Manipulating LOS and NLOS MIMO Propagation Environments Using Passive Repeaters

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Abstract—This paper presents a novel method of multiple input multiple output (MIMO) communication on the basis of a passive repeater that achieves enhanced performance in both line-of-sight and non-line-of-sight environments. The passive repeater is implemented as a back-to-back antenna system. The advantage of the proposed system is an increase in the effective aperture of the base station, which allows to sufficiently extend the communication distance and ensure spatial resolution. The configuration of the passive repeater is simple, based on two connected antennas with parabolic reflectors. This configuration helps to avoid phase controller that allows to spread repeaters in the communication environment. This spreading provides multipath propagation and improves MIMO performance. In this paper, we suggest to implement the proposed passive repeater with optimal placements to create multipath wave propagation and ensure spatial resolution in a line-of-sight environment, and to enhance coverage and access blind spots in a non-line-of-sight environment. The numerical analysis is performed to verify the validity of using the proposed repeater, and it is found that the proposed method helps to ensure features in the propagation environment which leads to enhanced MIMO performance.

1. INTRODUCTION

Multiple-input multiple-output (MIMO) techniques have been deployed in the current and future wireless networks to improve the channel capacity and reliable transmission. MIMO, on the other hand, can provide diversity gain that improves link reliability [1]. Spatial multiplexing can also be used in MIMO, allowing the use of the same frequency band at the same time for multiple streams/users and significantly improving spectral efficiency [2]. MIMO systems work well in the presence of a rich scattering environment. However, in line-of-sight (LOS) MIMO channels with little or no scattering, the effectiveness of the MIMO systems can become strongly influenced [3]. On the other hand, in non-line-of-sight (NLOS) may have blind spots where the radio wave from base stations of cellular mobile communications is blocked because of high and dense buildings or natural obstacles [4]. Different approaches have been introduced to enhance the performance of MIMO communications. Some literatures considered multiple active access points [5] or relays [6] or reflectarray [4] to enrich spatial diversity. In [7], a smart reflector with N antennas and phase configurations is used to increase the scattering in the environment to provide MIMO spatial multiplexing gain. Passive repeaters are also considered to enhance channel capacity and extend the communication distance in MIMO communications. Their simple configuration and low cost make them a convenient and practical solution [8]. A passive repeater consisting of a four-element folded-patch antenna (FPA) array, a planar Yagi-Uda antenna, and a power combiner is used in [9]. In [10], authors proposed passive repeater comprises multiple antennas where each of them has individual phase-shifter function. In [11], a passive

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repeater array which can reflect an incident power into a specific angle for removal of blind spot in NLOS path for 5G fixed wireless access (FWA) system is introduced and investigated.

This paper proposes to implement a back-to-back parabolic antenna system as a passive repeater in MIMO communication in both LOS and NLOS environments. This passive repeater has previously been used in point-to-point communications [12]. It is composed of two parts connected through a microwave connection line. Each part comprises a antenna and parabolic reflector. The no need of phase controller makes the configuration simple and inexpensive, allowing it to be widely used in MIMO communications. Novel points of this paper are summarized below:

(i) The concept of applying a back-to-back parabolic antenna system in MIMO environments. The flexibility of the repeater, with no need of phase controller, helps to spread repeaters in the communication environment, so the communication quality can be improved with no added complexity in the base station.

(ii) Angular resolution in a LOS environment using 1D configuration of repeaters.

(iii) Beamforming in a LOS environment with various 2D configurations of repeaters.

(iv) An algorithm for optimal placement of passive repeaters in an NLOS environment to access blind spots and extend coverage.

The validation of the proposed approaches is done by analytical analysis and numerical computation. Simulation results show that implementing the proposed passive repeaters helps to create conditions for enhancing MIMO performance in both LOS and NLOS environments in comparison with traditional base station-users communication.

2. PASSIVE REPEATER CONCEPT AND POSSIBLE CONFIGURATIONS

The proposed passive repeater consists of two parts. Both are parabolic reflectors with antennas at their focal points. The first part is directed towards the base station with LOS communication and the second part directed towards the users. The first part antenna is connected to the second part antenna by a flexible microwave connecting line. The length of the line is selected in accordance with the requirements for the placement of the first and second parts. The back-to-back parabolic antenna (Fig. 1) provides the following features:

- No phase shifter or controller, the repeater is completely passive. The second part of the repeater can be manually directed to any direction.

- The ability to design the repeater with any directivity and beamwidth by choosing an appropriate size of the parabolic reflector.

