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Localization in Multiple-Input Multiple-Output Systems Based on Passive Repeaters

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Abstract—This paper presents a novel localization method based on the implementation of passive repeaters in multiple-input multiple-output (MIMO) systems. Passive repeaters can help in localizing users by taking advantage of their spreading in the communication environments. In the proposed method, the target area is divided into a grid. Each location in this grid has a unique field interference created by repeaters. Because of the unique field interference, each location causes a unique field signature at the base station when a user in that location transmits signals. The field signature corresponding to the center of each grid cell is used as a fingerprint for localizing users in that cell, and for all cells, a bank of matched filters corresponding to all stored fingerprints is constructed. When a signal arrives at the base station, the generated field signature is correlated with the bank of matched filters, and the location is determined based on the maximum correlation value. The numerical analysis is performed to verify the validity of the proposed method, and it is found that by means of passive repeaters, the user location can be determined with no need of calculating additional parameters.

1. INTRODUCTION

User localization for determining the geographic positions of users in wireless networks is needed for network operations and many other applications such as emergency services, safety, gaming, and commercial services [1]. Time of arrival (TOA) or time difference of arrival (TDoA) [2], angle of arrival (AOA) or direction of arrival (DOA) [3, 4], and received signal strength indicator (RSSI) [5] are known techniques used to determine the locations of users.

In multiple-input multiple-output (MIMO) systems, with the great communication advantages, localization continues to receive considerable attention. The large number of antennas at the base station in massive MIMO provides the ability to precisely estimate the direction of arrival of the individual multipath components [6]. In massive MIMO transmission systems, with the availability of accurate direction information from electromagnetic beams, a least squares (ls) based method for localization is suggested [7].

A fingerprinting solution is also proposed for localization in MIMO. Savic and Larsson propose the Gaussian process regression method to find the position of users using fingerprinting techniques based on a vector of received signal strengths [8]. A fingerprint positioning method based on the affinity propagation clustering (APC) and Gaussian process regression (GPR) is presented to estimate the user's position using the uplink received signal strength (RSS) in a distributed massive MIMO [9].

To further improve positioning accuracy, angle of arrival estimation by combining lens antennas with a massive antenna array (MAA) system in a multipath propagation scenario is proposed [10]. Lens antenna array is also used with the implementation of the beam-space multiple signal classification (MUSIC) algorithm to estimate the angle of arrival after antenna grouping [11].

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Direct approaches are also used for the location of the target to sort the best matched position corresponding to the measured data [12]. Garcia et al. propose direct localization based on the compressed sensing framework for massive MIMO in a multipath propagation environment [13]. Beam-space direct localization method is presented for large-scale antenna arrays. The computational complexity is reduced by proving that the high-dimensional array signal can be represented in a low-dimensional beam-space without information loss [14].

Sensors are also used for improving localization accuracy. An array sensor with temporal and spatial features is used for device-free passive (DFP) technique to enhance localization accuracy [15]. Kan et al. formulated a generalized modeling of incorrect data, in addition to a reliable data cleansing algorithm to improve localization when a crowd of sensors participate the localization process to estimate the source position [16]. The coherent processing and non-coherent processing of distributed MIMO radar, configured with multiple transmitting and receiving sensors, are independently considered to deduce the target position Cramer-Rao lower bound (CRLB) [17].

In general, target localization requires multiple stations at known locations to receive signals [12]. However, many base stations may be not available, for example, in a suburban environment [8]. For that, in this article, we propose a new approach to user localization in MIMO systems in the case when one base station (BS) is available. The proposed approach uses passive repeaters, which are suggested in many researches to enhance the performance in MIMO communication [18, 19]. By spreading these repeaters in the propagation environment, every user's location is covered by a different field interference created by repeaters, then a unique field-signature is generated at the BS when a user in any location transmits signals. These unique field-signatures for certain locations (grid cell centers) are used as fingerprints for localizing users.

The proposed approach is presented using a back-to-back parabolic antenna system as a passive repeater. This repeater is suggested in [20, 21] for manipulating propagation environments in the case where the transmitter and receiver are within line-of-sight of each other and in none line-of-sight (NLOS) MIMO communications. The repeater has two parts. The first part is directed to the base station with a line-of-sight (LOS) communication, whereas the second part is used to cover users. The two parts are connected through a flexible connector. The proposed repeater has many properties such as flexibility and the ability to design the repeater with any directivity by choosing the appropriate reflector size. These characteristics make this repeater a suitable solution for manipulating propagation environments to enhance MIMO communications. The deployment of these repeaters in propagation environments can be used to localize users using the proposed approach. Compared with the previous research, the proposed method has the following advantages:

(i) The proposed method is applicable with a single base station.
(ii) Passive repeaters are not used only for localization, as the case with sensors and lenses. Passive repeaters are also deployed to enrich scattering and manipulate propagation environments.
(iii) There is no need for synchronization between users and the base station. Localization is performed using only received signals.
(iv) The basic principle of the proposed method is simple. User localization is achieved using a correlation process with the stored fingerprints.

However, the proposed method is time-consuming, and the time needed to achieve user localization increases as the number of cells or used frequencies increases. In the following sections, the concept of the field-signature based localization using passive repeaters in MIMO systems is presented. Then, the localization of users in the case when there is a synchronization between BS and users is introduced and discussed. After that, the synchronization is avoided by normalizing the amplitude and phase of the field-signatures at the BS with respect to a reference antenna and using more than one frequency to build the fingerprints. The validation of the proposed approaches is done by analytical analysis and numerical computation. Simulation results show that user localization can be achieved using only the received signals and without synchronization between the BS and users.

