeater system for enhancing the signal coverage.

3.1 Single-Edge Diffraction and Hallway Junctions

The simplest possible scenario is a two-dimensional single-diffraction case, which is a corner formed by two impenetrable walls. This scenario is shown in Figure 2 by eliminating the penetrating ray through the walls. This propagation model has the highest possible path loss without a repeater, and is thus the ideal scenario for a repeater. However, because an indoor scenario is never formed by a single corner but rather of multiple rooms, hallways, and hallway junctions, the path loss around realistic hallway junctions needs to be investigated, as well. A shoot-and-bounce ray-tracing approach was applied to various hallway junctions, as shown in Figure 7 [15]. The ray-tracing method also included diffractions at the hallway corners, which were calculated with the Geometrical Theory of Diffraction with a heuristic adjustment of the diffraction coefficients for dielectric materials [16]. The path loss was computed along the path R2 of Figure 7 with a distance of 11 m between the transmitter and the hallway junction at 2.4 GHz, omitting wall penetration. The transmitter was 11 m away from the junction, and the dielectric constant of the wall was assumed to be 4.8, with a conductivity of 0.02 S/m, representing concrete.

Figure 8 shows the path loss of all hallway junctions compared to the diffraction around a single corner. It was shown that the received field in non-line-of-sight hallways was, on average, about 30 dB higher than the signal level for the single-diffraction case. This was due to the guiding effects of the hallway and the higher diffraction coefficient for the reflected rays that impinged on the corner at a less-steep incident angle, as shown in Figure 9. Another feature observed in Figure 8 was the fast fading resulting from constructive and destructive interferences for the rays. While the edge diffraction due to the shortest path (without wall reflections) in the hallway was very weak, the edge diffraction of a multiply reflected ray was strong, leading to a higher received field, as shown in Figure 9.

Now the placement of the radio repeater in the hallway junction could be considered, and coverage enhancement due to the overall repeater gain could be analyzed. For simplification,

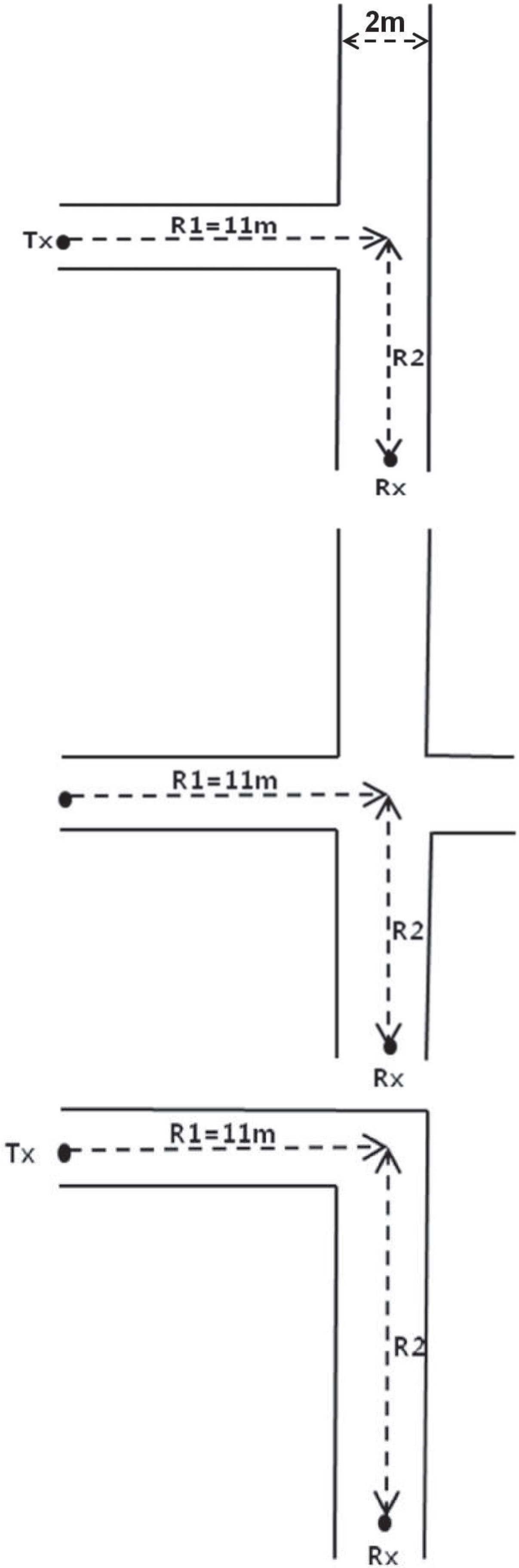


Figure 7. Possible hallway junctions: (a) T-type, (b) X-type, and (c) L-type.