- The ability to use different polarizations for the two parts of the repeater. This property can help in two points:
    - The first point is to prevent interference between the direct wave which may propagate to the terminal distant due to direct path, diffraction, scattering, or any other means and that from passive repeater. If the two waves are out of phase, fading or cancellation may happen. This problem can be solved using cross polarized antennas in the two parts [12].
    - The second point is to increase the throughput using passive repeaters next to each other with cross polarization between the antennas of the first parts of these repeaters at every repeater possible location, while the second parts can have the same polarization. This configuration increases the channel capacity and reduces the keyhole effect if the distant terminal can receive signals only through one repeater placement.

3. PASSIVE REPEATERS FOR MIMO APPLICATION

In MIMO systems, we propose to use passive repeaters (Fig. 1) both to ensure multipath wave propagation with spatial resolution and to access blind areas in LOS and NLOS environments. The key concept of the proposed method is to use the passive repeater as an intermediate stage between the base station and users with the following configuration: narrow beam directed to the base station and wide
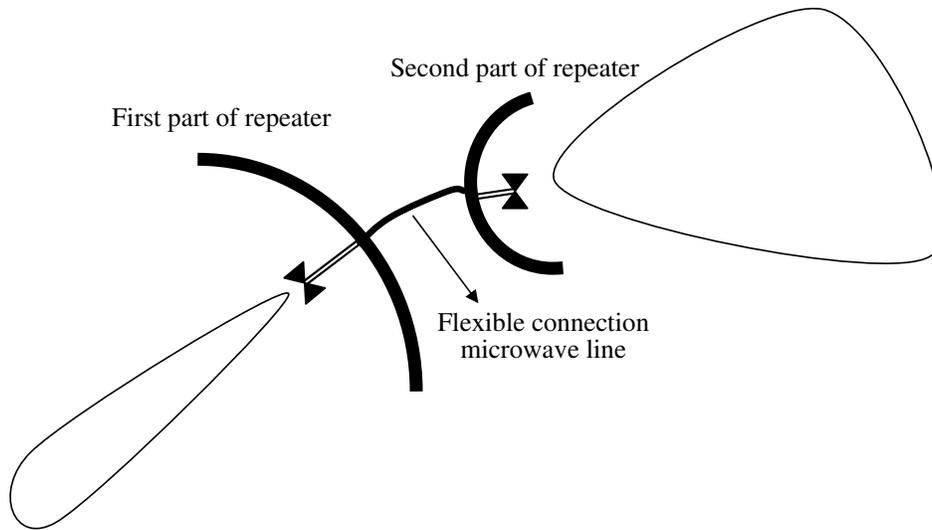
Figure 1. Passive repeater as back-to-back antenna system.

(or multi-beam) directivity for users. The distance between the repeaters should be sufficient for the base station to have the ability to choose any of them separately. In the following, applications of the proposed repeater in LOS communication with angular resolution and beamforming are discussed. In addition, for an NLOS communication, an algorithm for optimal placement of the proposed repeaters for enhancing coverage and illuminating blind spots is introduced and simulated.

3.1. Application of the Proposed Repeater in LOS Environments

In a LOS environment, with no multi-path wave propagation, it is possible to establish only one communication channel between transmitter and receiver MIMO arrays in the case of enormous distances. This problem is usually solved by adding artificial scatterers that help to get multi-path wave propagation. In this paper, we propose the use of directive repeaters to get multi-path propagation, delivering signals from repeaters to users with acceptance strength and ensure spatial resolution. The spatial resolution results from the interference of fields retransmitted by distributed directed repeaters. The ability of resolution is determined by diffraction limit distance:

$$\Delta x \approx \frac{z\lambda}{B} \tag{1}$$

where z is the distance from base station to users, and B is the aperture size of the base station. If B is not large enough, the base station cannot communicate separately with nearby users at the same time and frequency. Repeaters can significantly increase the effective aperture of the base station which helps to increase resolution by using Eq. (1). The angular resolution can be obtained using 1D plane of repeaters, while for beamforming a 2D plane of repeaters is required.

3.1.1. Angular Resolution Using Passive Repeaters

For an angular resolution, it is important to get unique radiation pattern for each user in the base station. Placing repeaters at one side for users cannot give the desired uniqueness of the filed pattern. In this paper, we propose to place repeaters in an arc (Fig. 2), so that users are illuminated from different directions, and a unique field pattern is created for each user. The length and shape of the arc are restricted to the need to maintain a LOS communication between the first part of each repeater and the base station as well as to prevent interferences between repeaters. Such placement of repeaters effectively increases the aperture size of the base station.

