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Exploration on DOA Algorithms in LTE-A HetNet Interference Suppression

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Abstract. *An exploration on the application of DOA in LTE-A Heterogeneous Network (HetNet) is made in this paper. The main idea of our method is mitigating Femto downlink interference from the perspective of array signal processing. To this end, WSF and beamforming technique is introduced to improve the communication quality of unregistered Macrocell User Equipments (MUE) located within Femtos coverage. The proposed scheme can be executed without complex network configuration which leads to a simple but efficient way for its implementation. In contrast to Enhanced Inter Cell Interference Coordination (eICIC), our scheme avoids strict timing synchronization restriction and prevents degradation in system switching performance. Simulation results have verified the feasibility and effectiveness of our proposed approach.*
Keywords: HetNet, Interference Suppression, DOA, Beamforming

1. **Introduction.** The users' desire for high-speed indoor mobile data services becomes more and more intense when the telecommunications industry ushering in the 4G era. 3GPP organization introduces low-power nodes into LTE-A to increase nodes and data transmission rate of the system. As a member of these nodes, Femto is designed to address problems of indoor signal coverage and data hotspots communication. As a supplement of Macrocell, Femto has the advantages of flexible deployment, easy operation, etc. It can be purchased, configured and installed by users without any assistance. However, sometimes Femto can be a co-channel interference source to unregistered Macrocell User Equipments (MUE), especially when it shares the same bandwidth with Macrocell.

LTE release 10 proposes Enhanced Inter Cell Interference Coordination (eICIC) to solve interference problems between Femto and MUE. eICIC allows Femto to allocate Almost Blank Subframes (ABS) for unauthorized MUE accessing co-channel Macrocell [1]. Femto will cancel its transmission during ABS and reduce the interference significantly. Although eICIC has an excellent theoretical behavior, strict requirements for timing synchronization as well as serious switching performance degradation prevent its further application [2].

Due to the wide utilization of array processing techniques, it has received considerable attention from other academic fields [3]. A variety of DOA estimation and beamforming algorithms have been proposed to meet the requirements of different situations. Among the existing techniques, subspace fitting methods, like Weighted Subspace Fitting (WSF) [4], are proved to be more outstanding than the other approaches. Their powerful capability in DOA estimation of coherent signals provides huge advantages for multi-path communication applications.

In [5–7], DOA estimation and beamforming technique are used to suppress the interference between primary and secondary communication system. All these schemes are still in the stage of theoretical exploration. Some of them need a perfect prior knowledge of propagation channels and the others can only measure the direction of a single propagation path. The neglect of multi-path effect makes them impracticable in actual communication system.

MUSIC algorithm and beamforming are introduced into LTE-A system for the first time by authors in paper [8] and [9]. They provide a novel idea for the development of interference suppression technology in Heterogeneous Network (HetNet). Comparing with eICIC,the new idea tries to solve problems from the perspective of cognition, so that avoiding constraints from strict timing synchronization. However, the limitation of MUSIC in coherent sources estimation will lead to a failure of this scheme when it is applied in a real LTE-A HetNet system.

Inspired by [8,9], a novel HetNet interference method based on WSF and beamforming technique is proposed in this paper. We take the DOA estimation of coherent signals generated by multi-path effect into consideration and choose WSF for getting a better estimation performance. We simulate the actual LTE-A multi-path communication environment and make a test for the performance of proposed method. Simulation results have shown the validity and effectiveness of our approach.