2. FIELD-SIGNATURE BASED LOCALIZATION

The goal is to localize users after receiving their signals at the BS using stored fingerprints. Therefore, we propose to use a grid configuration with repeaters as shown in Fig. 1. In this grid, each location has a unique field interference created by repeaters which results in a different field pattern being generated at the BS. Then, for each grid cell, a matched filter is designed based on the field pattern generated at the BS when a user located in the center of this cell transmits signals.

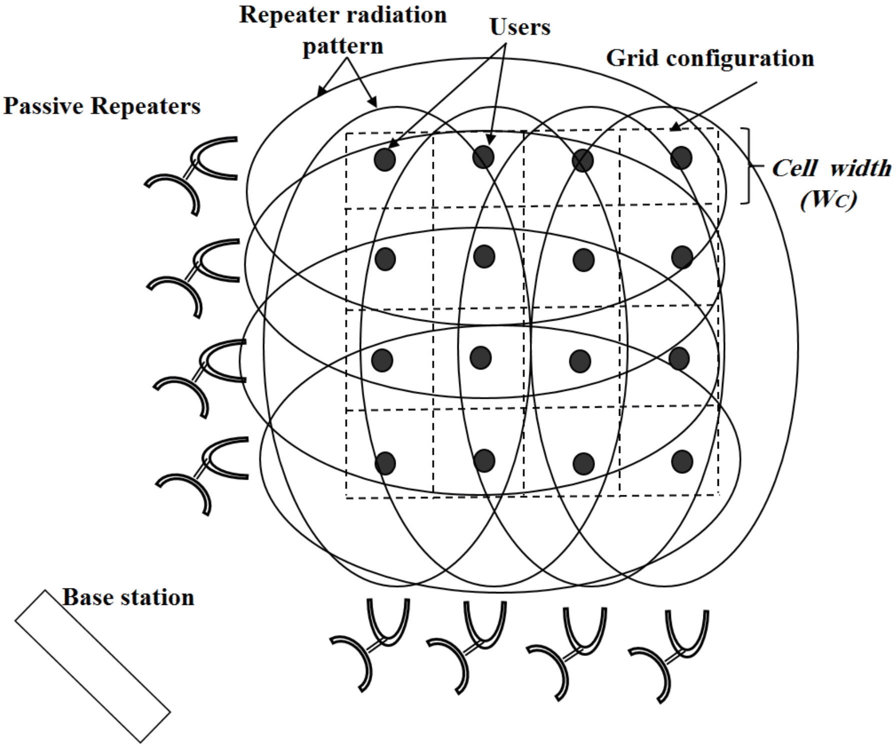


Figure 1. Grid configuration using passive repeaters for user localization.

We consider a grid with L cells and M repeaters. Each repeater is considered using the field pattern of the parabolic reflector. The radiation pattern of the parabolic reflector antenna is determined based on the field radiated by a feed antenna positioned at the focus of the parabola. Different feed antennas can be used, such as Hertzian dipole feed, waveguide feed, and horn feed [22]. However, the far field of the parabolic reflector can be approximated using the far field of a circular aperture [20]. Then the far field of the repeater toward the user area can be written as:

$$E_m(\varphi) = G * \frac{J_1((\pi D/\lambda)\sin(\varphi))}{(\pi \frac{D}{2}/\lambda)\sin(\varphi)} \cdot \frac{\exp(i \cdot \kappa \cdot r_m)}{r_m} \tag{1}$$

where J_1 is the first-order Bessel function; D is the diameter of the aperture of the repeater parabolic antenna on the user side; r_m is the distance between the m^{th} repeater and user location; κ is the wave number; λ is the wavelength; G is the repeater gain; φ is the angle between the user's position and repeater with respect to the direction of the main beam of the repeater toward user area.

Signals from a user located in a cell with coordinate $\boldsymbol{u} = (x, y)$ propagate through repeaters located in $\boldsymbol{R}_m = (x_m, y_m)$, $1 \leq m \leq M$, and impinge on a symmetric uniform linear array (ULA) with N antennas located in $\boldsymbol{B}_n = (x_n, y_n)$, $1 \leq n \leq N$. The field signature generated in the n^{th} antenna in the BS can be expressed as:

$$A_n(\boldsymbol{u}) = \sum_{m=1}^{M} \frac{\exp(i\kappa(|\boldsymbol{u} - \boldsymbol{R}_m| + |\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{u} - \boldsymbol{R}_m| \cdot |\boldsymbol{R}_m - \boldsymbol{B}_n|} \cdot D"_m(\boldsymbol{u}) \cdot D'_m(\boldsymbol{B}_n) \tag{2}$$

$$\begin{aligned} D"_m(\boldsymbol{u}) &= E_m(\arccos(\frac{(\boldsymbol{u}-\boldsymbol{R}_m)\cdot \boldsymbol{v}_m}{|\boldsymbol{u}-\boldsymbol{R}_m|})) \\ D'_m(\boldsymbol{B}_n) &= E_m(\arccos(\frac{(\boldsymbol{B}_n-\boldsymbol{R}_m)\cdot \boldsymbol{V}_m}{|\boldsymbol{B}_n-\boldsymbol{R}_m|})) \end{aligned}$$

where $|\boldsymbol{E}-\boldsymbol{F}| = \sqrt{(x_E-x_F)^2+(y_E-y_F)^2}$; $D"_m(\boldsymbol{u})$ is the radiation pattern of the second part of the repeater which covers users; $D'_m(\boldsymbol{B}_n)$ is the radiation pattern of the first part that has a LOS communication with the BS; $\boldsymbol{v}_m$ is the unit directivity vector of the repeater antenna toward the users' area; $\boldsymbol{V}_m$ is the unit directivity vector of the repeater antenna toward the BS.

