Multi-Carrier Cooperated Interference Cancelation via Macro-BS Broadcasting in HetNet

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***Abstract*—In next generation cellular system, heterogeneous network will be widely used to improve the spatial spectrum efficiency. In this paper, we propose a new interference cancelation scheme to increase the achievable sum-rate of multi-carrier interference channels in heterogeneous networks. The subcarriers are cooperated where one group subcarriers transmit in full-rate as if there is no interference and another group subcarriers transmit redundancy information to help interference cancellation. To improve the transmission efficiency, in mixed interference scenarios we only require macro-BS to broadcast the redundancy information. We will introduce the channel conditions for selecting these two groups of subcarriers, and study an optimized subcarrier allocation method. Finally, simulation results in practical heterogeneous network settings are provided to show the performance improvement.**

I. Introduction

Heterogeneous networks deploy low power access points to deal with the explosive wireless traffic demand. It has the potential to provide the next significant performance leap in cellular networks [1]. Macro-cells are able to provide basic coverage and support fast mobility, while pico-cells are deployed to provide high-capacity transmission for hot spot zones. In such kind of networks, the interference scenarios become more complicated than that in homogeneous networks. Operated in the same frequency band, macro-BS will cause strong interference to most pico-users, and pico-BS also has opportunity to cause strong interference to the nearby macro-users [2].

With one pico-cell coexisted with the macro-cell, the transmission of the macro-user and pico-user forms a two-user interference channel. The best known transmission scheme for two-user Gaussian interference channel is Han-Kobayashi (H-K) coding [3, 4], where each user divides its transmit information into private and common portions. The private information is only decoded at the intended receiver, and the common information is decoded at both receivers. However, H-K coding is a single-carrier transmission scheme, which did not consider the possible benefit of subcarriers cooperation in multi-carrier interference channels. As indicated in [5], the capacity of a parallel interference channel is larger than the sum capacity of each separated interference channels.

In frequency-selective channels, different subcarriers suffer from different levels of small-scale fadings, leading to different interference scenarios [6]. In [7], a multi-carrier cooperation transmission scheme was proposed to improve the sum-rate of two interfering users. All the subcarriers are categorized as three groups. Group A subcarriers transmit in conventional single-carrier schemes, group B subcarriers transmit in direct-link as if there is no interference, and group C subcarriers transmit in cross-link to send redundancy information to the interfering user, so that the interference occurred in group B subcarriers can be canceled. However, since it is also an interference channel in group C subcarriers although the desired information is transmit in cross-link, the interference problem should be dealt with in the transmissions. Furthermore, the sum-rate gain relies on strong cross-link channels, thus the method selects subcarriers as group C when both users suffer from strong interference.

In heterogeneous networks, the mixed interference scenarios are more common, where macro-BS causes strong interference to pico-users and pico-BS causes weak interference to macro-users. To improve the transmission efficiency of the multi-carrier cooperation scheme in this case, we propose a macro-BS broadcasting scheme to transmit redundancy information in group C subcarriers. The broadcasted information will be received by the interfered user to help canceling the interference, and will also be received by the desired user to help decoding the signal. Because of the property of mixed interference channel, the new cooperation scheme will achieve significant sum-rate gain than the existed methods.

In the rest of the paper, we will first introduce the proposed multi-carrier cooperated interference cancellation scheme in Section II. Then in Section III, we will study the channel selection conditions of different group subcarriers, and find an optimized subcarrier allocation algorithm. Simulation results will be provided in Section IV to show the sum-rate improvement of the proposed scheme in practical heterogeneous network settings. Finally, Section V concludes the paper.

II. Multi-Carrier Cooperated Interference Cancellation Scheme

A. System Model

We consider two-user Gaussian interference channel with M subcarriers, where transmitter 1 and 2 represent macro-BS and pico-BS, respectively, and receiver 1 and 2 represent macro-user and pico-user, respectively. The received signals

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on the m-th subcarrier can be expressed as

$$y_1^m = h_{11}^m x_1^m + h_{12}^m x_2^m + z_1^m, \quad (1)$$
$$y_2^m = h_{22}^m x_2^m + h_{21}^m x_1^m + z_2^m, \quad (2)$$

where y_i^m is the received symbol at receiver i, h_{ij}^m denotes the channel gain from transmitter j to receiver i, x_j^m is the symbol sent by transmitter j with transmit power P_j^m, z_i is the circular symmetric complex Gaussian noise with zero mean and variance N_0, and $i, j \in \{1, 2\}$, $m \in \{1, 2...M\}$.