2. **Basis of DOA Estimation.** Suppose that there is a uniform linear array (ULA) composed of M isotropic sensors. Q far-field narrowband source signals impinge on the array from distinct directions $\{\theta_1,\ldots,\theta_Q\}$. The $M\times 1$ observation vector can be described by

$$\boldsymbol{x}(t) = \mathbf{A}\boldsymbol{s}(t) + \boldsymbol{n}(t), \tag{1}$$

where $\boldsymbol{x}(t)$ is the observation vector, $\boldsymbol{s}(t) = [s_1(t), \ldots, s_Q(t)]$ is the $Q\times 1$ signal vector, $\mathbf{A} = [\boldsymbol{a}(\theta_1), \ldots, \boldsymbol{a}(\theta_Q)]$ is the $M\times Q$ array manifold, $\boldsymbol{a}(\theta_q)$ is $M\times 1$ steering vector corresponding to the direction $\theta_q(q{=}1,\ldots,Q)$ and can be expressed as

$$\boldsymbol{a}(\theta_q) = [1, e^{-j2\pi\sin(\theta_q)d/\lambda}, \ldots, e^{-j2\pi(M-1)\sin(\theta_q)d/\lambda}]^T. \tag{2}$$

In equation (2), λ is the carrier wavelength, $d = \lambda/2$ is the spacing between array elements and $[\cdot]^T$ stands for matrix transpose. $\boldsymbol{n}(t)$ represents zero mean additive white Gaussian noise which is uncorrelated with signal. The covariance matrix of array output is given by

$$\mathbf{R} = E[\boldsymbol{x}(t)\boldsymbol{x}(t)^H] = \mathbf{A}\mathbf{R}_s\mathbf{A}^H + \sigma_n^2\mathbf{I}_M. \tag{3}$$

Here $\mathbf{R}_s = E[\boldsymbol{s}(t)\boldsymbol{s}(t)^H]$ is a $Q\times Q$ covariance matrix of signal, σ_n^2 is the variance (power) of noise, $\mathbf{I}_M$ is the $M\times M$ identity matrix, $E[\cdot]$ denotes expectation operator and $[\cdot]^H$ represents Hermitian transpose.

In practice, only sample estimates can be obtained by us. Suppose the number of snapshots is N, then sample covariance matrix $\hat{\mathbf{R}}$ can be expressed as

$$\hat{\mathbf{R}} = \frac{1}{N}\sum_{t=1}^{N}\boldsymbol{x}(t)\boldsymbol{x}^H(t) = \frac{1}{N}\mathbf{X}\mathbf{X}^H, \tag{4}$$

where $\mathbf{X} = [\boldsymbol{x}(1), ..., \boldsymbol{x}(N)]$ is the $M\times N$ sampled data matrix. The eigen-decomposition of equation (4) can be written as

$$\hat{\mathbf{R}} = \hat{\mathbf{U}}_s\hat{\Lambda}_s\hat{\mathbf{U}}_s^H + \hat{\mathbf{U}}_n\hat{\Lambda}_n\hat{\mathbf{U}}_n^H. \tag{5}$$

$\hat{\Lambda}_s = diag\{\lambda_1, \ldots, \lambda_Q\}$ contains Q largest eigen-values, while $\hat{\Lambda}_n = diag\{\lambda_{Q+1}, \ldots, \lambda_M\}$ contains the remaining ones. The elements in them are all arranged in descending order. Matrix $\hat{\mathbf{U}}_s$ and $\hat{\mathbf{U}}_n$ are made up of the corresponding eigenvectors and they are called signal and noise subspace, respectively. $diag\{\cdot\}$ denotes the operator of diagonal matrix.

3. **Key Technologies of LTE-A.**

3.1. **LTE-A Uplink Signal Model.** SC-FDMA is the key technology which is utilized to transmit uplink signal in LTE-A system. An overview of SC-FDMA processing is illustrated in Figure 1.

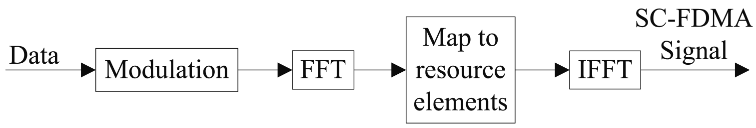


FIGURE 1. Overview of SC-FDMA processing.