To demonstrate the concept of the proposed method, we performed a numerical simulation. The simulated area is $1\,\text{km}^2$ with frequency $f = 50\,\text{MHz}$; the base station aperture size is $100\,\text{m}$, and the
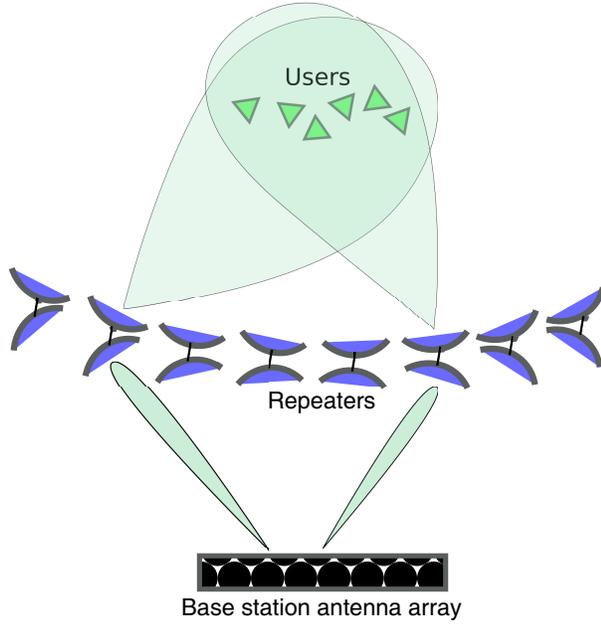
Figure 2. Placement of repeaters for angular resolution in a LOS environment.
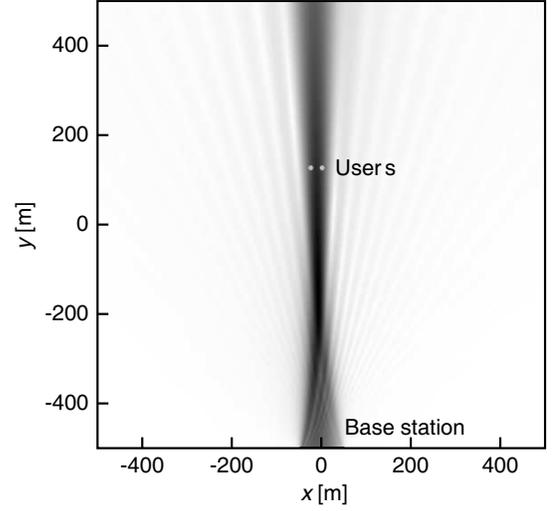
Figure 3. LOS communication with no use of repeaters.

number of antennas in the base station is $N = 51$. Fig. 3 shows the LOS communication between the base station and users without the use of repeaters. It is clear that users are not separated.

In the next step, we add repeaters to the environment (for example, $M = 17$). We define $(\widetilde{X}_m, \widetilde{Y}_m)$ as the position coordinate of the mth repeater. To determine the far field of the mth repeater on the user side, we consider the far field of a parabolic reflector. In [13], the radiation pattern of a parabolic reflector is derived using three kinds of feed: Hertzian Dipole Feed, Waveguide Feed, and Horn Feed. To simplify the computation, a circular aperture with a diameter equal to the diameter of the repeater's parabolic aperture (D) is usually used. The far field of a circular aperture is given by Eq. (2a) [13]. Considering the gain and directivity, the rectangular aperture with dimensions $(D*D)$ can also be used with the same results. The far field of a rectangular aperture is given by Eq. (2b) [13]:

$$E_m(x, y) = G\frac{J_1\left((\pi D/\lambda_0)\sin(\varphi - \phi_m)\right)}{(\pi\frac{D}{2}/\lambda_0)\sin(\varphi - \phi_m)}\frac{\exp(ikR_m)}{R_m} \tag{2a}$$

$$E_m(x, y) = G\frac{\sin\left((\pi D/\lambda_0)\sin(\varphi - \phi_m)\right)}{(\pi D/\lambda_0)\sin(\varphi - \phi_m)}\frac{\exp(ikR_m)}{R_m} \tag{2b}$$

where J_1 is the first-order Bessel function; $\varphi = \arctan\left(\frac{x-\widetilde{X}_m}{y-\widetilde{Y}_m}\right)$ is the angular direction from the the mth repeater to the user position; D is the diameter of the aperture of the repeater parabolic antenna on the user side; $R_m = \sqrt{(x - \widetilde{X}_m)^2 + (y - \widetilde{Y}_m)^2}$ is the distance between the mth repeater and user position; k is the wave number; λ_0 is the wavelength; ϕ_m is the main beam direction of the mth repeater; G is the repeater gain.

