Experimental Investigation of MIMO Performance Using Passive Repeater in Multipath Environment

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***Abstract*—A passive repeater (PR), comprising a four-element folded-patch antenna (FPA) array, a planar Yagi–Uda antenna, and a power combiner, was fabricated to experimentally investigate the multiple-input–multiple-output (MIMO) performance in multipath environment. It was found that the PR could realize polarization transition and broad-angle scattering. The received power and the MIMO channel capacity, which reflect MIMO performance, were discussed to demonstrate the effectiveness of the four-unit PR in improving the propagation channel in MIMO communications. It was found that the medians of the received power of Rx1 and Rx2 were improved by about 17 dB as compared to those without the PR. Also, when the received noise level was supposed to be −120 dBm/Hz, the median of the MIMO channel capacity with the PR was increased by 6.4 bps/Hz as compared to that without the PR.**

***Index Terms*—Communication blindness, multiple-input–multiple-output (MIMO) system, passive repeater (PR).**

I. Introduction

BLOCKING of radio waves from base stations of cellular mobile communications by high and dense buildings in urban areas is a serious problem, particularly in narrow streets, because it very much weakens the signal level and greatly affects the quality of communications. Many efforts were made to deal with this problem and the attendant poor signal-to-noise ratio (SNR), which dramatically degrades the efficiency of data transmission between mobile users and base stations. The blockage of a propagation channel in a blind area may greatly decrease the channel capacity for a multiple-input–multiple-output (MIMO) system. Generally, in cases where a direct microwave path cannot be established [i.e., non-line of sight (NLOS)] between two points, it is possible to reconstruct a path by using a repeater. The function of a repeater is to enable the microwave beam to pass around or over the obstacle (e.g., a building or hill). Passive repeaters (PRs) are attractive candidates to be used in MIMO system due to their lower cost of manufacturing, operation, and maintenance compared to traditional active repeaters [1], [2].

Recently, Li *et al.* designed a broadband reflectarray antenna as a PR to overcome the problem of blind areas [3]. However, the aperture efficiency of the reflectarray degraded greatly when a very large scattering angle was attempted for because of a physical limitation of the reflectarray. In [4], although a dual-antenna system (DAS), composed of patch array and open-ended waveguide, was proposed to realize a large scattering angle, there were still some disadvantages in the design such as bulky size, high cost, small equivalent bistatic radar cross section (BRCS), etc. A quasi-planar DAS was proposed for solving these problems in [5], but only numerical analyses were performed. It is important to demonstrate the effectiveness of the proposed DAS in wireless communication applications. In this letter, a quasi-planar PR, which consists of a four-element folded-patch antenna (FPA) array, a planar Yagi–Uda antenna, and a power combiner, was fabricated. Experiments were carried out in a multipath environment to demonstrate the improvement of MIMO channel by using the PR. It was assumed that the PR was mounted on the vertical wall of a building to establish microwave links between mobile terminals and base stations as shown in [3] and [5]. The polarization of incident wave from the base station was vertical to the ground plane, whereas that of the mobile terminal was mainly horizontal. Therefore, it became necessary to design the PR to have a polarization transition property. Because both the transmitting and receiving antennas were placed on the ground plane for this experiment, transmitting antennas, which could be seen as base station, were fixed to horizontal polarization. Accordingly, the polarization of the FPA was also horizontal.

The remaining part of this letter is organized as follows. The basic configuration of the fabricated PR is presented in Section II. Anechoic chamber measurement and the MIMO measurement are introduced in Sections III and IV, respectively. Experimental results are presented and discussed in Section V. Finally, concluding remarks are offered in Section VI.

