Joint precoding vector and modulation and coding scheme recalculation for LTE-A multi-user MIMO

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***Abstract*—Multi-user MIMO techniques were born due to the urge of high data rates and spectral efficiency in 4G systems. For scenarios with a large number of users to be served in one cell, high capacity gains can be achieved by transmitting independent data streams to different users sharing the same time-frequency resources through the use of MIMO precoding. With enough channel state information (CSI) at the transmitter, MIMO precoding allows to increase multi-user diversity gain. However, without a correct precoding vector selection, the interference between users can seriously degrade the overall network data rate. In a close-loop configuration, the base station (BS) receives from each user the preferred precoding vector and modulation and coding scheme (MCS). To achieve the highest multi-user diversity gains and avoid users' interference, the BS needs to recalculate the precoding vector and MCS for each user. The goal of this paper is to investigate the performance and complexity of state-of-the-art methods for recalculation of precoding vectors such as zero-forcing (ZF) and minimum mean square error (MMSE) for LTE-A scenarios. Additionally, we propose a low-complexity method that jointly recalculates the precoding vector and MCS with a codebook-based approach. We then evaluate our method in terms of throughput and with an LTE simulator.**

***Keywords*— LTE, MU-MIMO, feedback recalculation, ZF, MMSE**

I. INTRODUCTION

Multiple input-multiple output (MIMO) techniques are essential features in 3GPP LTE and LTE-A systems in order to achieve high data rates and high system capacity. When a large number of users needs to be served in one cell, high capacity gains can be achieved by transmitting independent data streams to different users sharing the same time-frequency resources. This is called multi-user MIMO (MU-MIMO) and it can be realized through the use of MIMO precoding. Several precoding techniques applicable to the LTE standard have been introduced and discussed in the past few years [1-7].

In a closed-loop configuration, the receiving user obtains downlink channel state information (CSI) by calculating three values that are feedbacked to the base station (BS): channel quality indicator (CQI), rank indicator (RI), and precoding matrix indicator (PMI). With this information, the BS becomes aware of the channel quality of the users and can therefore choose the proper transmit modulation and coding schemes (MCS) for each of them. On the other hand, the PMI shows the precoding vector preferred by the user according to a certain criterion, for example, mutual information. However, these CSI feedback values reported by each user do not consider the interference created to the rest of the users on the same time-frequency resources. The base station should recalculate the PMI and MCS in order to avoid user interference. If we directly apply the CSI values feedbacked by the users in a MU-MIMO transmission, the system performance can be degraded significantly due to interferences between users [7].

With the concerns above, we evaluate in this paper a joint precoding vector and MCS recalculation method which only relies on single user CSI feedback and propose some techniques to reduce its complexity. For this, we first simulate a MU-MIMO transmission from one BS with CSI feedback from different users, and then recalculate MCS with this feedback. Then we adopt Zero Forcing (ZF) or Minimum Mean Square Error (MMSE) algorithms to recalculate the precoding vectors to reduce the interference toward other simultaneously scheduled users. The simulations are based on LTE-A simulator from [8]. Additionally, we discuss about the complexity of the recalculation computation.

The paper is organized as follows. The system model is introduced in section II. The CSI feedback principles are presented in section III, and MCS recalculation methods for normal MU-MIMO, ZF MU-MIMO and MMSE MU-MIMO mode with single user feedback are presented in section IV. Practical considerations and complexity issues are discussed in section V. Simulation results are provided in section VI. Finally section VII draws some conclusions.

II. SYSTEM MODEL

We consider a MIMO-OFDM system with *M* transmit antennas at BS and *S* users each one equipped with 1 receive antenna. The input-output relation is given by

$$\mathbf{y_k} = \mathbf{H_k W_k u_k} + \mathbf{n_k} = \boldsymbol{G_k u_k} + \boldsymbol{n_k} \tag{1}$$

where $\mathbf{u_k}$ is the vector of *S* independent data symbols transmitted in parallel by *M* transmit antennas and **k** is the subcarrier index. **W** is the *MxS* precoder applied at the BS. The precoding vector feedbacked by the users is codebook-based as defined in LTE standard [9]. **y** is the vector of signals individually received by the *S* users and **n** is the Gaussian noise vector. The *SxM* matrix $\mathrm{H} = [\, h_1^T, \ldots, h_M^T \,]^T$ contains the transpose MIMO channel coefficients from the *M* antennas to the *S* users.

III. CSI FEEDBACK PRINCIPLES

The general problem of the feedback algorithm consists in choosing the precoder W_j that maximizes the mutual information on each subcarrier *k*, as given by

$$\mathrm{W_i^*} = \ arg\max_{Wi} \sum_{k=1}^{K} I_k(W_i) \tag{2}$$

where

$$I_k = \ \sum_{s=1}^{S} log_2 \,(\, 1 + SINR_k^s(W_i)) \tag{3}$$

and $SINR_k$ is the signal-to-interference-plus-noise ratio at subcarrier *k* for user *s*

$$SINR_k^s = \frac{|G_k^{ss}|^2}{\sum_{i \neq s} |G_k^{si}|^2 + \sigma^2} \tag{4}$$

and W_i is the codebook-based precoder vector defined in LTE standard [9] and σ^2 is the noise power.

For MU-MIMO we consider rank-one feedback, i.e. only one data stream is transmitted to each user. For CQI feedback, as shown in [4] [10], we calculate post-equalization SINR for each subcarrier and map the CQI value to the maximum MCS such that a block error rate (BLER) lower than 0.1 is achieved.