Since each cell center has a different coordinate $\boldsymbol{u_l} = (x_l, y_l), 1 \le l \le L$, a unique fingerprint $\{A_{1\le n\le N}\}$ is associated with each cell using Eq. (2). When a signal from a user with coordinate $\boldsymbol{u}_0 = (x_0, y_0)$ arrives at the BS, the correlation process with all stored fingerprints is performed, and the correlation process is defined as:

$$p(\boldsymbol{u_l}) = \sum_n A_n(\boldsymbol{u}_0)\cdot A_n^*(\boldsymbol{u}_l) \tag{3}$$

The maximum correlation value gives the cell where the user exists. Two points must be fulfilled in Eq. (3) in order to obtain the desired result:

(i) Eq. (3) gives maximum value when $\boldsymbol{u}_0 = \boldsymbol{u}_l$ or $\boldsymbol{u}_0$ closer to $\boldsymbol{u}_l$.

(ii) $\{A_{1\le n\le N}\}$ vectors are different for different locations.

The first point follows directly from the correlation characteristic, whereas the second point is obtained from the fact that each location has a different spatial coordinate illuminated by a unique field pattern caused by repeaters. The proposed procedure is summarized in Fig. 2.

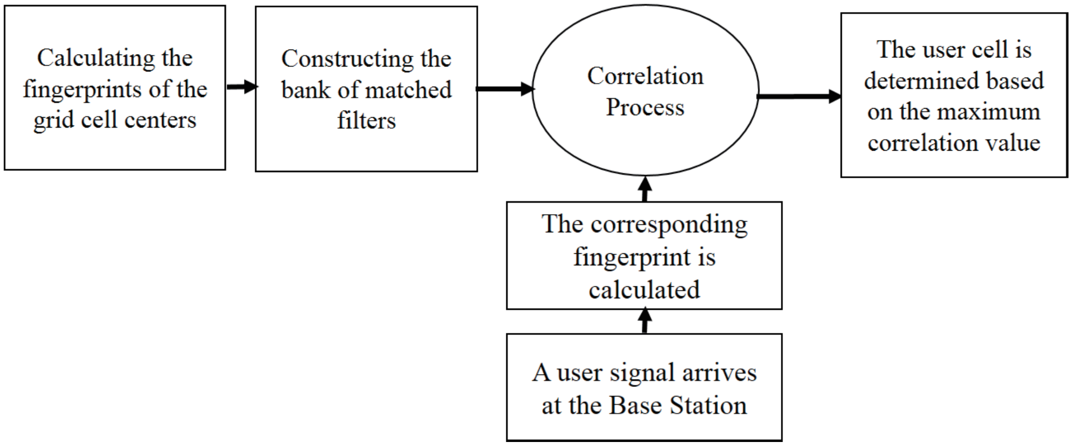


Figure 2. Flow chart of the proposed localization method.

In order to make the field interference at each user location stronger and distinct from other user locations, all repeaters are involved in covering all users. Therefore, the far field pattern of each repeater is designed so that the second part covers all users. The first part is designed to have a LOS communication with high directivity and gain with the BS. Taking this into account, the uniqueness of the fingerprint defined in Eq. (2) can be proven. Since the second part of each repeater covers all users, $D"_m(\boldsymbol{u}_l)$ can be ignored in Eq. (2). In addition, we can assume without loss the generality that $D'_m(\boldsymbol{B}_n)$ is the same for all repeaters, then Eq. (2) becomes:

$$A_n(\boldsymbol{u}_l) = \alpha \sum_{m=1}^{M} \frac{exp(i\kappa(|\boldsymbol{u}_l-\boldsymbol{R}_m|+|\boldsymbol{R}_m-\boldsymbol{B}_n|))}{|\boldsymbol{u}_l-\boldsymbol{R}_m|\cdot|\boldsymbol{R}_m-\boldsymbol{B}_n|} \tag{4}$$

For two coordinates: $\boldsymbol{u}_1$ and $\boldsymbol{u}_2$, if we assume that $A_n(\boldsymbol{u}_1) = A_n(\boldsymbol{u}_2)$, then:

$$\sum_{m=1}^{M} \frac{\exp(i\kappa(|\boldsymbol{u}_1 - \boldsymbol{R}_m| + |\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{u}_1 - \boldsymbol{R}_m| \cdot |\boldsymbol{R}_m - \boldsymbol{B}_n|} = \sum_{m=1}^{M} \frac{\exp(i\kappa(|\boldsymbol{u}_2 - \boldsymbol{R}_m| + |\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{u}_2 - \boldsymbol{R}_m| . |\boldsymbol{R}_m - \boldsymbol{B}_n|}$$

$$\sum_{m=1}^{M} \left(\frac{\exp(i\kappa(|\boldsymbol{u}_1 - \boldsymbol{R}_m| + |\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{u}_1 - \boldsymbol{R}_m| \cdot |\boldsymbol{R}_m - \boldsymbol{B}_n|} - \frac{\exp(i\kappa(|\boldsymbol{u}_2 - \boldsymbol{R}_m| + |\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{u}_2 - \boldsymbol{R}_m| \cdot |\boldsymbol{R}_m - \boldsymbol{B}_n|}\right) = 0$$

$$\sum_{m=1}^{M} \frac{\exp(i\kappa(|\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{R}_m - \boldsymbol{B}_n|} \left(\frac{\exp(i\kappa(|\boldsymbol{u}_1 - \boldsymbol{R}_m|))}{|\boldsymbol{u}_1 - \boldsymbol{R}_m|} - \frac{\exp(i\kappa(|\boldsymbol{u}_2 - \boldsymbol{R}_m|))}{|\boldsymbol{u}_2 - \boldsymbol{R}_m|}\right) = 0$$