The resulting field distribution for all repeaters in the case, when only the nth antenna of the base station transmits a signal using the superposition principle, is given by:

$$U_n = \sum_m E_m \cdot \exp(i \cdot k \cdot r_{n,m}) \tag{3}$$

where $r_{n,m} = \sqrt{(x_n - \widetilde{X}_m)^2 + (y_n - \widetilde{Y}_m)^2}$ is the distance between the nth antenna of the base station and the mth repeater. For a user in a position (x_0, y_0), the base station can generate the appropriate

magnitude-phase distribution using the field pattern A_n corresponding to the user's location.

$$A_n = \frac{U_n^*(x_0, y_0)}{|U_n(x_0, y_0)|},$$

(4)

where (∗) refers to the complex conjugate. Fig. 4 shows the results of adding repeaters to the LOS environment.

(a)

(b)
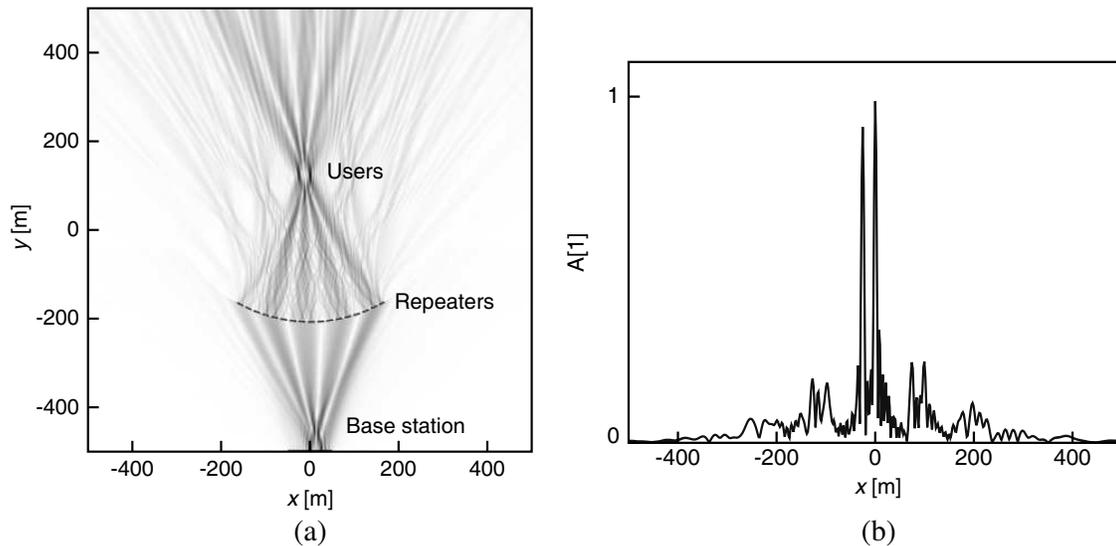
Figure 4. Field simulation and angular resolution. (a) LOS communication with repeaters. (b) Normalized magnitude of field in users locations.

In Fig. 4, results show that users are distinguished by the base station field. Each user can receive a different phase and magnitude at the same time and frequency. Using 1D plane of repeaters, angular resolution of users is obtained with no distant resolution. For beamforming, 2D arrangements for base station and repeaters are used.

### 3.1.2. Beamforming Using Passive Repeaters

At present, beamforming is needed in mobile communications, since it enhances capacity and frequency reuse. In this paper, we propose to use passive repeaters in MIMO communication to get beamforming without any increased complexity in the base station. A 1D plane of repeaters is not enough for beamforming. The proposed passive repeater structure makes it convenient to distribute the repeaters in a 2D plane, so that each repeater can connect to the base station through LOS communication in addition to preventing interference between repeaters as shown in Fig. 5. In this application, the second part (at user direction) is considered to have non-directional pattern.