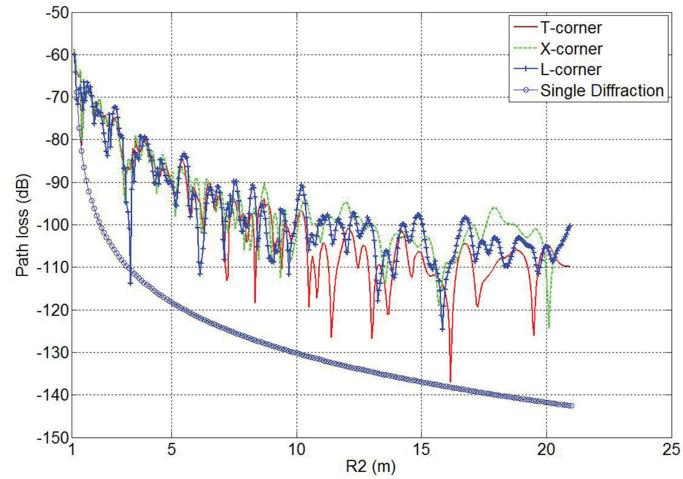


Figure 8. The path loss along different hallway junctions shown in Figure 7 at 2.4 GHz. The path loss is also shown for a single corner. In all cases, the transmitter was 11 m away from the corner.

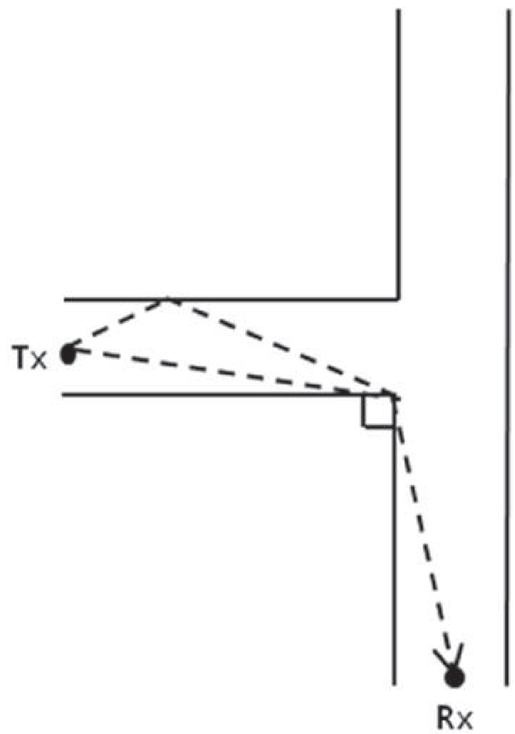


Figure 9. Multiple diffracted rays in the T-type hallway.

the path loss along the hallway was compared with the line-of-sight from the transmitter to the repeater, and from the repeater to the receiver. Figure 10 shows the path loss resulting from wave propagations through the radio repeater having various repeater gain values of 10 dB, 20 dB, and 30 dB. Although this neglected the fast-fading effects of the hallway that might add to the line-of-sight path, it was a good estimation of the average field through the repeater, and indicated that deployment of radio repeaters for gain values greater than 20 dB can enhance the signal coverage. It was also shown that for gain values higher than 30 dB, the dominant signal component went through the repeater. 30 dB gain achieved about 10 dB margin compared to the coupling at the hallway junction.

3.2 Realistic Floor Plan

The previous results already showed that a reasonable repeater gain of 20 dB could help the signal coverage along hallways. However, in a realistic indoor scenario, one also has to consider the whole entire layout, including penetration through walls. Simulations were therefore carried out for a realistic floor plan and repeater placement, and coverage enhancement was evaluated. The wall in the scenario was thick drywall with $\varepsilon_r = 2.5$ and $\sigma = 0.015$ S/m. Figure 11 shows the path loss along the hallways overlaid with the building layout. As could be seen, the color of the region of $y > 15$ m in the hallway of $x = -8$ m was dark. This suggested that although the rooms in the center were penetrable, the signal strength in the hallway further away from the transmitter was low at $x = -8$ m and $y > 15$ m. This low received signal strength could be enhanced via placement of a repeater in a hallway junction. Figure 12 shows the resulting path loss of the floor including

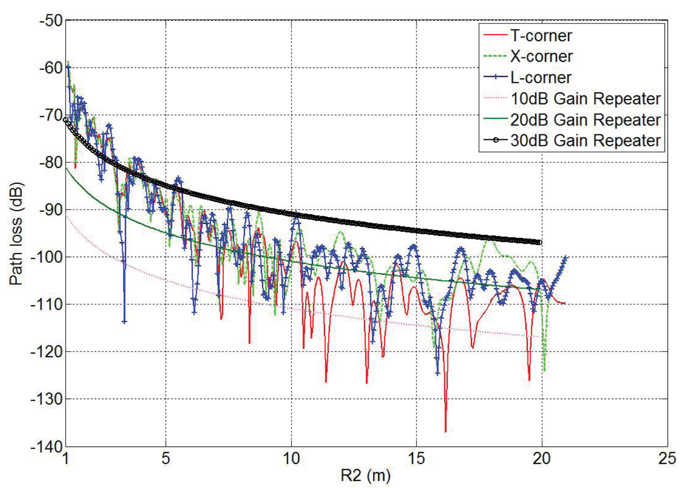


Figure 10. The path loss along the hallway of Figure 7 at 2.4 GHz compared to the path loss of line-of-sight propagation through a repeater placed at the hallway junction.