It is clearly satisfied when $\boldsymbol{u}_1 = \boldsymbol{u}_2$, for any values of κ. The side lobes of the base station array and repeater array may cause some cells to have similar fingerprints. However, this problem can be overcome by using suitable number of antennas, repeaters, and frequencies (multiple frequencies to build the fingerprint).

In order to achieve the desired directivity and gain for the first part of each repeater, the reflector size must be chosen properly. The 3-dB beamwidth of a reflector antenna with diameter D can be estimated by rule of thumb [23]:

$$\Delta\theta_{3dB} = k\frac{\lambda}{D} \tag{5}$$

where k is a factor that depends on the shape of the reflector and the method of illumination. As a typical value $k = 1.22$ for an angle measured in radian. Using Eq. (5) and for a certain $\Delta\theta_{3\,\mathrm{dB}}$, D can be determined. In the following, the number of cells is considered as $L = Nx * Ny$, where Nx is the number of cells on the x-axis, and Ny is the number of cells on the y-axis.

3. SIMULATION AND DISCUSSION

To demonstrate the concept of the proposed method, we performed a numerical simulation considering the scenario shown in Fig. 1. The simulated area is $500\,\mathrm{m} * 500\,\mathrm{m}$ with frequency $f_0 = 100\,\mathrm{MHz}$. The BS contains $N = 16$ antennas with inter-element spacing equal to λ. The number of repeaters is M (each side contains $M/2$ repeaters, evenly spaced). This information is included in Fig. 3, along with the coordinates of the repeaters and BS antennas. For the grid, the width of the cells must be smaller than $\lambda/2$ according to the sampling theorem. However, to ensure localizing users correctly, it is preferable to use $\lambda/4$ or less as a cell width.

For $L = 700 * 700$ cells (so the width of each cell and the distance between the centers of every two adjacent cells is $W_C \approx \lambda/4$), L fingerprints are stored. Fig. 4 shows an example of the generated field signatures at the BS for two adjacent cells (0, 0) and (W_C, 0), using $M = 80$ repeaters. It is clear that field signatures are different.

For $f_0 = 100\,\mathrm{MHz}$, $M = 80$, and $700 * 700$ cells, it is possible to localize users anywhere in the grid using Eq. (3). Fig. 5 shows the normalized correlation results for a user sending signals from the cell (0, 0). Obviously, the user is correctly localized. In Fig. 5, the cell index starts from the first cell $(-\frac{Dx}{2}, \frac{Dy}{2})$ and then the other cells row by row.

It can be seen in Fig. 5 that the correlation values in some other cells are close to the desired one. This makes the error probability very high. In addition, in this work, our goal is to localize users using only the received signals at the BS. By normalizing the amplitude and phase of the field-signatures to a reference antenna at the BS (The first antenna is chosen as the reference), only the spatial coherence is used, and there is no need for time synchronization between BS and users. As a result, a user sends signals, and only the received signals at the BS are used to localize that user. In addition, we aim to reduce the number of used repeaters.

3.1. Single User Localization without Synchronization

Using $M = 16$ repeaters, and by normalizing the amplitude and phase of stored fingerprints to the first antenna in the BS, we aim to localize users without synchronization with the BS. Then, if a user