Define signal-to-noise ratio (SNR) and interference-to-noise ratio (INR) at each receiver as follows,

$$\mathrm{SNR}_1^m = |h_{11}^m|^2 P_1^m / N_0, \quad \mathrm{SNR}_2^m = |h_{22}^m|^2 P_2^m / N_0,$$
$$\mathrm{INR}_1^m = |h_{12}^m|^2 P_2^m / N_0, \quad \mathrm{INR}_2^m = |h_{21}^m|^2 P_1^m / N_0.$$

Consider that there is a central unit to coordinate the transmission of macro-BS and pico-BS, who has all the channel information. In the following, we will first introduce the basic ideas of the proposed multi-carrier cooperated interference cancellation scheme, and then develop the transmission schemes for group B and group C subcarriers in detail.

B. Basic Ideas

To improve the sum-rate of the multi-carrier interference channel, the basic idea is to introduce cooperation among subcarriers. The subcarriers are categorized into three groups. In group A, conventional transmission scheme is used, i.e., each subcarrier is a separated coding system and the decoding does not rely on any information from other subcarriers. In group B, each transmitter transmits in full data rate as if there is no interference, but actually the received signals at both receivers have been contaminated. In group C, only macro-BS transmits, i.e., broadcasts, the redundancy information which has been transmitted through group B subcarriers and has caused interference to pico-user.

The broadcasted information in group C will be received at both receivers without interference. For pico-user, this information will be used to do interference cancellation; and for macro-user, this information will be used to recover the contaminated desired signal. Although no new information is transmitted through group C subcarriers, they contribute to the sum-rate by helping the interference-free transmission in group B subcarriers. As long as the contribution is greater than the loss, the network throughput can be improved. Fortunately, it is easy to find this kind of interference scenarios in heterogeneous networks.

With the help of group C subcarriers, it is interference-free transmission for group B subcarriers and the achievable rate on the m-th subcarrier can be expressed as,

$$r_{\mathrm{B}}^m = \log_2(1 + \mathrm{SNR}_1^m) + \log_2(1 + \mathrm{SNR}_2^m). \quad (3)$$

In group A, there are many choices for transmission schemes to handle the interference, such as the conventional interference cancellation scheme, or orthogonal transmissions. Assuming that the achieved sum-rate of the m-th subcarrier

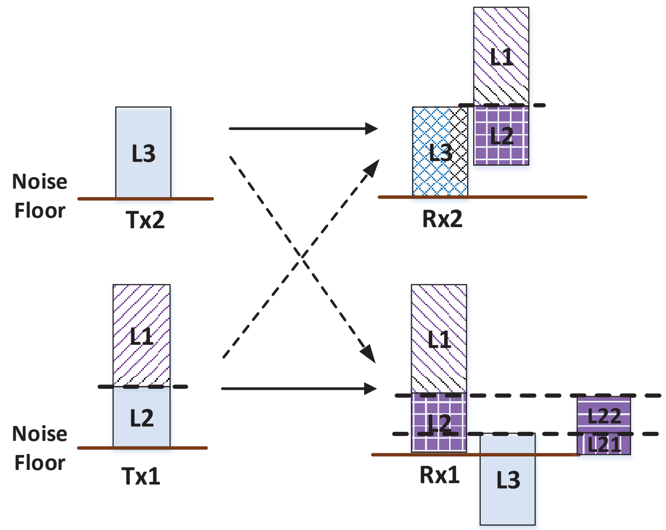

Fig. 1. Layered transmission on a subcarrier in group B.

in group A is r_{A}^m, the network throughput of two users can be expressed as

$$R = \sum_{m \in A} r_{\mathrm{A}}^m + \sum_{m \in B} r_{\mathrm{B}}^m. \quad (4)$$

C. Transmission Scheme for Group B Subcarriers

To have better cooperation performance, we choose subcarriers with specific mixed interference conditions as group B. On these subcarriers, macro-BS causes strong interference to pico-user while pico-BS causes relatively low interference to macro-user. Due to the variety of small-scale fading, such a scenario will emerge at certain probability regardless of the location of pico-BS and the users. However, due to the large-scale fading, when pico-BS is close to macro-BS, this kind of interference scenarios are more likely to appear.