II. Configuration of the PR

Fig. 1 shows the configuration of a one-unit PR comprising a four-element FPA array, a planar Yagi–Uda antenna, and a power combiner. The element in the FPA array building on the top side of the substrate is chosen as the same as Set 1 in [6] because of its compact size. As is well known, there is a tradeoff between the antenna's size and gain. Thus, if high gain is of primary concern in applications, other planar antenna

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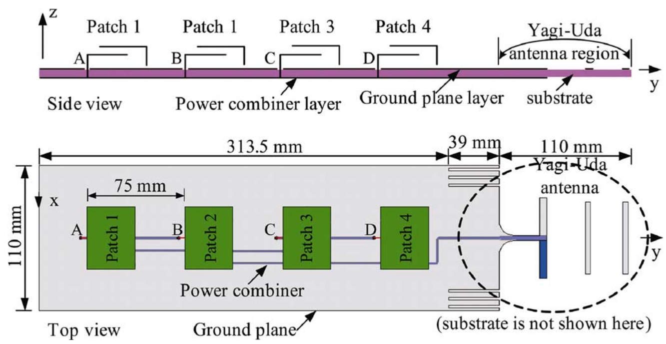
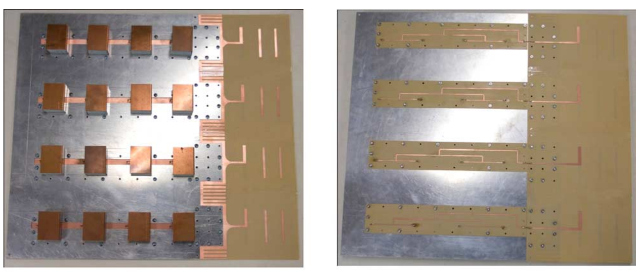


Fig. 1. Configuration of one-unit PR.



(a) (b)

Fig. 2. Photographs of the fabricated four-unit PR. (a) Top layer. (b) Bottom layer.

types with slightly larger sizes can also be chosen to meet the requirement, such as the broadband patch antennas proposed in [7]. The Yagi–Uda antenna employed here has one driven element and two directors, and the ground plane acts as the reflector. The ground plane is corrugated periodically to suppress the sidelobes in H-plane, and the antenna gain can be enhanced effectively [8]. The power combiner is mounted on the bottom side and connected to the input port of the planar Yagi–Uda antenna. Feeding probes A, B, C, and D of four patch elements are connected to four input ports of the power combiner through four via-holes on the ground plane. When the incident wave impinges on the FPA array, the received electromagnetic (EM) wave will be delivered to the Yagi–Uda antenna through a power combiner for reradiation. Further details about the PR can be found in [5]. To verify the design, the authors fabricated a four-unit PR prototype shown in Fig. 2. A substrate with a thickness of 0.8 mm and relative permittivity of 3.3 was utilized for supporting the power combiner and the Yagi–Uda antenna.

III. Anechoic Chamber Measurement

To validate the basic characteristics of the four-unit PR, an experiment was carried out to get an equivalent BRCS as defined in [3]–[5] of the four-unit PR in an anechoic chamber. In the experimental setup, shown in Fig. 3, a half-wavelength dipole antenna at 2 GHz with horizontal polarization was used as the transmitting antenna and kept 0.9 m away from the center of the four-unit PR. The receiving antenna was a half-wavelength dipole antenna at 2 GHz with vertical polarization and was 1.45 m away from the center of the four-unit PR. The location of the four-unit PR, as also of the transmitting antenna, was fixed, while that of the receiving antenna was kept moving

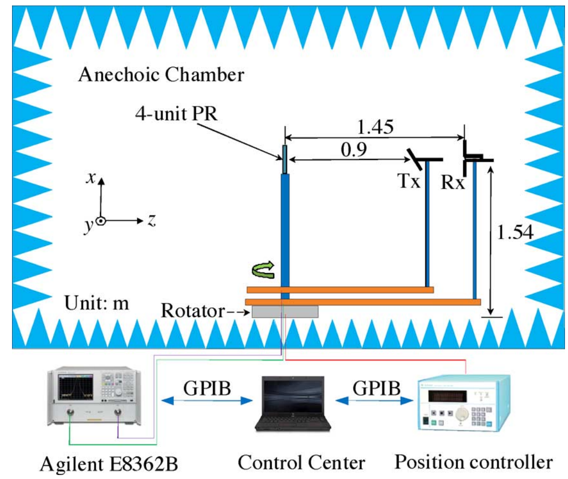


Fig. 3. Measurement system in the anechoic chamber.