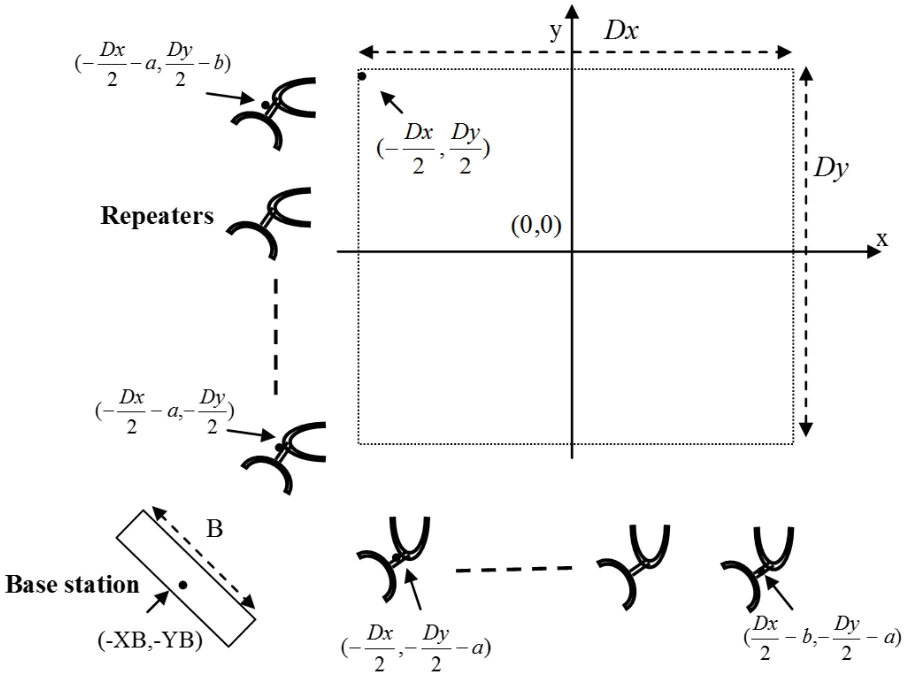
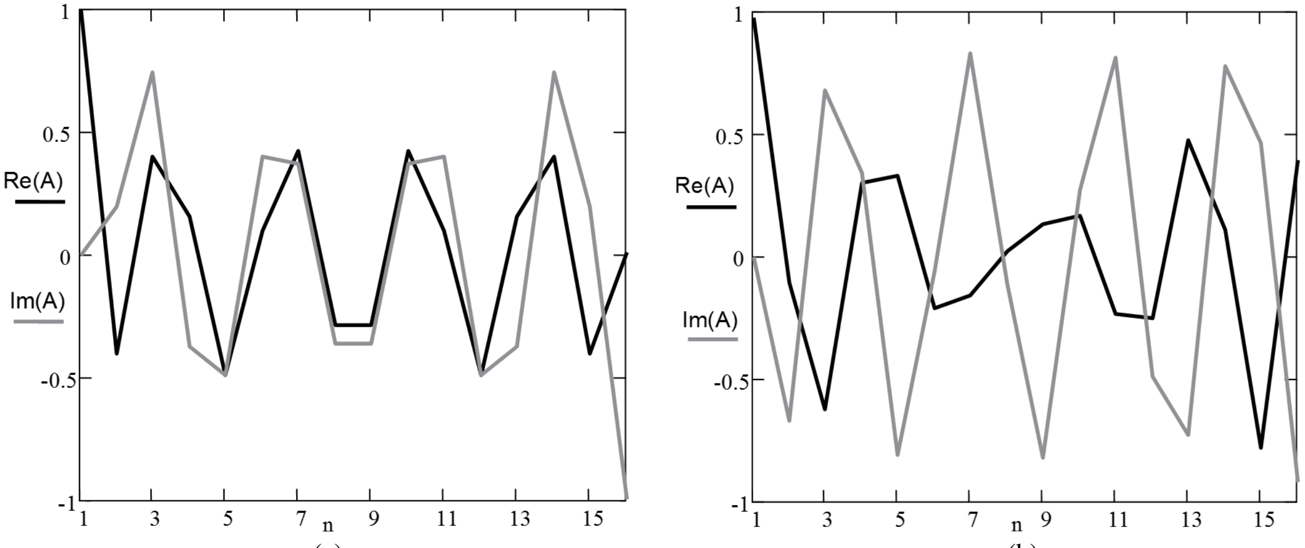


Figure 3. Simulation environment with the coordinates of the repeaters and base station antennas; $Dx = 500\,\text{m}$, $Dy = 500\,\text{m}$, $a = \frac{Dx}{2}$, $b = 35\,\text{m}$, $XB = 3 \cdot Dx$, $YB = 3 \cdot Dy$, $B = (N-1) \cdot \lambda$.



(a) (b)

Figure 4. The field-signatures of two adjacent cells at $f = 100\,\text{MHz}$ and $M = 80$: (a) the cell (0, 0), (b) the cell (W_C, 0).

located in the cell (0, 0) transmits signals to the BS, the generated field signature is normalized to the first antenna and correlated with all stored fingerprints.

Without time synchronization, there would be uncertainty in determining the user's location. Multiple frequencies (at least two) are required for proper localization. This is because different frequencies mean different wavelengths and different field interferences, thus a new additional fingerprint vector is added for each location using Eq. (2). As a result, the uniqueness of the total fingerprint of

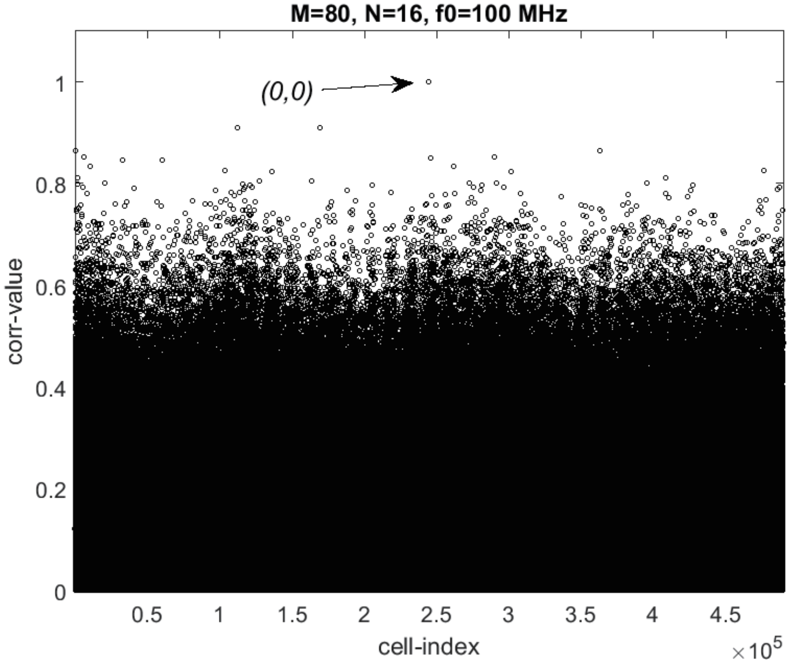


Figure 5. Normalized correlation results for a user exists in the cell (0, 0) with $M = 80$ and $f = 100\,\text{MHz}$.

each cell center and other locations is increased.