The mathematical model of SC-FDMA can be expressed as

$$s_l(t) = \sum_{k=-\lfloor 6\times N_{RB}^{UL} \rfloor}^{\lceil 6\times N_{RB}^{UL} \rceil - 1} a_{k,l} \times e^{j2\pi \frac{k+1}{2} \times 15000 \times (t - N_{CP}T_s)}, \quad (6)$$

where k and l represent the index of frequency-domain and time-domain, respectively. $a_{k,l}$ is the value of resource element (k, l). N_{RB}^{UL} is the uplink bandwidth configuration, N_{CP} is the length of cyclic prefix. T_s is defined as sampling rate and its value is 32.55 ns [10].

3.2. **Sounding Reference Signal.** The quality of uplink channel can be measured by Sounding Reference Signal (SRS) over a section of the whole channel bandwidth. In LTE-A system, the eNodeB can use this information for resource scheduling and downlink parameter adjustment. SRS plays an important role in HetNet interference suppression. It can be used to support DOA measurements for downlink beamforming. A simple transmitter and receiver chain of SRS is shown in Figure 2 [1].

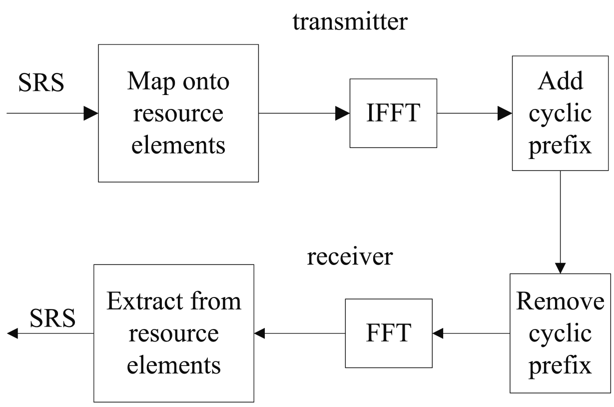


FIGURE 2. Simple transmitter and receiver chain of SRS

3.3. Downlink Beamforming. Beamforming is a kind of transmission technology used in small spacing antenna array. A beam of radiated power in the specific direction can be generated by using multiple antennas in conventional beamforming.

An eNodeB can direct downlink resource block transmission towards an appropriate User Equipment (UE) by using beamforming. It is achieved by adjusting the weight of each antenna element and makes the downlink signal combine constructively at the UE. By using beamforming technology, LTE-A system can increase the gain of specific UE and help to decrease inter-cell interference at cell edge. The general concept of LTE-A downlink beamforming is displayed in Figure 3 (The dash line in figure 3 indicates the uplink DOA information measured by SRS).

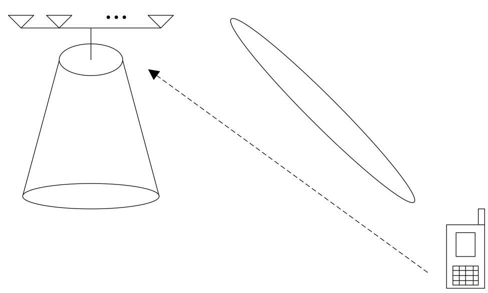


Figure 3. LTE-A downlink beamforming

4. Proposed HetNet Interference Suppression Method.

4.1. Reason of HetNet Interference. Although the introduction of Femto provides an efficient and cost-effective solution for indoor coverage, the randomness of its deployment also makes the interference problem in HetNet more difficult to control. In order to improve the efficiency of spectrum utilization, Femto often share the same bandwidth with the Macrocell. When operating in Closed Subscriber Groups (CSG) mode, only registered UE can access Femto. A MUE in the coverage of Femto will be rejected to access if it is not authorized. At this moment, the signal received by MUE will suffer a severe interference from Femto and it may even lead to a communication interruption between MUE and its Macrocell. The interference model of Femto is shown in Figure 4.