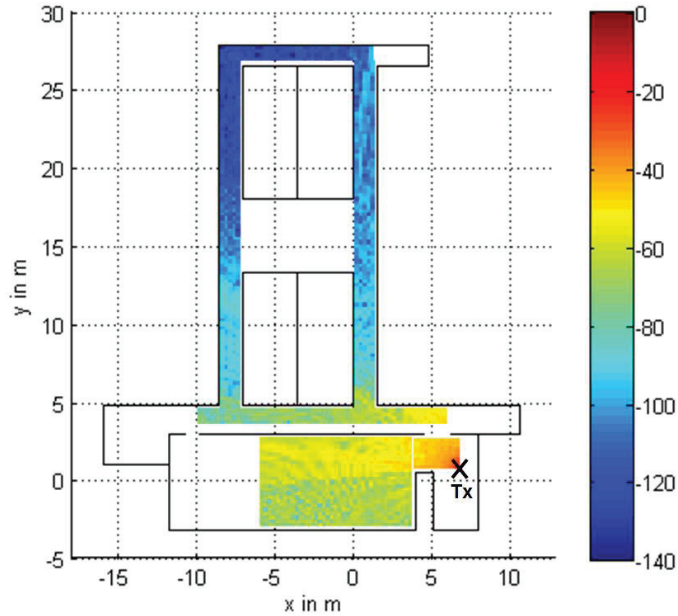


Figure 11. The path loss of a sample floor layout with the transmitter at $x = 6.6$ m and $y = 0.75$ m at 2.4 GHz.

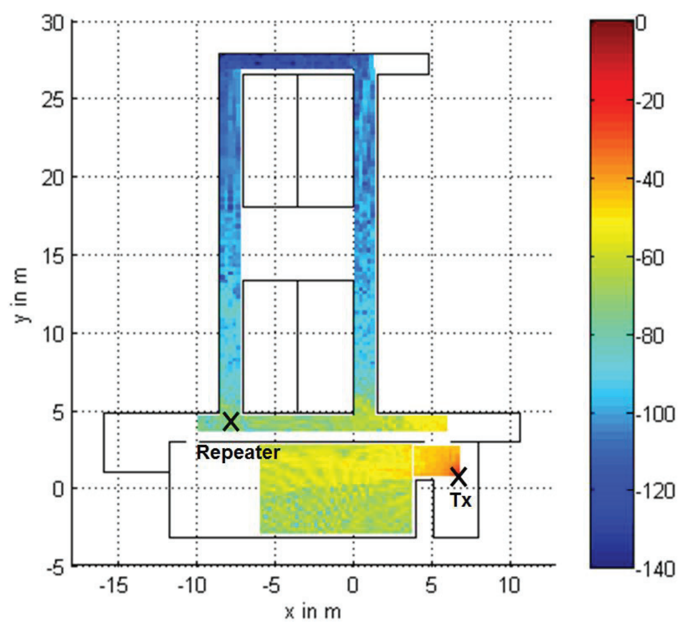


Figure 12. The path loss of a sample floor layout with the transmitter at $x = 6.6$ m and $y = 0.75$ m, and a repeater (with an overall gain of 35 dB) placed at $x = -8.0$ m and $y = 4.5$ m, at 2.4 GHz.

the repeater, with an overall gain of 35 dB. The repeater was placed at the entrance of the junction ($x = -8$ m and $y = 4.5$ m), where the average path loss was about -70 dB. It was observed that compared to the region of $x = -8$ m and $y > 15$ m in Figure 11, the color in the same region of Figure 12 was brighter. This indicated that with the repeater, the received field coverage at $x = -8$ m and $y > 15$ m could be enhanced by up to 20 dB.

4. Measurements

The simulation results showed that a strategic repeater placement in hallway junctions, far away from the transmitter but still in the line-of-sight of the transmitter, could significantly enhance field coverage along the shadowed hallway, if the overall repeater gain was about 35 dB. This result was validated against signal-coverage measurements in real buildings. For the measurements, a bench-top repeater system, consisting of two dipole antennas tuned to 2.4 GHz and a variable gain amplifier, was used. Similar antennas were used for the transmitter and receiver. The transmitting antenna was connected to a signal generator, and the receiving antenna was connected to a spectrum analyzer for quantitative signal measurements. The output power from the signal generator was 20 dBm. Two amplifiers were put in between the receiver antenna and the spectrum analyzer to increase the receiver's sensitivity. The gain of the two amplifiers was 18 dB, and the noise level of the spectrum analyzer was about -85 dBm.

According to the simulation results, two scenarios were chosen. One example is plotted in Figure 13 (the third floor of the EECS building at the University of Michigan). There, the direct path from the transmitter to the receiver was attenuated by many obstacles such as the elevators, leaving the hallway diffraction as the main propagation path. Initially, the repeater's performance was synthesized by first placing the receiver at the corner junction in the line-of-sight with the transmitter, as shown in Figure 13. The transmitter was then moved to the previous receiver location, and then the receiver was placed in the intended receiving location, and the received signal was recorded. Using high-enough-gain amplifiers in the receiver, all the measured points were derived when their peak value was above the noise level. These data were then used to synthesize the received signal in the presence of a repeater at the corner with a gain of 25 dB. Without the repeater, the received field along $\overline{AB}$ was dominated by the multipath and diffraction. However, after the repeater was put at the intersection, the line-of-sight formed between the transmitter and receiver became dominant. Figure 14 shows the measured path loss along $\overline{AB}$ in Figure 13.