Specifically, the conditions to choose group B subcarriers are

$$\mathrm{INR}_2^m \geq \mathrm{SNR}_2^m, \quad (5)$$

$$\log_2(1 + \mathrm{INR}_1^m) \leq \log_2(1 + \mathrm{SNR}_1^m) - \log_2\left(\frac{1 + \mathrm{INR}_2^m}{1 + \mathrm{SNR}_2^m}\right). \quad (6)$$

The physical meanings of these two conditions are illustrated in Fig. 1. Given the direct-link SNR_i^m and cross-link INR_i^m on the subcarrier m, $m \in B$, $i \in \{1, 2\}$, there is a layer partitioning pattern at each receiver. For transmitter i, the SNR_i^m of the direct-link corresponds to a bar with a height of $\log_2(1 + \mathrm{SNR}_i^m)$, which represents the data rate for the transmission. At receiver i, there are two bars representing the received signal and interference, respectively. Their relative positions depend on the corresponding relationship between SNR_i^m and INR_i^m. For the bar of transmitter j at receiver i, $i \neq j$, the upper and lower boundaries are $\log_2(1 + \mathrm{INR}_i^m)$ and $\log_2(1 + \mathrm{INR}_i^m) - \log_2(1 + \mathrm{SNR}_j^m)$, respectively.

As shown in Fig. 1, at each receiver, the boundary of one signal will divide the bar of the other signal into two layers. For example, at receiver 2, if the bar of transmitter 1 overlaps with the bar of transmitter 2, the bar of transmitter 1 will be split at the intersecting boundary position, where we call the divided two layer as L1 and L2. At receiver 1, if the bar of transmitter 2 overlaps with the bar of transmitter 1, L2 layer will be split again at the intersecting boundary position, and we call these two new layers as L21 and L22. Because of the requirement of channel conditions in (5) and (6), at receiver 2, the upper boundary of L1 layer must be higher than the upper boundary of L3 layer; and at receiver 1, the upper boundary of L3 layer must be lower than the upper boundary of L2 layer.

The data rate of different layer can be expressed as:

$$r_{\mathrm{L1}}^m = \min\left\{\log_2(1+\mathrm{SNR}_1^m), \log_2\left(\frac{1+\mathrm{INR}_2^m}{1+\mathrm{SNR}_2^m}\right)\right\}, \quad (7)$$

$$r_{\mathrm{L2}}^m = \log_2(1+\mathrm{SNR}_1^m) - r_{\mathrm{L1}}^m, \quad (8)$$

$$r_{\mathrm{L3}}^m = \log_2(1+\mathrm{SNR}_2^m), \quad (9)$$

$$r_{\mathrm{L21}}^m = \log_2(1+\mathrm{INR}_1^m), \quad (10)$$

$$r_{\mathrm{L22}}^m = r_{\mathrm{L2}}^m - r_{\mathrm{L21}}^m. \quad (11)$$

We call L2 layer as the overlap layer. It is easy to find that, if both receivers can obtain the information of this layer through a broadcast channel, the interference-free transmission in group B will be achieved.

D. Transmission Scheme for Group C Subcarriers

Group C subcarriers work as assistance to help the decoding in group B subcarriers. On group C subcarriers, transmitter 1 broadcasts the information of the overlap layer that has been transmitted in group B subcarriers. Both receiver will obtain this information and will use it to cancel the interference or to decode the desired signal in group B subcarriers.

When we put a subcarrier into group C, since it does not transmit any new information, we lose certain data rate which can be achieved by conventional separated coding schemes. But on the other hand, the group C subcarriers will contribute to the data rate improvement in group B subcarriers. In order to guarantee the increasing of network sum-rate, when we select group C subcarriers we must make sure that the improvement in group B is greater than the loss in group C.

To obtain sum-rate increasement, the group C subcarriers should meet the following two conditions:

$$\mathrm{INR}_2^m \geq \mathrm{SNR}_2^m, \quad (12)$$

$$\mathrm{INR}_2^m \geq \mathrm{SNR}_1^m. \quad (13)$$

The proof is shortly stated as follows. Because of the condition in (12), we have

$$\log_2(1+\mathrm{SNR}_1^m) + \log_2(1+\mathrm{INR}_2^m) \geq \log_2(1+\mathrm{SNR}_1^m) + \log_2(1+\mathrm{SNR}_2^m), \quad (14)$$

where the left hand side of (14) refers to the sum-rate that this subcarrier can transmit as a group C subcarrier, and the right hand side of (14) refers to the sum-rate upper bound that this subcarrier can transmit as a group A subcarrier. The upper bound is obtained when we assume that there is no interference between the two links. Thus (14) means that the transmission capability of this subcarrier is greater as a group C subcarrier than as a group A subcarrier. In other word, if we put this subcarrier into group C, the data rate improvement will be larger than the data rate loss. Meanwhile, from Fig.1 we can see that receiver 2 need more information than receiver 1, thus in order to utilize the spectrum and transmit power more efficiently, we choose subcarriers that $|h_{21}^m| > |h_{11}^m|$ as group C subcarriers. That is why condition (13) is required.