In connection with beamforming and reducing Side-Lobe Level (SLL), concentric circular arrays have always proven their superiority in the generation of beams with highly reduced SLLs over other arrays [14]. For this advantage, this paper proposes to use two concentric circular arrays with optimizing number of repeaters and radius of each circle. The free space far-field pattern of a concentric circular repeater array shown in Fig. 6(a) excited by N antennas in the base station is given by:

$$E(x, y) = \sum_n^N \sum_m^M A_n \frac{\exp(ik(r_{n,m} + r_m(x, y)))}{r_{n,m} \cdot r_m(x, y)}$$

(5)

The normalized absolute power pattern is given by:

$$\widetilde{E}(x, y) = \frac{|E(x, y)|}{|E(x, y)|_{\max}}$$

(6)
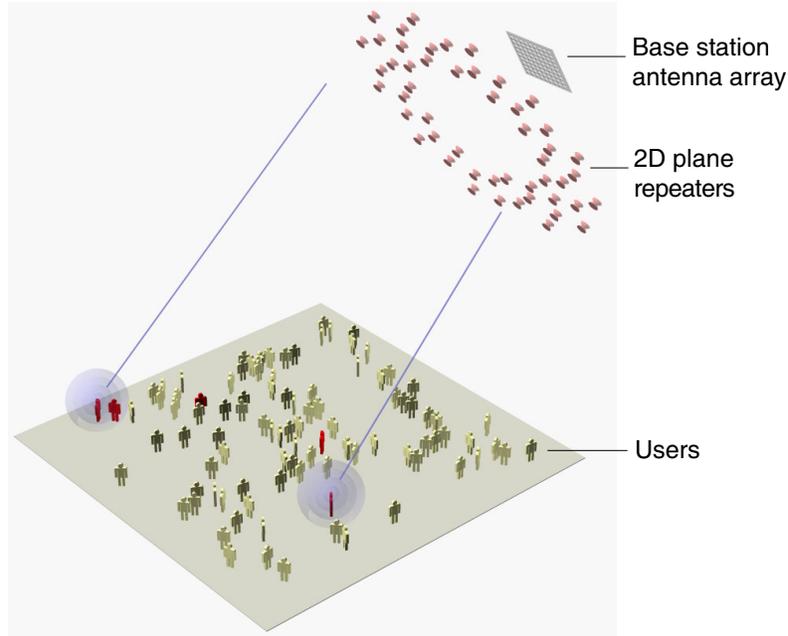
Figure 5. Beamforming using 2D repeaters arrangement.

In Eqs. (5) and (6), N refers to the number of antennas in the base station; M refers to the total number of repeaters which equals $M_1 + M_2$, where M_i is the number of repeaters in the ith ring (circle); $r_{n,m}$ is the distance between the nth antenna in the base station and mth repeater; $r_m(x, y)$ is the distance between the mth repeater and user position.

It is assumed that repeaters are uniformly distributed in each circle, so the position of each repeater in the ith ring is related to ring radius R_i and number of repeaters M_i. In this paper, we perform an optimization to find concentric circular array parameters (R_1, R_2, M_1, M_2) that minimize SSL, with the following criteria: $R_1, R_2 \leq 27\lambda_0$ and $M_1, M_2 \leq 64$. In the base station $N = 64$ with $\frac{\lambda_0}{2}$ inter-element spacing and $f = 1\,\text{GHz}$. Exhaustive search is performed, and with a precision of two digits after the decimal point, many solutions give the minimum SSL, and the solution with minimum number of repeaters is considered as follows: $R_1 = 10 \cdot \lambda_0$, $R_2 = 17 \cdot \lambda_0$, $M_1 = 26$, $M_2 = 24$. The result of simulation is shown in Fig. 6 with the maximum normalized SSL equal to 0.22.

The same number of repeaters $(M = 50)$ is used with logarithmic spiral architecture. The parameters of repeaters position shown in Eq. (7) are optimized to obtain minimum SSL.

$$\begin{aligned}
\widetilde{X} &= a \cdot \exp(b \cdot \theta_m) \cos(\theta_m) \\
\widetilde{Y} &= a \cdot \exp(b \cdot \theta_m) \sin(\theta_m)
\end{aligned} \tag{7}$$

The exhaustive search result shows that with $a = 0.9$, $b = 0.05$, and angular step $\theta = \frac{\pi}{6}$, the maximum normalized SSL is 0.17. The resulting repeaters configuration is shown in Fig. 7(a), and the simulation result is shown in Fig. 7(b). We can notice that the logarithmic spiral architecture gives lower SSL without considering the beamwidth.