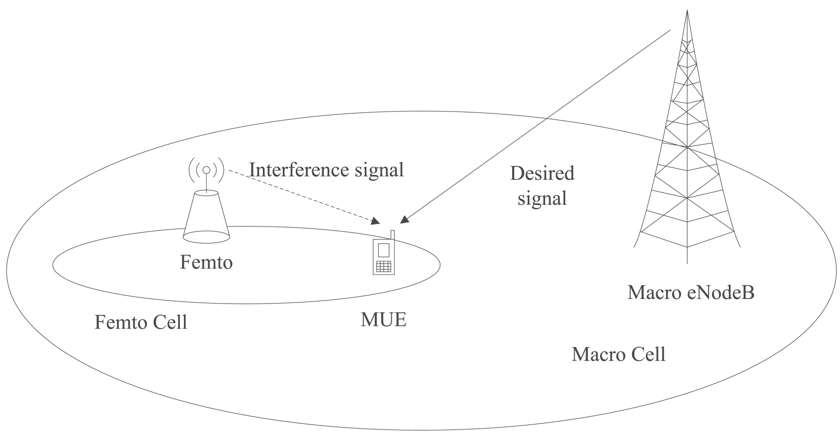


Figure 4. Interference model of Femto

Existing interference suppression solutions include the following two types:

1. eICIC is introduced in LTE release 10 to solve the interference problem from the network configuration. And its function has been stated in Introduction. However, eICIC requires strict synchronization between Femto and Macrocell which will lead to degeneration in switching performance.
2. Array processing approach with MUSIC is efficient in single path environment. Unfortunately, weakness of MUSIC on coherent signal DOA estimation makes the whole system invalid in multi-path communication conditions.

In this paper, we solve the interference problem in HetNet from the view of WSF and try to make an exploration on its performance in an almost real multi-path communication situation.

4.2. **Proposed Interference Suppression Method Using WSF and MODE.** The WSF algorithm is constructed by using a fitted relationship between signal subspace and array manifold. The estimator of WSF can be written as

$$\theta = arg\{\underset{\theta}{max} tr\{\mathbf{P}_A \hat{\mathbf{U}}_s \mathbf{W} \hat{\mathbf{U}}_s^H\}\}, \tag{7}$$

where $\mathbf{P}_A = \mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H$ is the projection matrix of $\mathbf{A}$. The weighting matrix should be written as

$$\mathbf{W} = (\hat{\Lambda}_s - \hat{\sigma}_n^2 \mathbf{I}_Q)^2 \hat{\Lambda}_s^{-1}, \quad \hat{\sigma}_n^2 = \frac{1}{M-Q} tr\{\hat{\Lambda}_n\}, \tag{8}$$

The WSF method involves multidimensional searching problem and can lead to a high computational cost in parameter space. In [11], an efficient approach called MODE is proposed to solve the implementation problem of WSF. The spectral function of MODE can be expressed as

$$\hat{\theta}_q = arcsin(\frac{\lambda}{2\pi d} \arg\{\hat{z}_q\}), \quad q = 1, \ldots, Q, \tag{9}$$

where $\hat{z}_q (q = 1, \ldots, Q)$ are polynomial roots.

WSF outperforms MUSIC and the other classic subspace decomposition algorithms under the same condition. More importantly, WSF can estimate the DOA of coherent sources directly which makes it possible for the application in a multi-path propagation environment.

With the limitation of antenna array, the maximum resource number that can be identified by WSF is $M-1$. In order to obtain a better estimation performance, the number of incident sources is preferably not more than $M/2$.

The proposed scheme can be divided into two stages. In the first stage, DOA of MUE uplink signal is estimated by Femto with a build-in ULA. This process can be carried out by using the azimuth information contained in SRS. Due to the existence of multi-path effect, the actual data received by ULA should be replicas of MUE uplink signal with different time delay. These replicas are mutually coherent signals and their DOA estimation can be performed using WSF mentioned above.