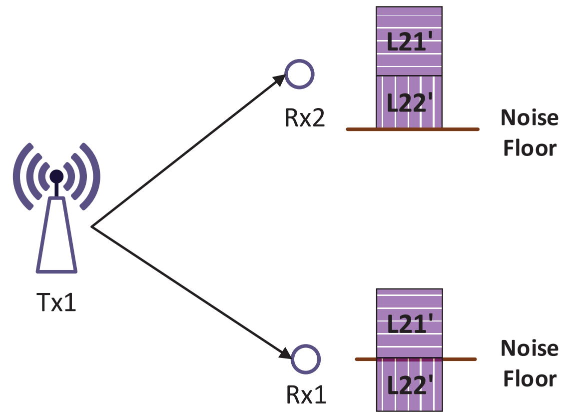

Fig. 2. Layered broadcasting on a subcarrier in group C.

The detailed transmission scheme on group C subcarriers is shown in Fig 2. The transmit signal is divided into two layers, which are called L21′ and L22′, respectively. L21′ layer involves information of L21 layer in group B subcarriers, while L22′ layer involves information of L22 layer in group B subcarriers. Moreover, in the broadcasting transmission, L21′ layer is on top of L22′ layer. Namely, we made a power level reversion as compared with the transmission in group B subcarriers. The reason is that, in group B subcarriers receiver 1 only require L21 layer to recover the desired signal while receiver 2 require both L21 and L22 layers to cancel the interference. In addition, in group C subcarriers the channel h_{21}^m is better than h_{11}^m, thus the cross-link has larger capacity than the direct-link transmission. When we arrange L21′ layer transmitting in higher power level and L22′ layer transmitting in lower power level, receiver 2 can decode both layers while receiver 1 can only decode L21′ layer. In this way, we can improve the transmission efficiency of group C subcarriers.

The transmission capability of L21′ and L22′ layers are determined by the corresponding channel conditions, i.e.,

$$r_{\mathrm{L21'}}^m = r_{\mathrm{C1}}^m = \log_2(1+\mathrm{SNR}_1^m) \quad (15)$$

$$r_{\mathrm{L22'}}^m + r_{\mathrm{L21'}}^m = r_{\mathrm{C2}}^m = \log_2(1+\mathrm{INR}_2^m) \quad (16)$$

III. Subcarrier Allocation Algorithm

Because of the frequency-selective fading, the SNRs and INRs on each subcarrier are variant. To obtain a high network throughput, we need to allocate right subcarriers to appropriate groups.

First, we calculate the data rate requirement of all subcarriers in group B, i.e.,

$$R_{\mathrm{L21}} = \sum_{m \in B} r^m_{\mathrm{L21}}, \tag{17}$$

$$R_{\mathrm{L2}} = \sum_{m \in B} r^m_{\mathrm{L2}}. \tag{18}$$

These data rates should be satisfied by the broadcasting on group C subcarriers. That is to say, when we allocate subcarriers in group B and group C, the following conditions are required,

$$\sum_{m \in C} r^m_{\mathrm{C1}} \geq \sum_{m \in B} r^m_{\mathrm{L21}}, \tag{19}$$

$$\sum_{m \in C} r^m_{\mathrm{C2}} \geq \sum_{m \in B} r^m_{\mathrm{L2}}. \tag{20}$$

The above two equations (19) and (20) indicate that group C subcarriers can offer all the information that group B subcarriers required to accomplish the interference-free transmission. However, we also need to guarantee that group C subcarriers are not wasted. Considering both aspects, we propose an optimized subcarrier allocation algorithm as follows.