4. APPLICATION OF THE PROPOSED REPEATER IN NLOS ENVIRONMENT

For an NLOS environment, we need to consider shadow effects and any changes in wave direction caused by obstacles or any scatterers. For that, It is appropriate to place repeaters in locations that allow them to illuminate users, even in the shadow of obstacles, taking into account the phenomena of reflection, refraction, and diffraction that can be used to illuminate blind spots. In this paper, we propose an algorithm for placing repeaters in a way that they maximally illuminate users. The principle of the algorithm is based on the possibility of summing the intensities produced by repeaters. This is due to

(a)

(b)
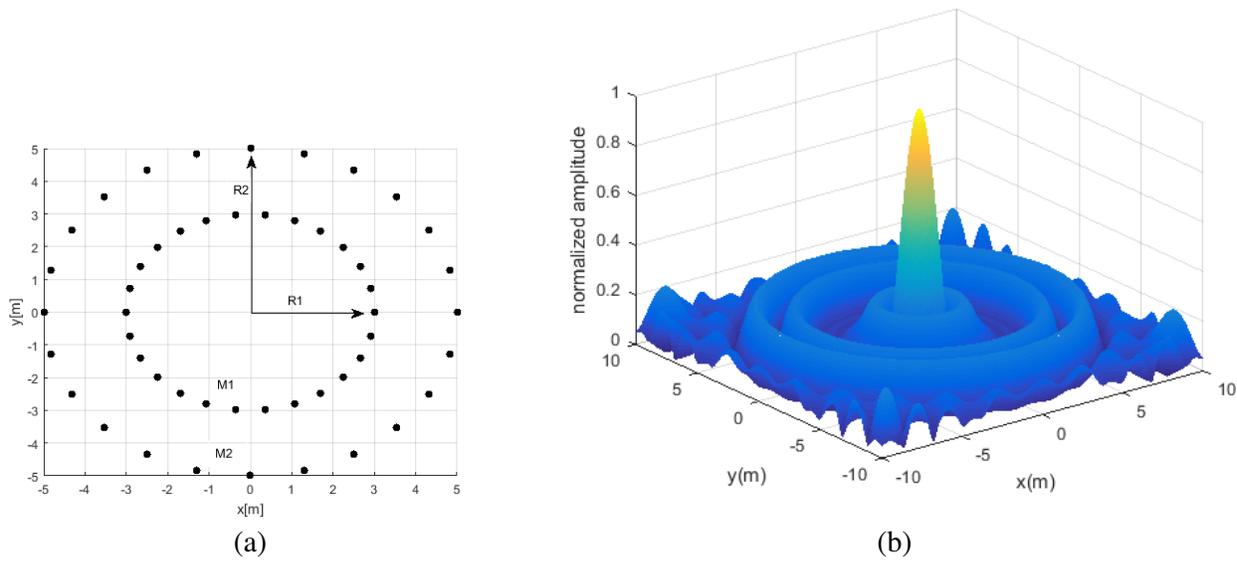
Figure 6. (a) Concentric circular array of repeaters. (b) Radiation pattern of optimized configuration for low SSL using concentric circular array of repeaters.

(a)

(b)
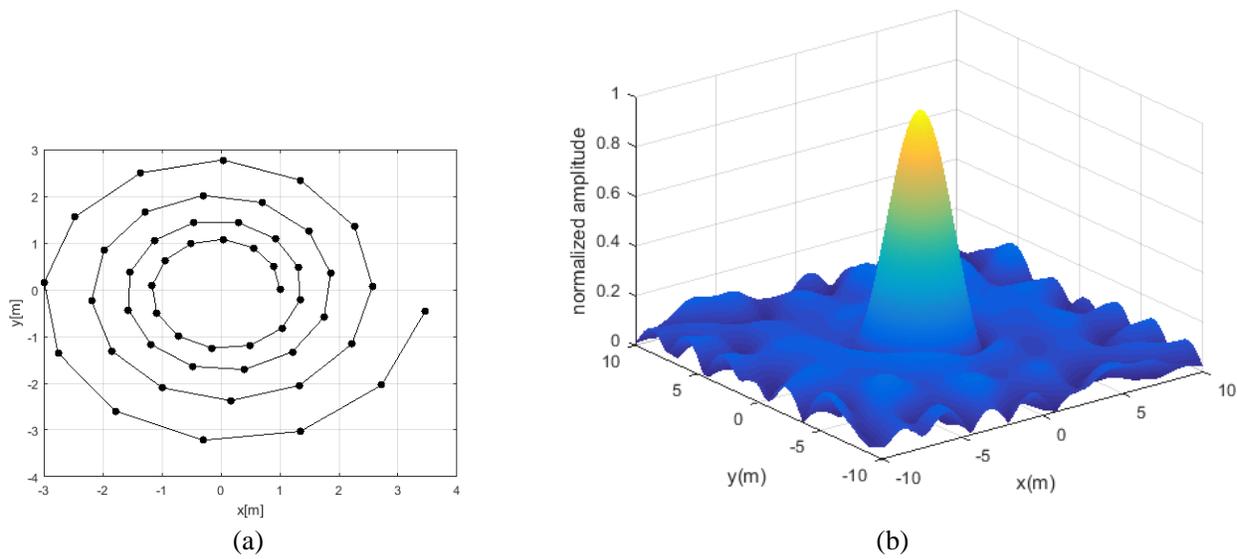
Figure 7. (a) Logarithmic spiral configuration of repeaters. (b) Radiation pattern of optimized configuration for low SSL using logarithmic spiral configuration.