The path loss using the repeater was enhanced by more than 10 dB. Furthermore, the received field strength through the repeater showed less fading compared to the original signal.

A hallway including a staircase in a different building was used as a second example for demonstrating the coverage enhancement using a radio repeater (Figure 12). In this case, the repeater performance was also synthesized through two successive measurements, as described before. The transmitter was put on the second floor, and the receiver was put on the first floor. The repeater was placed at a proper position to establish a line-of-sight between the receiver and transmitter, as shown in Figure 15. The measured results showed that the path loss of -119.3 dB could be improved to -110.6 dB, once a repeater with an overall gain of 25 dB was utilized.

In the next set of experiments, we utilized a bench-top repeater system that was used for demonstrating the performance enhancement of indoor wave propagation in the presence of a radio repeater with an omnidirectional radiation pattern.

4.1 Configuration of a Bench-Top Repeater System

Figure 16 shows the components of a simple bench-top repeater system used to investigate the feasibility of subwavelength micro-repeaters [10]. This system consisted of a bandpass filter, an attenuator, two dipole antennas, and a high-gain amplifier. The bandpass filter was used to block the interference due to the unwanted signals such as cell phone, Bluetooth, etc. The gain of the repeater was varied from 20 dB to 50 dB in intervals of 2 dB by adjusting the attenuator, which allowed us to figure out the level coverage enhancement as a function of gain.

It should be noted that the maximum available gain of the repeater was limited by the isolation level between the receiving and retransmitting antennas, since the retransmitted signal from the repeater could be received not only by the desired receiver, but also by the receiver antenna in the repeater. In this radio-repeater system, the isolation level was defined as the path loss between the two antennas, including local scattering and reflection from the adjacent edges and walls. If the isolation level between the two antennas was less than the gain of the repeater, the repeater would go into oscillation. In this case, the amplifier gain dropped. It was therefore very important that the radio-repeater system be designed for maximum isolation between the two antennas.

4.2 Measurement in a Hallway Junction

A T-corner hallway was chosen for the measurement using the bench-top radio-repeater system, as shown in Figure 17. As discussed earlier, the isolation level between the receiving (RRX) and retransmitting (RTx) antennas was determined by the path loss between the two antennas. The path loss was affected by the distance between the two antennas, as well as the other channel environment factors, including the adjacent edges and walls. Spacing the repeater receiver and repeater transmitter therefore effectively controlled the feedback between the repeater transmitting and the repeater receiving antennas. In this measurement setup, the positions of the repeater receiving and repeater transmitting antennas