1) Initialize the three groups A, B and C. Select all subcarriers that met conditions (5) and (6) as group B; select the left subcarriers that met conditions (12) and (13) as group C; and then put all other subcarriers into group A.
2) If conditions (19) and (20) are satisfied, go into step 3); otherwise, go into step 4).
3) Move a subcarrier $J = \arg\max r^J_{\mathrm{A}}$ from group C into group A and recalculate $\sum_{m \in C} r^m_{\mathrm{C1}}$ and $\sum_{m \in C} r^m_{\mathrm{C2}}$. If conditions (19) and (20) are satisfied, repeat step 3); otherwise, jump to the end.
4) Move a subcarrier $K = \arg\min(r^K_{\mathrm{B}} - r^K_{\mathrm{A}})$ from group B into group A and recalculate $\sum_{m \in B} r^m_{\mathrm{L21}}$ and $\sum_{m \in B} r^m_{\mathrm{L2}}$. If condition (19) or (20) is not satisfied, repeat step 4); otherwise, jump to the end.

IV. Simulation Results

In this section, we evaluate the performance of the proposed multi-carrier cooperated interference cancellation in heterogeneous networks, and compare the achieved network sum-rate with the joint coding scheme proposed in [7], the conventional interference cancellation, treating interference as noise and orthogonal multiplexing schemes.

The considered network configurations are as follows. The transmit power of the Macro-BS is 46 dBm, the transmit power of the Pico-BS is 30 dBm. Single antenna is considered both in the BS and in the user, and 200 subcarriers are used. The coverage of the macro-cell is 500m, where the SNR at the cell edge is 5 dB. The radius of the pico-cell is set as 60 m. The path loss models for the Macro-BS and Pico-BS are from 3GPP channel models [8], which are

$$\begin{aligned} PL_{\text{MBS-UE}} &= 15.3 + 37.6\log_{10}(D), \\ PL_{\text{PBS-UE}} &= 30.6 + 36.7\log_{10}(D), \end{aligned}$$

where D is the distance between a BS and a user, $PL_{\text{MBS-UE}}$ applies to the path loss of the macro-BS to macro-user link and macro-BS to pico-user link, and $PL_{\text{PBS-UE}}$ applies to the path loss of the pico-BS to macro-user link and pico-BS to pico-user link. To avoid near-field effect, the pico-BS, macro-user and pico-user are not allowed to be close to the macro-BS within 35 m.

To show the system performance under different interference scenarios, we fix the position of the macro-user at 250 m away from the macro-BS, and move the pico-cell from macro-cell center to macro-cell edge while keep the relative position between pico-BS and pico-user fixed. Fig. 3 shows the subcarrier allocation results of the proposed transmission scheme. We can see that when the pico-cell is relatively close to the macro-cell center, the number of group C subcarriers is much less than the number of group B subcarriers. In this case, macro-BS causes strong interference to pico-user while pico-BS only causes weak interference to macro-user. Since the cross-link from macro-BS to pico-user is strong, one subcarrier in group C can transmit information that required by several subcarriers in group B. When the pico-cell moves further to the macro-cell edge, the number of group C subcarriers is almost the same with the number of group B subcarriers, that means the cooperation efficiency reduces when the cross-link becomes weak.

Fig. 4 shows the network sum-rates of different transmission schemes. For the proposed scheme and the joint coding scheme in [7], there is cooperation among multiple subcarriers. For other transmission schemes, each subcarrier is transmitted separately. Along with the increasing distance between the pico-BS and macro-BS, the interference scenarios will change from mixed 1 to strong, to mixed 2, and to weak finally. In mixed 1 scenario, macro-BS causes strong interference while pico-BS causes weak interference; in mixed 2 scenario, pico-BS causes strong interference while macro-BS causes weak interference; in strong scenario both BSs causes strong interference, and in weak scenario both BSs causes weak interference. However, because of the small-scale fading and average of 100 times of channel realizations, there is no clear boundary between every two scenarios.

From Fig. 4 we can see that the proposed interference cancellation (IC) scheme achieves substantial sum-rate gain than other schemes in mixed 1 interference scenario, since in this scenario macro-BS broadcasting can achieve the highest efficiency to help interference cancellation. In strong interference scenario, the scheme proposed in [7] works the best, since for this scheme both BSs will transmit redundancy information to the interfered users though group C subcarriers. In practice, we can combine these two schemes so that the best performance can be obtained in both scenarios. In weak interference scenario, both kinds of multi-carrier cooperated IC schemes degrades to the conventional transmission scheme that treating interference as noise, thus they have almost the same sum-rate performance. From Fig. 3 we can also see that, in the weak interference scenario there are few group B and group C subcarriers, thus there is no cooperation gain in this