the arbitrary phase relations between these repeaters, since any repeater can be illuminated separately by the base station. The resulting intensity is used to find the configuration of repeaters that provides the most coverage. The Finite Difference Time Domain method (FDTD) is used to compute radiation pattern of each repeater taking into account existing obstacles. The steps of the algorithm are explained as follows:

1- The first step is to determine the spatial statistical distribution of users $D(x, y)$, and each location is associated with a value between 0 and 1, to determine the importance of each location. This value relates to the probability of occupation this location by users.

2- In the second step we determine all possible locations and directions of repeaters that can be used to deliver signals to users, with the following two conditions:

  – The first part of each repeater has a LOS communication with the base station.
  – Distances between repeaters are sufficient, so the base station can select any of them separately.

3- For each repeater and for different locations and directions, we calculate the corresponding radiation field pattern considering all obstacles, diffraction, refraction, and multiple reflections. We denote the field pattern of the mth repeater in the user area as $U_m(x, y)$. Then the intensity is computed
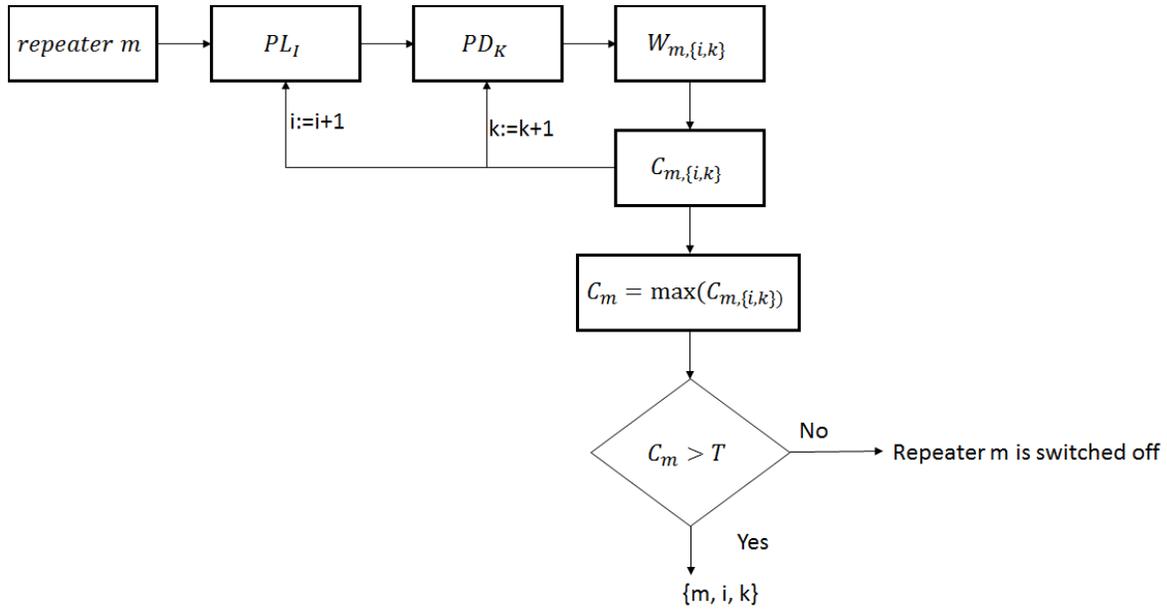