In the second stage, a power cancellation at Femto is applied to suppress its interference to Macrocell downlink signal. It is inspired by beamforming technique and can be realized by using DOA information. Suppose $\{\theta_1^{MUE}, \ldots, \theta_K^{MUE}\}$ are the $K(K < M)$ DOA estimation results obtained in the first stage and θ^F is the azimuth of strongest replica from Femto UE (FUE). Then, the weight vector $\boldsymbol{w}$ of beamformer should satisfy the following criterion,

$$\boldsymbol{w}^H[\boldsymbol{a}(\theta^F), \boldsymbol{a}(\theta_1^{MUE}), \ldots, \boldsymbol{a}(\theta_K^{MUE})] = [1, 0, \ldots, 0]^T. \tag{10}$$

If we set the vector $\boldsymbol{h} = [1, 0, \ldots, 0]$, the vector $\boldsymbol{w}$ can be expressed as

$$\boldsymbol{w}^H = \boldsymbol{h}^T \mathbf{A}^H (\mathbf{A}\mathbf{A}^H)^{-1} \tag{11}$$

For the sake of clarity, a pseudo-code of the suppression scheme is given in Table 1.

TABLE 1. Pseudo-code of suppression scheme

Step 1.	Apply WSF to SRS and obtain K DOA estimation results.
Step 2.	Calculate beamforming weights based on the results in step 1.
Step 3.	Adjust Femto downlink transmission power according to the weights in step 2 and finish the suppression scheme.

5. **Simulation.** Suppose a ULA with eight isotropic sensors is built into the Femto. Its inter-element spacing is set to half of the LTE-A uplink carrier wavelength (2 GHz). The multi-path effect is taken into account and its model is defined in ITU-R M.1225 [12]. To simplify the system, we assume that the number of MUE uplink replicas impinging upon ULA is known.

In the first experiment, the feasibility of the proposed scheme is verified. The azimuth of MUE main uplink signal (line-of-sight signal), its two multi-path replicas and FUE's strongest replica are set to $\theta_1^{MUE} = 10°$, $\theta_2^{MUE} = 20°$, $\theta_3^{MUE} = -20°$ and $\theta^F = 35°$, respectively. The bandwidth of Macrocell and Femto downlink is 3 MHz and SNR at Femto is -3 dB. MUE uplink bandwidth is 1.4 MHz while its SNR is 15 dB. Model of the entire transmission link is shown in Figure 5. Figure 6 displays the QPSK demodulation constellation of MUE, Figure 6(a) shows the result of Femto interference without suppression measures while in Figure 6(b) no interference is taken into account. There is a strong correlation between communication quality and demodulation results, which means the higher aggregation degree of the demodulation results, the better communication quality at MUE. Therefore, Figure 6 implies a serious interference on Non-CSG MUE QPSK demodulation accuracy generated by Femto downlink signal. If no measures are adopted, it is bound to be a great impact on the communication quality at UE.