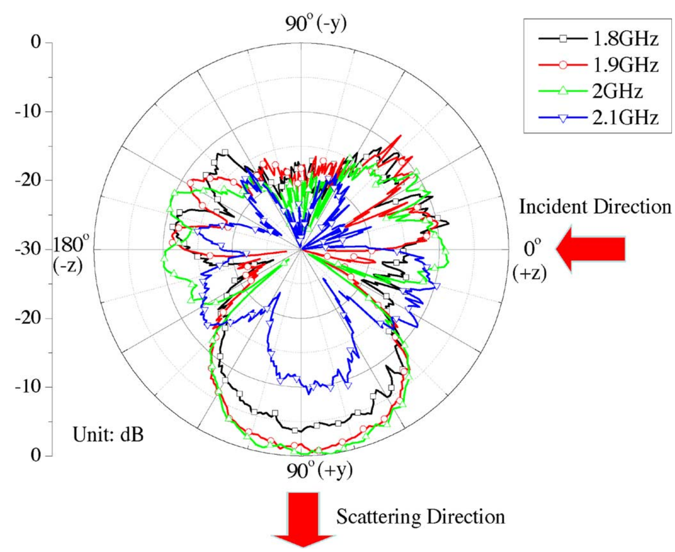


Fig. 4. Normalized BRCS of the four-unit PR at various frequencies.

clockwise by the turntable rotation. Because the PR was designed to receive normal incidence wave, the incident wave was always from $+z$-direction. In the experiments, measurement accuracy was improved by carrying out two measurements (one "with PR" and the other "without PR") to remove the effect of the incident field. In detail, the "Total Field," including the incident field and the scattering field, was first measured "with PR." Second, only the incident field was measured "without PR." Finally, the incident field component was eliminated from the "Total Field" for achieving accurate scattering field.

All the BRCS were normalized by the maximum BRCS in the entire results. Fig. 4 shows the normalized BRCS of the four-unit PR at various frequencies. They can provide insight into the operating principles of the four-unit PR. It is found that, although they were changed for various frequencies, a 100-MHz bandwidth from 1.9 to 2 GHz was realized. Furthermore, it is noted that the four-unit PR could achieve large orthogonal scattering with normal incidence, which cannot be realized by traditional reflectarray or other planar structures. In fact, the PR can scatter the incident wave to any desired direction by adjusting

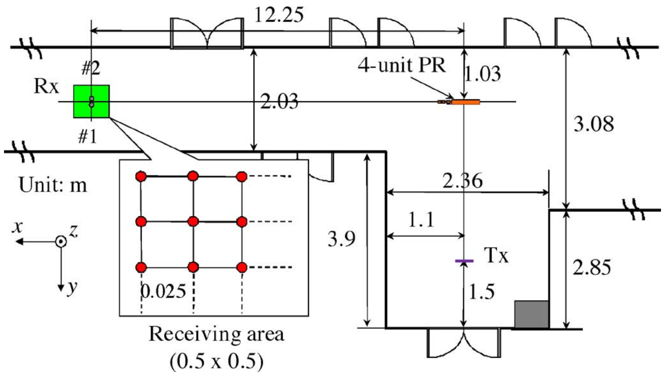


Fig. 5. MIMO measurement environment.

Fig. 6. Photograph of measurement site as viewed from four-unit PR.