Using two frequencies ($f_1 = f_0$, $f_2 = f_0 + 1\,\text{MHz}$), the correlation results are shown in Fig. 6(a1), and the correlation values distribution through the grid is shown in Fig. 6(a2). It is clear that there is a maximum in the corresponding cell, and the localization is achieved correctly. The discrimination of the maximum value relative to other values can be increased by using more frequencies.

For Nf frequencies and without synchronization, Eq. (2) and Eq. (3) become:

$$p(\boldsymbol{u}_l) = \sum_{i=1}^{Nf} \left| \sum_n A_n(\boldsymbol{u}_0, f_i) \cdot A_n^*(\boldsymbol{u}_l, f_i) \right| \tag{6}$$

where:

$$A_n(\boldsymbol{u}, f_i) = \sum_{m=1}^{M} \frac{\exp(i\kappa_i(|\boldsymbol{u} - \boldsymbol{R}_m| + |\boldsymbol{R}_m - \boldsymbol{B}_n|))}{|\boldsymbol{u} - \boldsymbol{R}_m| \cdot |\boldsymbol{R}_m - \boldsymbol{B}_n|} \cdot D"_m(\boldsymbol{u}) \cdot D'_m(\boldsymbol{B}_n) \tag{7}$$

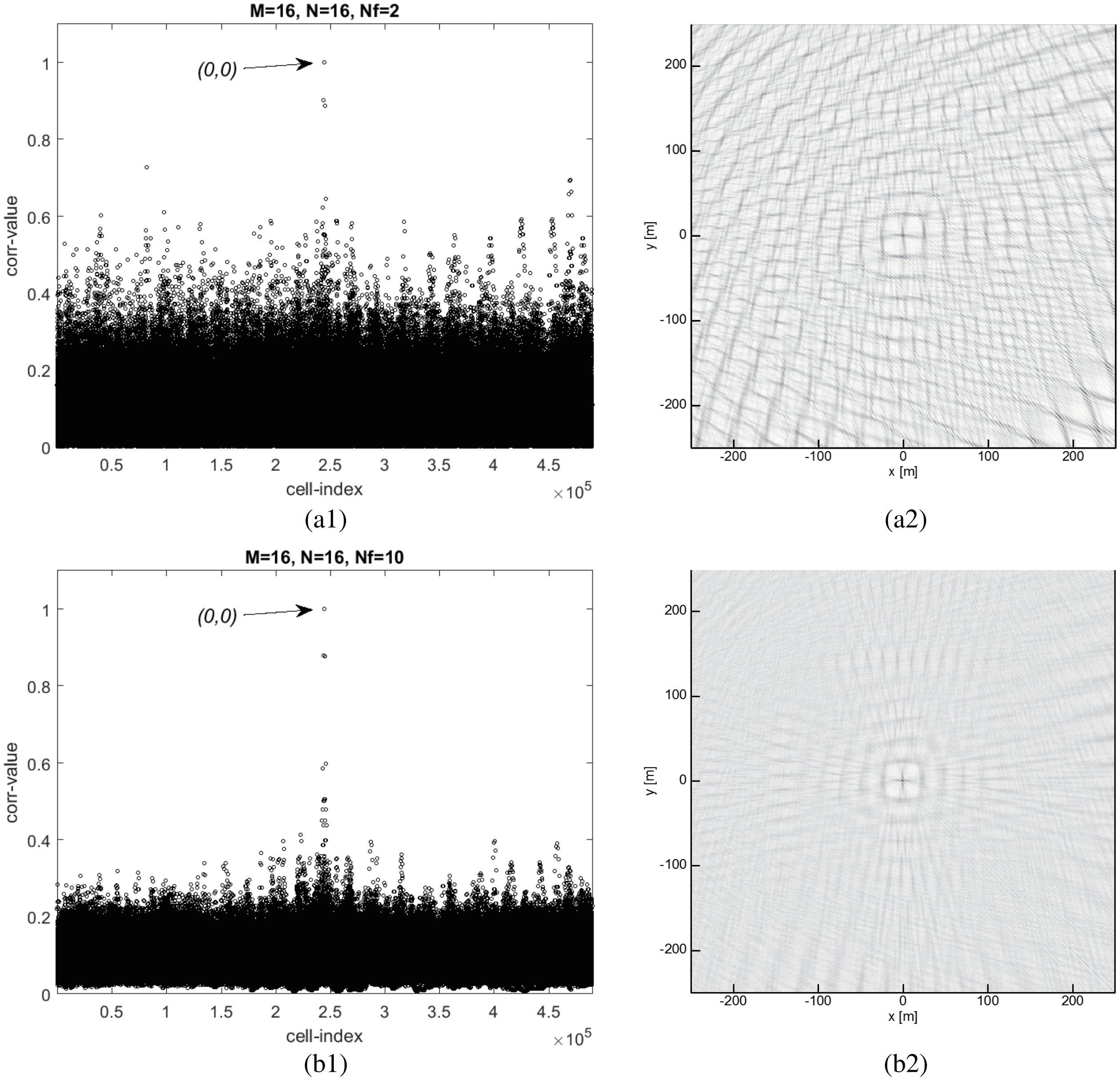
and:

$$\kappa_i = \frac{2\pi}{\lambda_i} = \frac{2\pi}{c} f_i \tag{8}$$

for a frequency step of 1 MHz. Fig. 6(b1) and Fig. 6(b2) show the correlation results and their distribution through the grid when $Nf = 10$. Obviously, the discrimination increases as the number of used frequencies increases. It is possible to note that there are many high correlation values even as the number of used frequencies increases. These high correlation values increase the probability of error due to noise or interference.