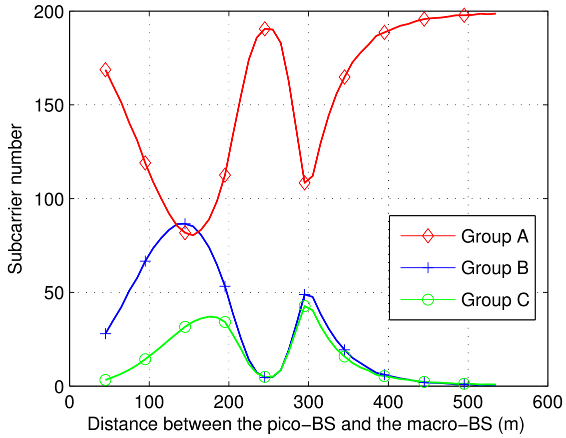

Fig. 3. Carrier allocation when the pico-BS moves from macro-cell center to macro-cell edge while the macro-user is fixed

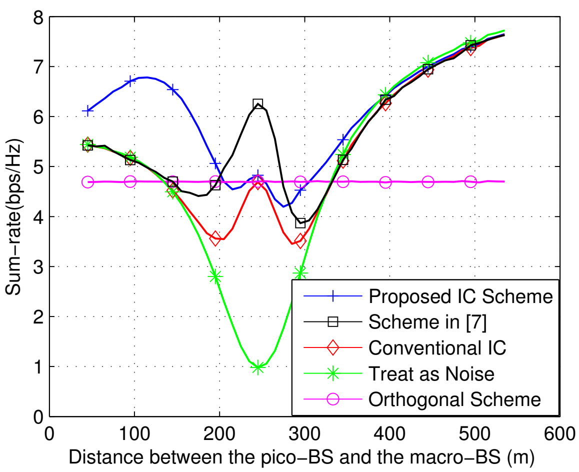

Fig. 4. Network throughput comparisons when the pico-BS moves from macro-cell center to macro-cell edge while the macro-user is fixed

case. The conventional IC scheme has a similar trend with the cooperated IC schemes, but without subcarrier cooperation it loses a lot of opportunities to improve the data rate. The sum-rate of orthogonal transmission is nearly a constant at different pico-BS and macro-BS distances, since there is no interference between two users and the SNRs are keeping constant.

V. Conclusion

We proposed a multi-carrier cooperated interference cancellation scheme in heterogeneous cellular networks. With cooperation among subcarriers, part of subcarriers can achieve interference-free transmission. To improve the transmission efficiency and thus the network sum-rate, we use a broadcasting scheme to transmit the redundancy information in group C subcarriers. The selecting criteria for different groups are studied and corresponding subcarrier allocation algorithm is developed. Simulation results show substantial performance gain over other schemes especially in mixed interference scenarios.

References

[1] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Q. S. Quek, and J. Zhang, "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 22–30, June 2011.

[2] B. Li, "An effective inter-cell interference coordination scheme for heterogeneous network," in *Proc. IEEE VTC Spring*, 2011.

[3] T. S. Han and K. Kobayashi, "A new achievable rate region for the interference channel," *IEEE Trans. Inform. Theory*, vol. 27, no. 1, pp. 49–60, Jan. 1981.

[4] R. H. Etkin, D. N. C. Tse, and H. Wang, "Gaussian interference channel capacity to within one bit," *IEEE Trans. Inform. Theory*, vol. 54, no. 12, pp. 5534–5562, Dec. 2008.

[5] V. R. Cadambe and S. A. Jafar, "Parallel Gaussian interference channels are not always separable," *IEEE Trans. Inform. Theory*, vol. 55, no. 9, pp. 3983–3990, Sep. 2009.

[6] Y. Tian, S. Lu, and C. Yang, "Macro-pico amplitude-space sharing with optimized Han-Kobayashi coding," *IEEE Trans. Commun.*, vol. 61, no. 10, pp. 4404–4415, Oct. 2013.

[7] Y. Wang, Y. Tian, C. Yang, and C. Sun, "Multi-carrier cooperated interference cancelation in heterogeneous cellular networks," in *IEEE PIMRC 2013*, pp. 154–158.

[8] 3GPP TR 36.814, "Further advancements for E-UTRA physical layer aspects (Release 9)," *3rd Generation Partnership Project*, 2010.