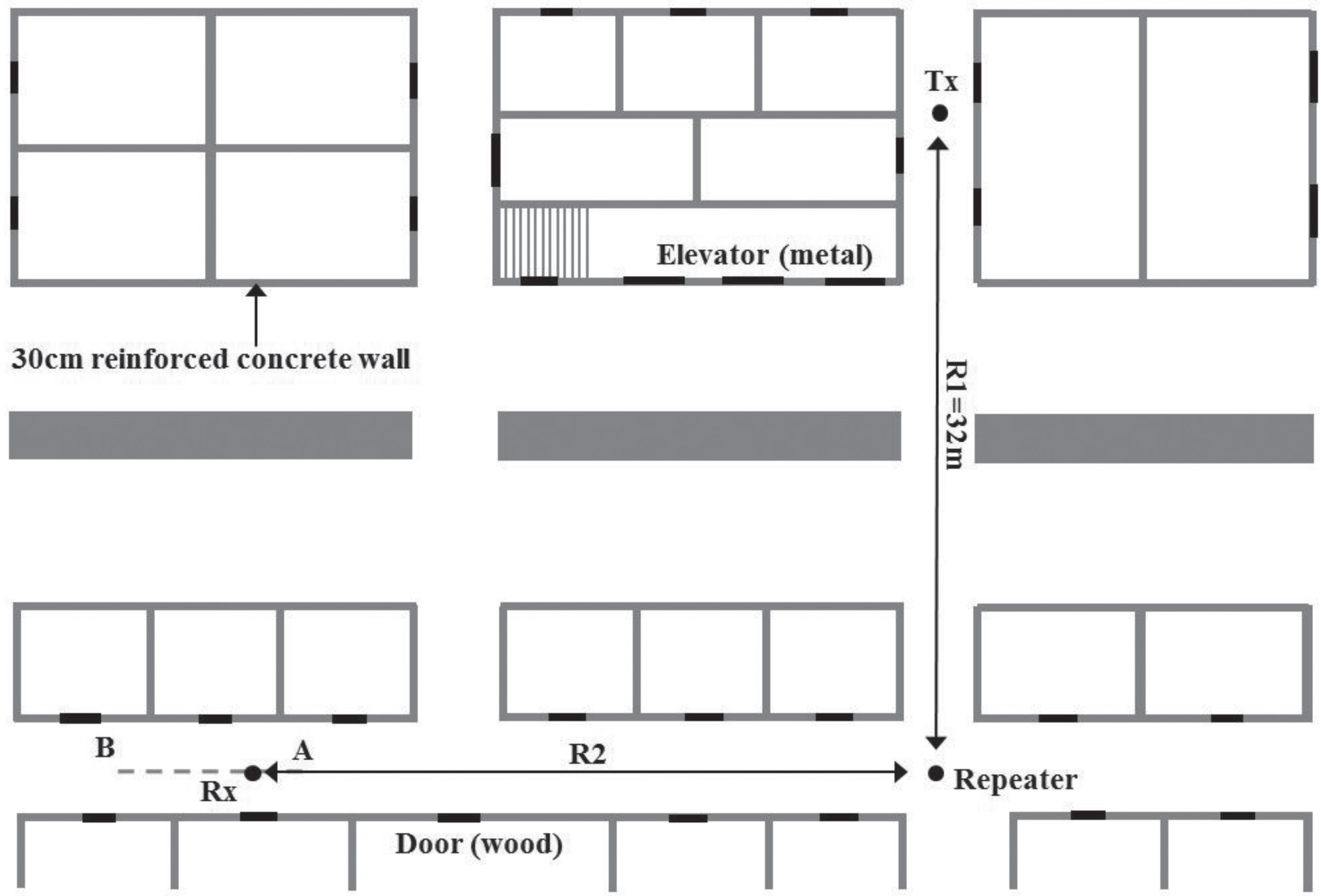


Figure 13. The third floor layout of the EECS building at the University of Michigan with the positions of the transmitter, receiver, and repeater, and the dimensions.

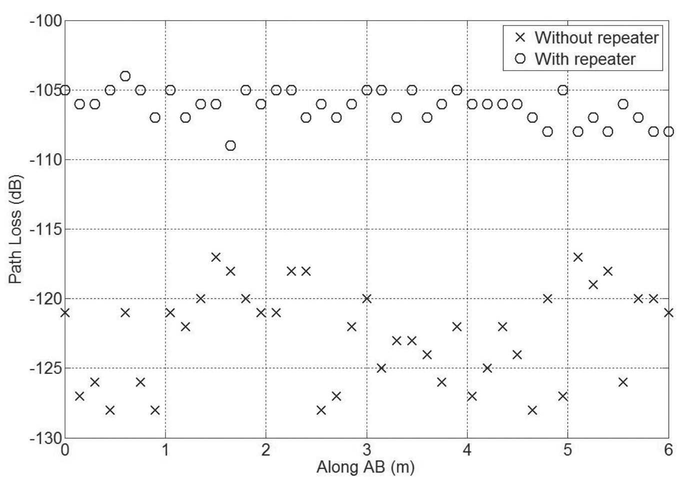


Figure 14. The measured path loss along $\overline{AB}$ in Figure 13 at 2.4 GHz with and without the assumed repeater at the hallway junction.

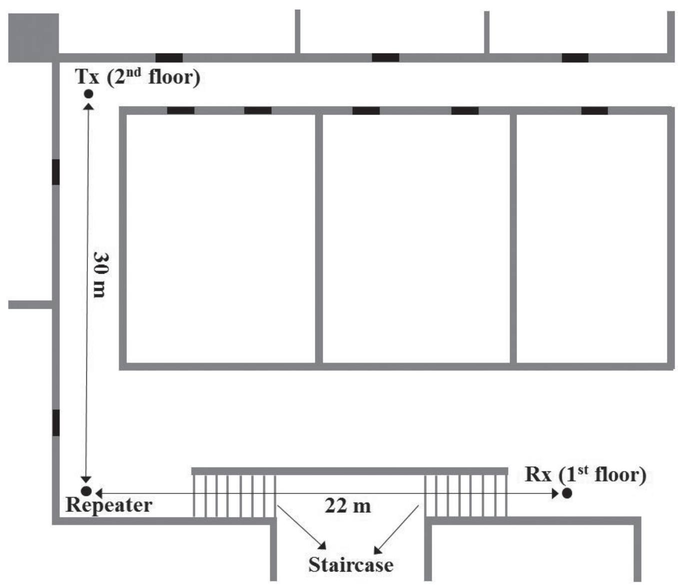


Figure 15. The floor layout of the Pierpont Commons building at the University of Michigan North Campus with the positions of the transmitter, receiver, and repeater, and the dimensions.

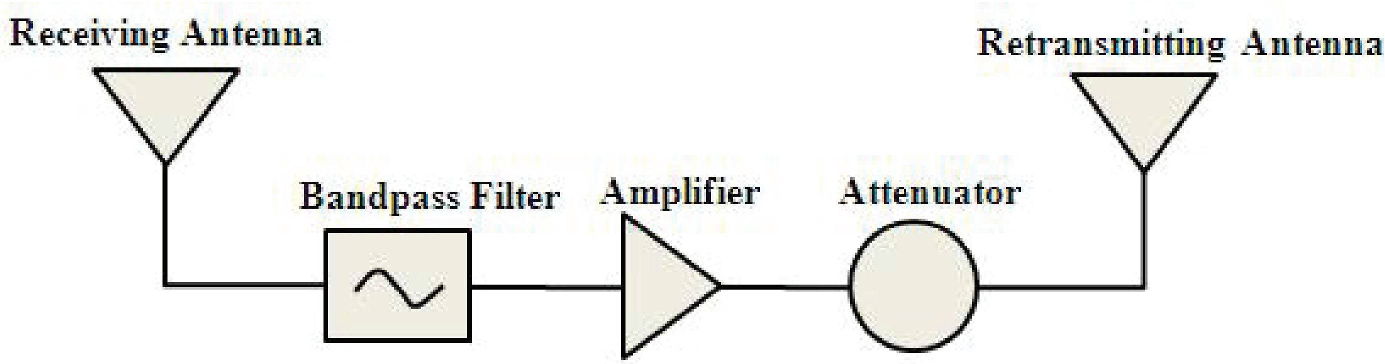


Figure 16. The configuration of the radio repeater.