3.2. Localization Accuracy and Error

Results in Fig. 6 show that there are many strong correlation values. These strong values are not a problem when localizing one user at a time and in the absence of noise and interference. However, when localizing multiple users, some of these values may be summed together and result in incorrect localization. Noise and interference can also lead to incorrect results.



(a1) (a2)

(b1) (b2)

Figure 6. Correlation results and their distribution through the grid. ((a1) and (a2)) using two frequencies with step = 1 MHz, ((b1) and (b2)) using ten frequencies with step = 1 MHz.

This problem is considered by defining the parameter E_C, which is the energy summation of cells that have high correlation values. For a threshold T and if any cell that has a correlation value $p > T$ is considered as a potential source of error, then E_C can be defined as:

$$E_C = \frac{\sum_{l=1}^{L} |p(\boldsymbol{u}_l)|(p(\boldsymbol{u}_l) > T)}{L} \tag{9}$$

For $T = 0.3$, the change of E_C with Nf is shown in Fig. 7. It can be seen that the value of E_C decreases as the number of used frequencies (Nf) increases. T can be determined experimentally in proportion to the communication environment.

For $Nf = 10$ and $700 * 700$ cells, the approach is verified in the presence of noise with SNR = 10 dB

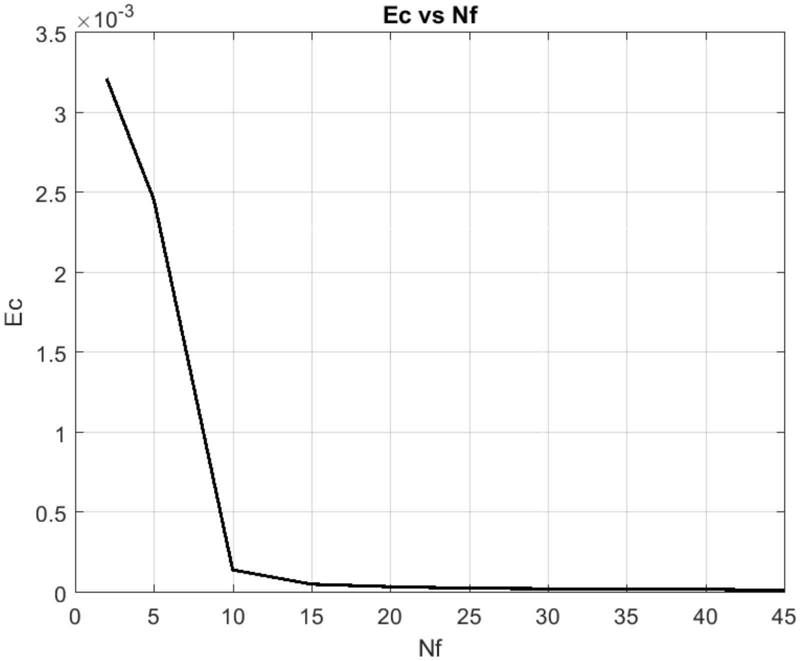
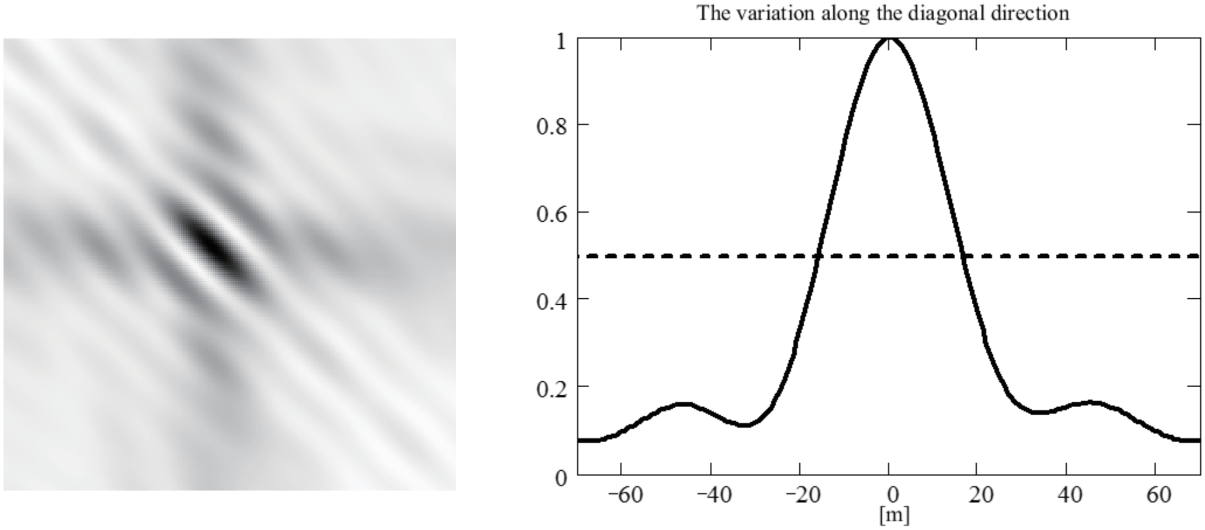


Figure 7. The degradation of Ec as the number of used frequencies (Nf) increases.