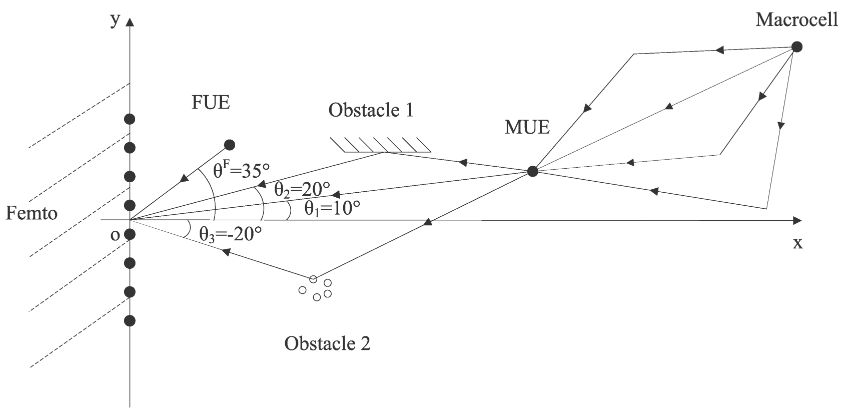
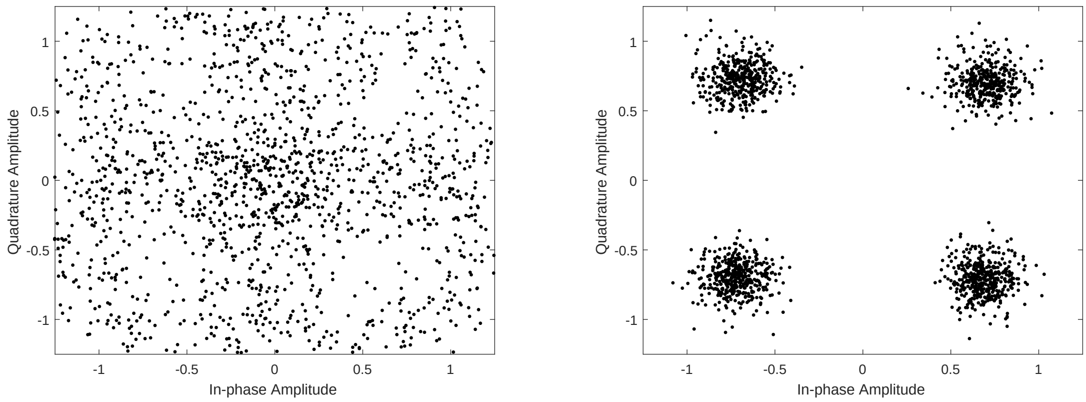


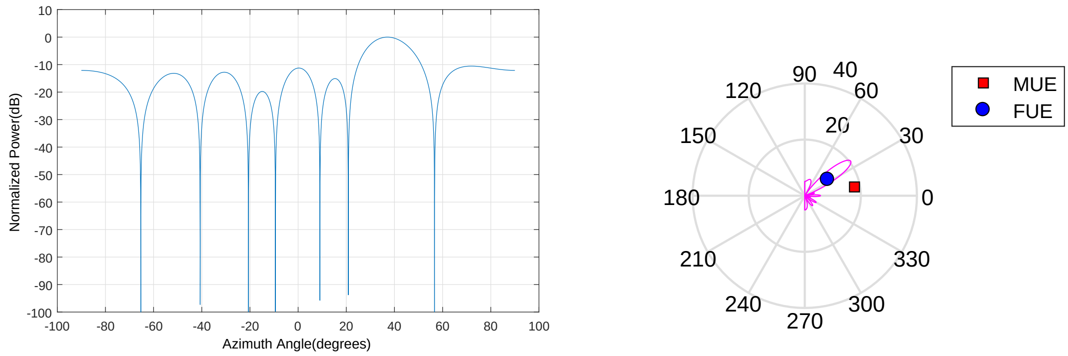
FIGURE 5. Transmission link model

Figure 7-8 show the simulation results after applying the proposed interference suppression method. Figure 7(a) and 7(b) demonstrate the distribution of Femto downlink power from perspective of beam pattern and polarization, respectively. The power corresponding to $\theta_i^{MUE}(i = 1,\ 2 \text{ and } 3)$ is eliminated while the beam radiated to θ^F is preserved successfully. Figure 8 shows the same measurement as Figure 6. But this time the accuracy of QPSK demodulation at MUE improved significantly after applying the proposed scheme. As a supplemental proof, a Bit Error Rate (BER) measurement is also presented in Table 2.