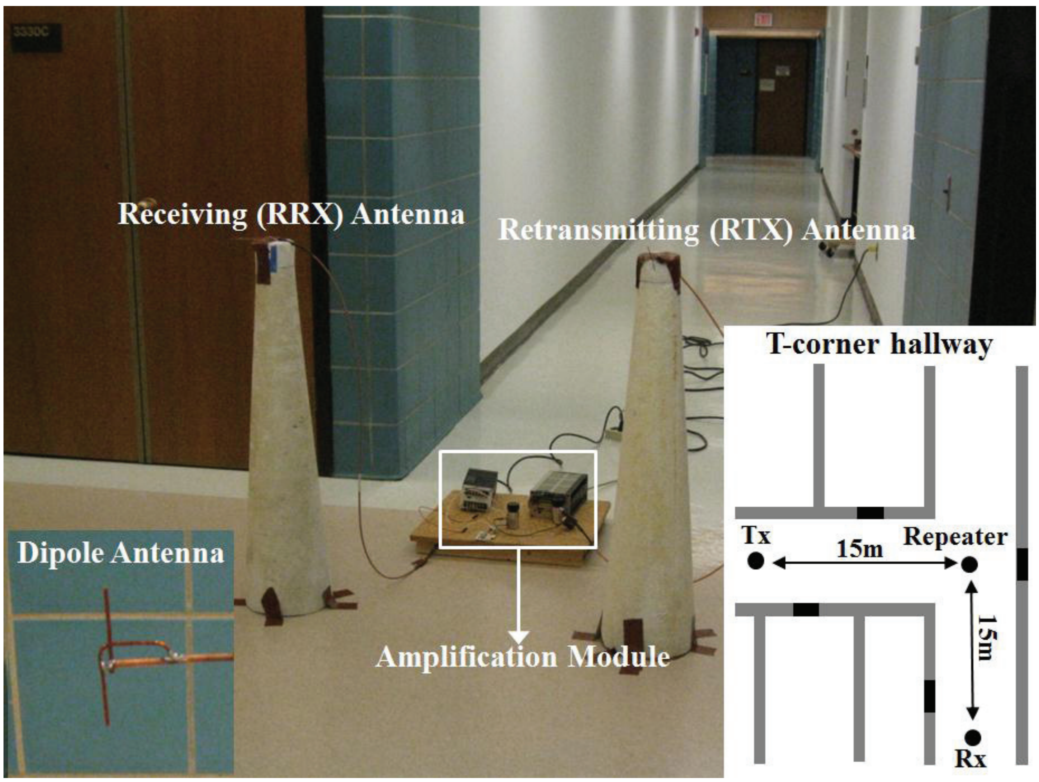


Figure 17. The repeater system set up in a T-corner hallway.

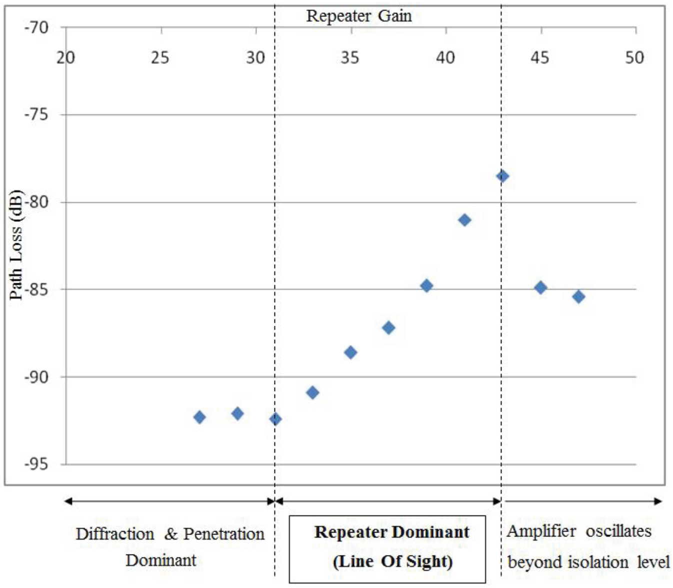


Figure 18. The measured path loss through a repeater at a hallway junction as a function of the overall repeater gain at 2.4 GHz.

were appropriately chosen to form the lines-of-sight between the transmitter antenna and repeater receiving antenna, and between the repeater transmitting antenna and receiver antenna. With the chosen setup, the measured isolation level between the repeater receiving and repeater transmitting antennas was about 42 dB. This means that if the repeater gain was over 42 dB, which was the isolation level between the repeater receiving and repeater transmitting antennas, the repeater system worked as a positive-feedback system. In other words, since the gain of the circulating signal path between the two antennas became undesirably positive, high input power injected at the amplifier resulted in the oscillation of the amplifier. This oscillation severely lowered the gain of the amplifier.