(a) (b)

Figure 8. (a) The variation of correlation values around the maximum value. (b) The maximum variation along the diagonal direction.

and 500 random locations in the grid. The algorithm correctly localized 433 locations (86.6%). The error is mainly caused by locations close to the boundaries of the cells. This error can be reduced by reducing the cell width, then locations in cells will be closer to the cell centers. However, reducing the cell width means increasing the cell number in addition to the number of stored fingerprints. As a result, the number of required calculations and the time required to execute will increase. The error can also be reduced by increasing the number of used frequencies as shown in Fig. 7.

For the accuracy of the proposed method, it is obvious that a clear maximum can be obtained in the target cell in the absence of noise and interference. However, in the presence of noise or interference, the maximum value may not be obtained. Instead, a shift from this maximum may occur. Taking this into account, it is necessary to determine the resolution of the proposed method considering any displacement from the maximum value.

In Fig. 6(b2), where $M = 16$, $N = 16$, $Nf = 10$, looking at the area around the maximum value, it is possible to consider the variation of correlation values around this maximum. This variation is shown in Fig. 8(a).

It can be seen that the maximum continuous variation is along the diagonal direction. This diagonal variation is shown in Fig. 8(b). By taking half of the maximum value, it can be shown that the resolution in the worst case is about 32 m.

The resolution depends on the number of passive repeaters and their locations, as well as the number of used frequencies. Since the number of passive repeaters and their arrangement are determined in such a way as to enrich scattering in the communication environment and improve the channel capacity, for each communication system that uses passive repeaters, it is possible to specify the corresponding resolution in localizing users.

3.3. Localization of Multiple Users Simultaneously

In real scenarios, signals from multiple users located in different cells may arrive at the BS at the same time. The interference caused by simultaneous arrival of signals from different users may lead to incorrect localization. The localization process can be made more resistant to noise and interference by increasing the number of frequencies at which the fingerprint is calculated. The required number of frequencies is related to the system requirements in terms of the number of users to be correctly localized at the same time. Considering the system shown in Fig. 3 and for $f_0 = 100\,\text{MHz}$, $M = 16$, $N = 16$ and $700 * 700$ cells, exhaustive search was performed, and it is found that in order to localize five users at the same time, using $T = 0.6$ as a threshold for the normalized correlation values, 100 frequencies with step equal to 1 MHz are required. The correlation results are shown in Fig. 9.

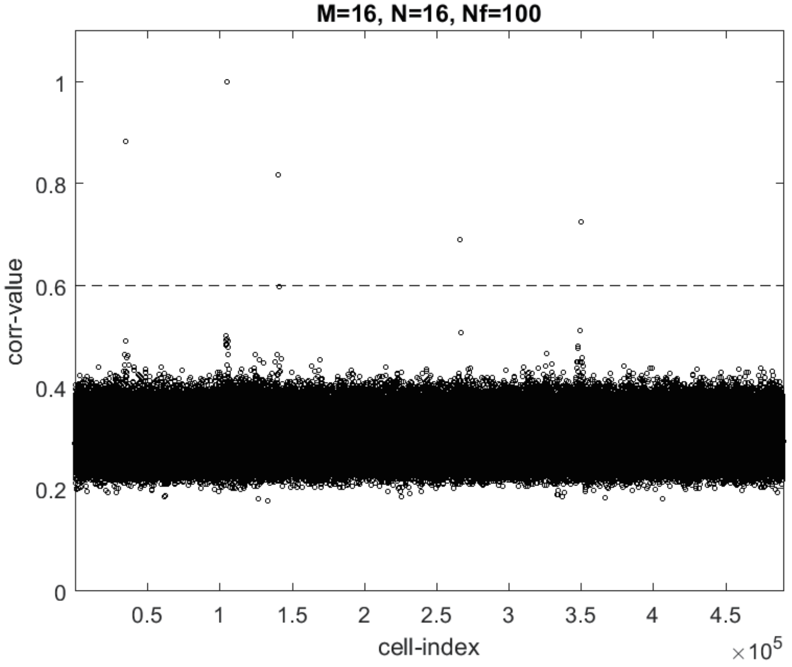


Figure 9. Normalized correlation results for five users with $M = 16$ and $Nf = 100$.

4. CONCLUSION

In this paper, we propose to use passive repeaters in localizing users. To achieve that, a grid configuration is considered. The field signature created at the BS for each grid cell center is used as a fingerprint. First, in the case of synchronization between the BS and users, the proposed method is verified using a single frequency to construct the fingerprints. The results show that localization is achieved correctly. Then, the synchronization between users and BS is avoided by normalizing the magnitude and phase of the fingerprints to the first antenna in the BS. For localizing one user, the fingerprint is built using at least two frequencies. For multiple users, the required number of frequencies is related to the system requirements in terms of the number of users to be correctly localized at the same time. The localization process is performed using only the received signals. After receiving signals from a user, the correlation process is carried out with the stored fingerprints, and the location of the user is determined. The numerical simulation shows that the proposed methods can localize users in MIMO environments using generated field-signatures, with no need of calculating additional parameters.

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