TABLE I
EXPERIMENTAL PARAMETERS

Radio Frequency	2 GHz (CW)
Transmitted Power	0 dBm
Received Noise power	-120 dBm/Hz
Transmitting antenna	$\lambda/2$ dipole antenna array (horizontal polarization)
Receiving antenna	$\lambda/2$ dipole antenna array (various polarization)
Propagation environment	None-Line-of-Sight (NLOS) equivalent to blind area
Distance d_1 between the center of 4-unit PR and that of receiving area	12.25m (81.67λ)
Distance d_2 between the center of 4-unit PR and transmitting antenna	3.4 m (22.67λ)
Array spacing of transmitting antenna	1.2λ
Array spacing of receiving antenna	0.5λ

the planar Yagi–Uda antenna direction. Therefore, the PR fulfills the requirements of polarization transition and broad-angle scattering.

IV. MIMO MEASUREMENT

A 2×2 MIMO system was used to demonstrate the effectiveness of the four-unit PR for improving the propagation channel in MIMO communications. The experiment was carried out on the second floor of a concrete building as shown in Fig. 5. Fig. 6 is a photograph of the measurement site as viewed from four-unit PR. Some parameters used in the experiment were listed in Table I. It is found that NLOS environment, equivalent to blind areas of urban area as shown in [3] and [5], was utilized. The operation frequency was 2 GHz with continuous wave (CW). Two $\lambda/2$ dipole antenna arrays with 1.2λ array spacing were used as the transmitting antennas. Agilent 89600S vector signal analyzer, with two RF input channels, was used to receive the signals from two $\lambda/2$ dipole antenna arrays with $\lambda/2$ array spacing. The transmitting antennas were fixed, while the receiving antenna was moved gradually by a step of 2.5 cm in a 50×50 cm^2 area. Therefore, measurement was repeated 21×21 times. Distance d_1 between the center of the four-unit PR and that of the receiving area was 12.25 m. Distance d_2 between the center of the four-unit PR and the transmitting antenna was 3.4 m. Ceiling height from the floor was 2.42 m. The receiving antennas, the center of transmitting antennas, and the four-unit PR were placed above the floor at the same height of 1.21 m. The transmitting antennas were fixed to horizontal polarization. The polarization directions of the receiving antennas were varied from vertical polarization ($\theta = 0°$) to horizontal polarization ($\theta = 90°$) in the xz plane, as shown in Fig. 7, to analyze the effectiveness of the four-unit PR for practical applications.

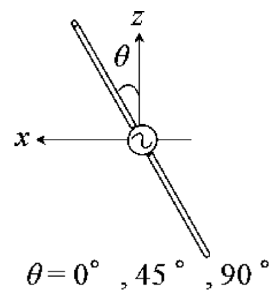


Fig. 7. Polarization directions of the receiving antennas.

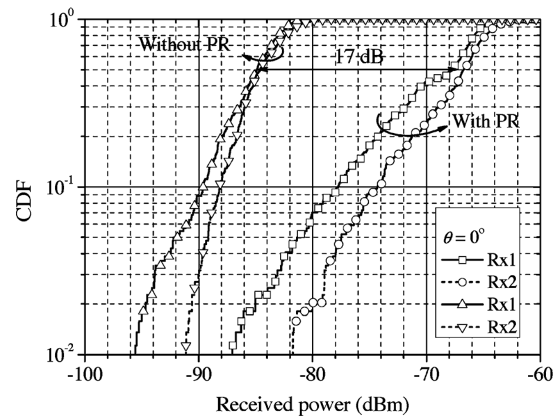


Fig. 8. CDF of the received power with/without four-unit PR for vertical polarization ($\theta = 0°$).

V. EXPERIMENTAL RESULTS

A total of 441 experimental results were obtained for various polarization directions, and the results were expressed in the form of cumulative distribution function (CDF).