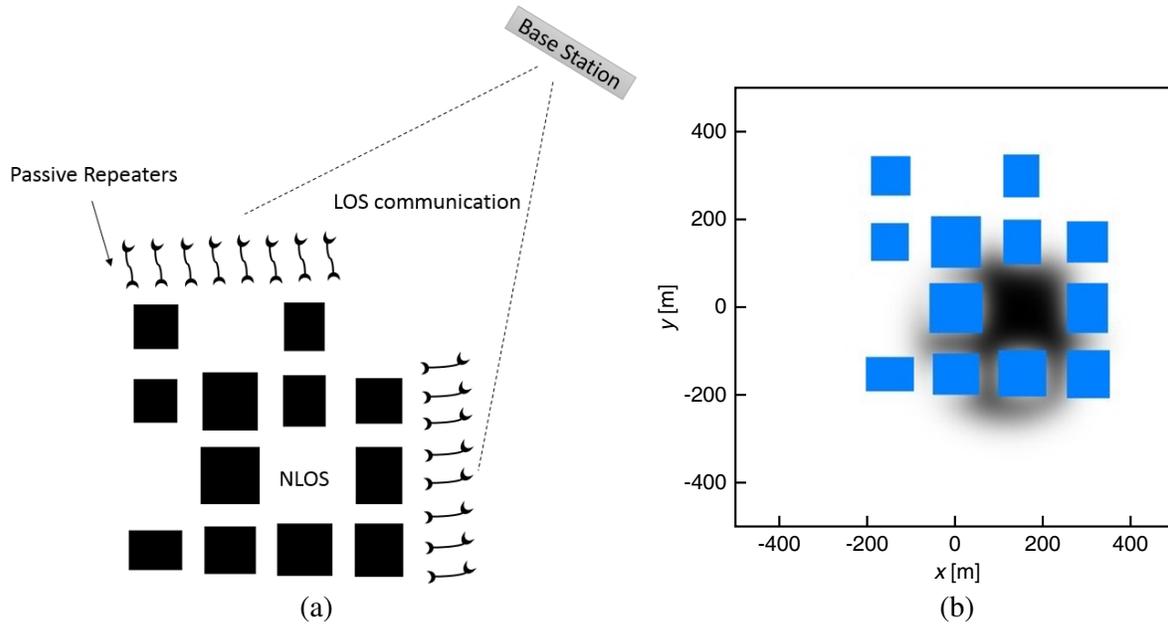**Figure 8.** Flow chart of the proposed algorithm.

Figure 9. A practical example of the proposed algorithm in a NLOS environment, (a) simulation environment, (b) $D(x, y)$.

as $W_m = |U_m(x, y)|^2$.

4- The last step is to choose the appropriate position and direction for each repeater that maximize its contribution to users' illumination with respecting to $D(x, y)$. A certain threshold T is used to ensure the effective use of each repeater.

The contribution of the mth repeater is computed using Eq. (8):

$$C_m = \sum_x \sum_y W_m(x, y) \cdot D(x, y) \qquad (8)$$

If $C_m < T$, the repeater is not used.

The entire algorithm is summarized in Fig. 8, where PL_I and PD_K refer to the possible arrangements for repeater locations and angles of directions, respectively.

For an application of the algorithm, we consider an NLOS scenario shown in Fig. 9(a). The locations of users with their importance (the darkest places are more important) are shown in Fig. 9(b). The locations of repeaters are fixed, and we apply the proposed algorithm to find the suitable angles. Fig. 10 shows the result of the proposed algorithm. Results show that only 7 repeaters are used with angles directed to locations of users, and the target area is almost covered.
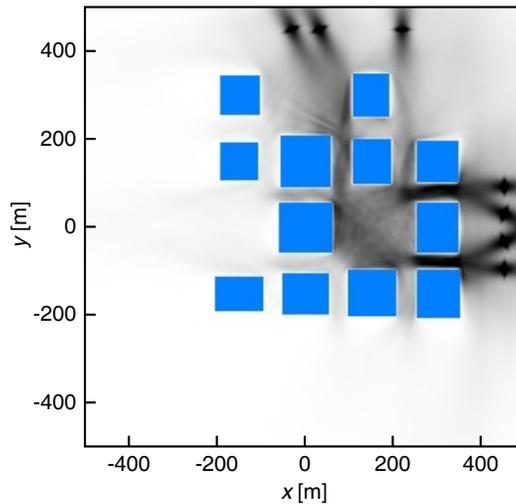
Figure 10. Results of applying the proposed algorithm: used repeaters (with positions and directions) and resulted summed intensity.

5. CONCLUSION

In this paper, we propose to implement passive repeater on the basis of a back-to-back antenna system to improve MIMO performance in both LOS and NLOS environments. The no need of phase shifter makes it convenient to spread these repeaters in propagation environments to ensure multipath propagation, spatial resolution, and enhance coverage. An arc arrangement of repeaters is used to achieve angular resolution in LOS environment. For beamforming, two 2D configurations of repeaters are proposed with parameters optimization to get minimum side lobe level. An algorithm to optimize positions and directions of repeaters in an NLOS environment to expand coverage is also presented. The numerical simulation shows that the proposed methods help to achieve better conditions for enhancing MIMO performance in communication environments.

ACKNOWLEDGMENT

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