Figure 18 shows the measured path loss between the transmitter and receiver in the presence of the repeater system, as a function of the repeater gain. In the region between 20 dB and 31 dB repeater gain, although the radio repeater gain increased, the path loss did not change, which indicated that other propagation mechanisms were still dominant. However, in the region from 32 dB to 42 dB, as the gain increased, path loss was also linearly improved, implying that the path through the repeater was the dominant communication link. Beyond 42 dB gain, the path loss increased. This was due to the fact that the isolation level between the two antennas was about 42 dB, and oscillation occurred beyond the isolation level. This measurement using the bench-top repeater system indicated that micro-repeater systems with an overall gain beyond 31 dB could enhance field coverage in this indoor setting. It must be noted that the level of repeater gain to be advantageous can be slightly changed depending on the position of the repeater due to fast-fading effects.

5. Conclusion

This paper investigated wireless signal-coverage enhancement by utilization of a micro-radio repeater in a complex indoor environment. The paper started with the modeling of repeaters as a scatterer in the environment having a large radar cross section with an omnidirectional pattern. Wave-propagation analysis using ray tracing revealed that placing such repeaters in appropriate locations with direct line of sight to both the transmitter and receiver can enhance the signal strength in shadowed areas. It was also shown that repeaters with enough gain – typically, more than 30 dB – can provide a signal component in the multipath environment that is dominant, and can thereby drastically reduce deep signal fading. This study sets forth useful indoor scenarios for the performance characteristics of such repeaters to be most effective. With some recent advancements in the design of micro-repeaters, it is anticipated that sub-wavelength repeater systems with gain values exceeding 50 dB are possible.

6. References

1. G. T. Sibley, M. H. Rahimi, and G. S. Sukhatme, “Robomote: A Tiny Mobile Robot Platform for Large-Scale Ad-Hoc Sensor Networks,” Proc ICRA2002, **2**, May 2002, pp. 1143-1148.

2. Kazutaka Tatara, Geunho Lee, and Nak Young Chong, “Self-Organizing Ad-hoc Robotic Sensor Networks Based on Locally Communicative Interactions,” Proceedings of the 8th International Conference on Ubiquitous Robots and Ambient Intelligence, November 2011, pp. 485-490.

3. D. Liao and K. Sarabandi, “Terminal-to-Terminal Hybrid Full-Wave Simulation of Low-Profile, Electrically-Small, Near-Ground Antennas,” *IEEE Transactions on Antennas and Propagation*, **AP-56**, 3, March 2008, pp. 806-814.

4. T. S. Rappaport (ed.), *Wireless Communications: Principles and Practice*, Upper Saddle River, NJ, Prentice Hall PRT, 2001.

5. H. Hristov, R. Feick, and W. Grote, “Improving Indoor Signal Coverage by Use of Through-Wall Passive Repeaters,” International Symposium on Antennas and Propagation, 2001.

6. Y. Huang, N. Yi, and X. Zhu, “Investigation of Using Passive Repeaters for Indoor Radio Coverage Improvement,” International Symposium on Antennas and Propagation, 2004.

7. Y. Serizawa, Y. Watanabe, and S. Takeshita, “Multipath Propagation Effects on Digital Radio Equipped with a Plane Reflector Repeater,” *IEE Proceeding Communications, Speech and Vision*, 1992.

8. A. H. Ali, “Coverage Enhancement Through Fixed Repeater Network in UMTS,” Proceeding of the International RF and Microwave Conference Putraja, Malaysia, 2006.

9. A. Wolfgang, M. Coldrey, P. Persson, and P. Bohlin, "Advanced Repeaters in Cellular Communication Systems," 3rd European Conference on Antennas and Propagation, 2009.

10. K. Sarabandi and Y. Song, "Subwavelength Radio Repeater System Utilizing Miniaturized Antennas and Metamaterial Channel Isolator," *IEEE Transactions on Antennas and Propagation*, **AP-59**, 7, 2011, pp. 2683-2690.

11. M. F. Iskander and Z. Yun, "Propagation Prediction Models for Wireless Communication Systems," *IEEE Transactions on Microwave Theory and Techniques*, **50**, 3, 2002, pp. 662-674.

12. S. Y. Seidel and T. S. Rappaport, "Site-Specific Propagation Prediction for Wireless In-Building Personal Communication System Design," *IEEE Transactions on Vehicular Technology*, **43**, 4, 1994, pp. 879-892.

13. Y. Wang, S. Safavi-Naeini, and S. K. Chaudhuri, "A Hybrid Technique Based on Combining Ray Tracing and FDTD Methods for Site-Specific Modeling of Indoor Radio Wave Propagation," *IEEE Transactions on Antennas and Propagation*, **AP-48**, 5, 2000, pp. 743-754.

14. J. Oh, M. Thiel, W. Hong, and X. Zhu, "Indoor Wave Propagation Measurements and Modeling for Evaluation of Coverage Enhancement Using a Repeater System," International Symposium on Antennas and Propagation, 2009.

15. M. Thiel and K. Sarabandi, "An Hybrid Method for Indoor Wave Propagation Modeling," *IEEE Transactions on Antennas and Propagation*, **AP-56**, 8, 2008, pp. 2703-2709.