Fig. 8 shows the CDF of the received power with/without the four-unit PR for vertical polarization ($\theta = 0°$). The results of Rx1 are denoted by a solid line, and those of Rx2 by a short-dashed line. It can be seen that when the four-unit PR was used, the medians of the received power of Rx1 and Rx2 were improved by about 17 dB as compared to those without the four-unit PR. It was found that the gradients of the fading of

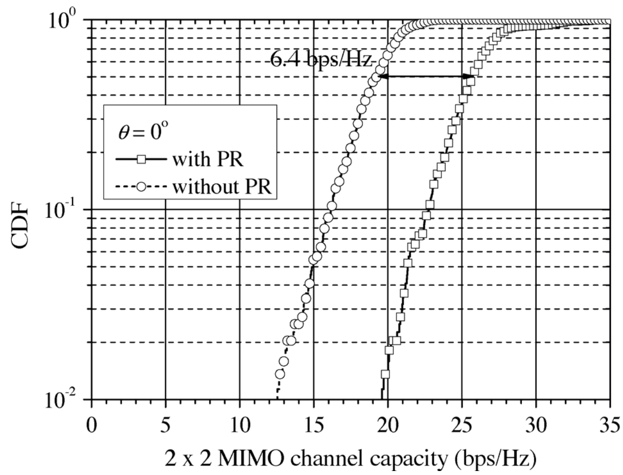


Fig. 9. CDF of the 2×2 MIMO channel capacity with/without four-unit PR for vertical polarization ($\theta = 0°$).

TABLE II
GAIN OF THE RECEIVED POWER AND THE MIMO CHANNEL CAPACITY

CDF = 0.5	$\theta = 0^o$	$\theta = 45^o$	$\theta = 90^o$
Median gain of the received power (dBm)	17.12 (Rx1) 17.88 (Rx2)	14.14 (Rx1) 14.56 (Rx2)	6.655 (Rx1) 9.29 (Rx2)
Median gain of the MIMO channel capacity (bps/Hz)	6.433	5.984	3.802
CDF = 0.1	$\theta = 0^o$	$\theta = 45^o$	$\theta = 90^o$
The gain of the received power (dBm)	11.86 (Rx1) 13.85 (Rx2)	12.215 (Rx1) 13.865 (Rx2)	6.625 (Rx1) 8.33 (Rx2)
The gain of the MIMO channel capacity (bps/Hz)	6.601	6.124	3.86

the channels, with and without the four-unit PR, were much different because by changing the field distribution in an indoor environment, the four-unit PR can produce more multipath routes than those without it. This can generate more uncorrelated signals and is good for antenna systems. It should certainly help to improve the performance of a MIMO system.

The channel capacity also was calculated for evaluating MIMO performance. Fig. 9 shows the CDF of the 2×2 MIMO channel capacity with/without the four-unit PR for vertical polarization ($\theta = 0°$). It can be found that when the received noise level was supposed to be -120 dBm/Hz, the median of the MIMO channel capacity with the four-unit PR was increased by 6.4 bps/Hz as compared to that without the four-unit PR. Similar conclusions for other polarization directions can be drawn and listed in Table II. In the case of $\theta = 90°$, it can be seen that the gain of the received power and the MIMO channel capacity were smaller than those of other cases because of cross-polarization problem. Furthermore, it is known that the gain of the MIMO channel capacity decreases nonlinearly with decreasing receiving power. The foregoing experimental results demonstrate the effectiveness of the four-unit PR in improving the propagation channel in MIMO communications.

VI. CONCLUSION

A four-unit PR was fabricated to investigate experimentally the MIMO performance in multipath environment. Based on the experimental results obtained, it is found that the four-unit PR can achieve 100-MHz bandwidth and large scattering angle. Furthermore, by using the four-unit PR, the received power and the MIMO channel capacity could clearly be improved, thereby establishing the validity of the four-unit PR for practical applications of MIMO system. Because of this application, at $\mathrm{CDF} = 0.5$ ($\theta = 0°$), about 17 dB improvement was obtained in the receiving power. Furthermore, when the received noise level was supposed to be -120 dBm/Hz, the median gain of the MIMO channel capacity was increased by 6.4 bps/Hz as well.

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