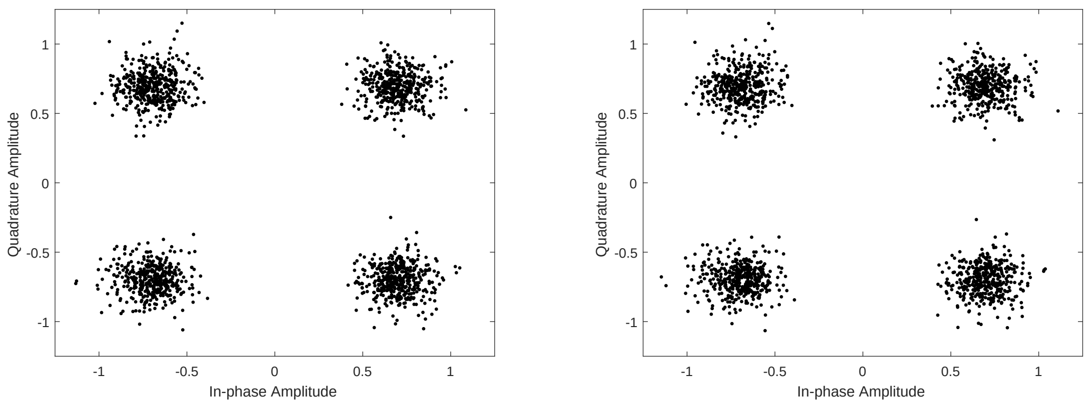
(a) No suppression measures (b) No interference

FIGURE 6. MUE QPSK demodulation constellation



(a) beam pattern (b) polarization

FIGURE 7. MUE QPSK demodulation constellation



(a) Interference suppression (b) No interference

FIGURE 8. MUE QPSK demodulation constellation

TABLE 2. BER measurement under different interference conditions

Interference condition	Bit Error Rate (BER)
No Femto downlink interference	0
Interference suppression with WSF	0
No interference suppression measures	17.48%

In the second simulation, performance of the proposed approach is tested under the condition of different SNR. The results have been presented in Figure 9. MUE uplink bandwidth of is set to be 5 MHz and Femto is assumed to share the same 10 MHz downlink bandwidth with Macrocell. The SNR at Femto is fixed to -5 dB and its value at Femto goes from -5 dB to 5 dB.

It can be observed from Figure 9 that the SNR at Femto has a great impact on performance of interference suppression. In low SNR regime, DOA estimation accuracy limits the behavior of proposed scheme. However, the path with strongest power can always be estimated accurately. Thus, eliminating radiation power toward the strongest path is sufficient to improve communication quality of MUE.

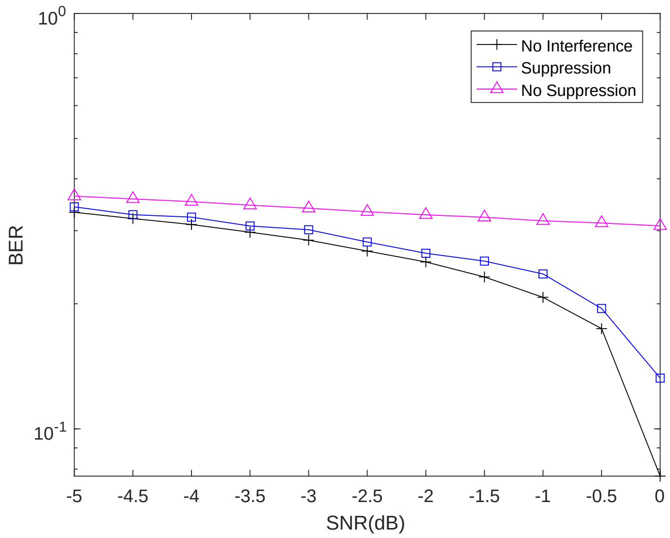


FIGURE 9. BER performance versus SNR

Finally, a conclusion can be drawn by summarizing the results above: WSF method can be applied successfully in HetNet multi-path transmission scenes and has an outstanding performance in interference suppression.

6. **Conclusions.** A LTE-A HetNet interference suppression method based on WSF and beamformer is proposed in this paper. The proposed scheme can be executed without any complex network configuration, thus avoiding the limitation of strict timing synchronization on system. In contrast to eICIC and method depend on MUSIC, our scheme permits to mitigate the effect of Femto downlink signal in an actual LTE-A communication scenario. Simulation results have shown the validity and effectiveness of our approach.

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