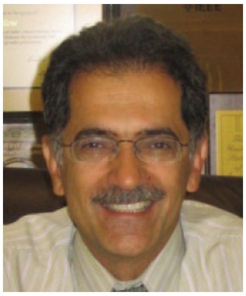
16. W. D. Burnside and K. W. Burgener, "High Frequency Scattering by a Thin Lossless Dielectric Slab," *IEEE Transactions on Antennas and Propagation*, **AP-31**, 1, 1983, pp. 104-111.

Introducing the Feature Article Authors

Jungsuek Oh received the BS and MS from Seoul National University, Korea, in 2002 and 2007. From 2002 to 2005, he worked as an associate software engineer in Kong Young DBM, Korea. From 2007 to 2008, he was with Korea Telecom as an associate research engineer, working on the development of RF devices using an inkjet printing process.

He is currently a Graduate Research Assistant with the Radiation Laboratory, the University of Michigan, while working toward the PhD. His research areas include antenna miniaturization for integrated systems, and radio propagation modeling for indoor scenarios. He was the recipient of the 2011 Rackham Predoctoral Fellowship Award, one of the highest awards bestowed on a graduate student at University of Michigan.

Michael Thiel received the Dipl-Ing in Electrical Engineering from the University of Ulm, Ulm, Germany, in 2005, and the PhD in Electrical Engineering from The University of Michigan, Ann Arbor, in 2010. Previously, he was a Graduate Student Research Assistant with the Radiation Laboratory at the University of Michigan. Since 2010, he has been with Schlumberger-Doll Research, Cambridge, MA. His research interests are indoor wave propagation modeling, through-the-wall radar imaging, and electromagnetic field theory and inversion.



Kamal Sarabandi received the BS in Electrical Engineering from the Sharif University of Technology, Tehran, Iran, in 1980; the MS in Electrical Engineering in 1986; the MS in Mathematics and the PhD in Electrical Engineering from the University of Michigan at Ann Arbor in 1989.

Dr. Sarabandi is currently the Director of the Radiation Laboratory and the Rufus S. Teesdale Professor of Engineering in the Department of Electrical Engineering and Computer Science, the University of Michigan at Ann Arbor. His research areas include microwave and millimeter-wave radar remote sensing, metamaterials, electromagnetic wave propagation, and antenna miniaturization. He possesses 25 years of experience with wave propagation in random media, communication-channel modeling, microwave sensors, and radar systems. He leads a large research group including two research scientists, 14 PhD students, and two MS students. He has graduated 40 PhD and supervised numerous post-doctoral students. He has served as the Principal Investigator on many projects sponsored by the National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory (JPL), Army Research Office (ARO), Office of Naval Research (ONR), Army Research Laboratory (ARL), National Science Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), and a large number of industries. Currently, he leads the Center for Microelectronics and Sensors funded by the Army Research Laboratory under the Micro-Autonomous Systems and Technology (MAST) Collaborative Technology Alliance (CTA) program.

He has published many book chapters and more than 185 papers in refereed journals on miniaturized and on-chip antennas, metamaterials, electromagnetic scattering, wireless channel modeling, random media modeling, microwave measurement techniques, radar calibration, inverse scattering problems, and microwave sensors. He has also had more than 442 papers and invited presentations in many national and international conferences and symposia on similar subjects.

Dr. Sarabandi served as a member of the NASA Advisory Council appointed by the NASA Administrator for two consecutive terms from 2006-2010. He is serving as a Vice President of the IEEE Geoscience and Remote Sensing Society (GRSS) and a member of the IEEE Technical Activities Board Awards Committee. He serves on the Editorial Board of the *Proceedings of the IEEE*. He was an Associate Editor of the *IEEE Transactions on Antennas and Propagation* and the *IEEE Sensors Journal*. He is a member of Commissions F and D of USNC-URSI, and is listed in *American Men and Women of Science*, *Who's Who in America*, and *Who's Who in Science and Engineering*. He was the recipient of the Henry Russel Award from the Regents of the University of Michigan at Ann Arbor. In 1999, he received a GAAC Distinguished Lecturer Award from the German Federal Ministry for Education, Science, and Technology, given to about ten individuals worldwide in all areas of engineering, science, medicine, and law. He was also a recipient of the 1996 EECS Department Teaching Excellence Award, and a 2004 College of Engineering Research Excellence Award. In 2005, he received two prestigious awards, the IEEE GRSS Distinguished Achievement Award and the University of Michigan Faculty Recognition Award. He also received the best paper award at the 2006 Army Science Conference. In 2008, he was awarded a Humboldt Research Award from the Alexander von Humboldt Foundation of Germany and Remote Sensing Symposium. He was also awarded the 2010 Distinguished Faculty Achievement Award from the University of Michigan. He was the recipient of the 2011 IEEE Judith A. Resnik medal. In the past several years, joint papers presented by his students at a number of international symposia (IEEE AP-S '95, '97, '00, '01, '03, '05, '06, '07; IEEE IGARSS '99, '02, '07; IEEE IMS '01; USNC-URSI '04, '05, '06, '10, '11; AMTA '06; URSI GA 2008) have received best paper awards.