IV. MCS AND PRECODING RECALCULATION AT THE BASE STATION

A. *Unitary precoding*

In a closed-loop transceiver configuration, each user will feedback CSI to let the BS acquire initial information about users' channel quality and preferred precoding vector. Then the BS will decide which user to schedule on each time-frequency resource block. In a MU-MIMO transmission, more than one user can be scheduled on the same time-frequency resources, creating interference among users. For example, figure 1 shows 4 possible precoding vectors (v**)** from the precoding codebook. Each user *s* selects a precoding vector V_s on subcarrier *k* that is the closest to the Hermitian of the channel vector h_s^H with an angle of departure θ_k. e_k is the error between h_k^H and the precoding vector v_k^s. We can express

$h_s = \|h_s\|(V_s + e_s)^H = \|h_s\|\widetilde{h_s}$. Due to this error, the user selecting v_1 will create some interference on users selecting v_2.

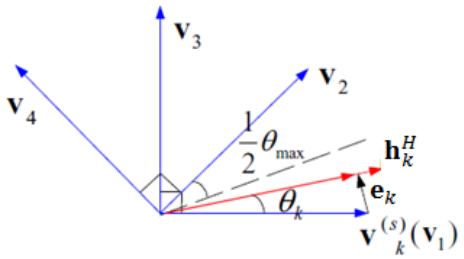

Fig. 1. Codebook-based precoding representation with 4 vectors. User with channel vector h_k^H creates interference on users selecting v_2.

For single user rank-one feedback, each user is not aware of other users' precoding or CQI selection [7], which makes the mapping of a CQI value to a MCS inaccurate. Therefore, CQI recalculation CQI_k^{re} is necessary at BS. Several recalculation schemes have been discussed in recent years. It is often recalculated as

$$CQI_s^{re} = \frac{\frac{P}{S}|h_s V_s|^2}{\frac{P}{S}\sum_{q\neq s}|h_q V_q|^2 + 1} = \frac{|1+e_s V_s|^2 CQI_s}{\frac{P}{S}\sum_{q\neq s}|\tilde{h}_q V_s|^2 CQI_k + S|1+e_s V_s|^2} \quad (5)$$

where P is the total power available at the BS and S is the number of users and $CQI_s = P|h_s V_s|^2$ as assumed by the authors in [1]. The numerator represents the signal strength, and the denominator represents the interference from other users. V_s stands for precoding vector on subcarrier k selected by user s and V_q are precoding vectors for other q scheduled users on subcarrier k.

Our contribution to reduce complexity in the calculation of equation (5) is to use the feedback CQI index (instead of $CQI_s = P|h_s V_s|^2$) that corresponds to the received SNR and θ_{max} which is known based on the codebook structure. Hence equation (5) can be simply implemented as a lower bound as

$$CQI_s^{re} \geq \frac{t^2 CQI_s}{\alpha \times CQI_s + St^2} \quad (6)$$

where $t = \cos\frac{\theta_{max}}{2}$ and the factor α serves to adjust the amount of interference. In this paper we assume it fixed as we only consider a simple 4 vector codebook.

B. *Zero forcing precoding*

With unitary precoding, the BS transmits data using the precoding vector feedbacked by the user directly without recalculation on the precoder. However, interference due to the precoding vector selection is still present. To improve performance, a pre-equalization step can be applied at transmitter side. For this, the BS calculates a set of beamforming weights in order to maximize the gain towards the user of interest and at the same time minimizing interference towards other simultaneously scheduled users. The principle and the BS operation using ZF is presented in [4]. Let us review the process here.

Step 1: Each user feedbacks its preferred PMI from the precoding codebook. In our case, users choose the PMI that maximizes throughput.

Step 2: Each user reports the CQI such that

$$CQI_s^{ZF} = \frac{\frac{P}{S}\|h_s\|^2 cos^2\theta_s}{1 + \frac{P}{S}\|h_s\|^2 sin^2\theta_s} \quad (7)$$

which is a simplification of equation (5). We can note that equation (7) needs the computation of the angle θ_s between the channel vector and the closest precoding vector, which can only be known if the user feedbacks the channel vector to the BS.

Step 3: We denote with $\widehat{H} = \left[\hat{h}_1^T, \ldots, \hat{h}_k^T\right]^T$ the transpose of the quantized channel vector which is closest to a certain precoding vector from the codebook. We then redefine the precoding vector W as

$$W_{\mathbf{ZF}} = \mathbf{F}\,\mathrm{diag}(\mathbf{p})^{1/2} = \widehat{H}^H \left(\widehat{H}\widehat{H}^H\right)^{-1} \mathrm{diag}(\mathbf{p})^{1/2} \tag{8}$$

Where **p** is a vector of transmit powers. Thanks to this pre-equalization step at the BS, the CQI does not need to be recalculated. However, to guarantee equal power allocation across the selected users [1][4], the BS estimates the CQI as

$$CQI_s^{ZF_re} = \frac{p_s}{P/S} CQI_s^{ZF} = \frac{p_s}{P/S} \times \frac{\frac{P}{S}\|f_s\|^2 \times \|h_s\|^2 \cos^2\theta_s}{1+\frac{P}{S}\times\|h_s\|^2 \sin^2\theta_s} = \frac{S(S\times\|f_s\|^2)^{-1}\, CQI_s \cos^2\theta_s}{S+\, CQI_s\, \sin^2\theta_s} \tag{9}$$

where f_s denotes the *s*th column of **F**. In order to reduce the complexity of equation (9), we propose to create a lower bound in function of the CQI index and θ_{max} such that

$$CQI_s^{ZF_re} \geq \frac{S\left(S\times\|f_s\|^2\right)^{-1}\, CQI_s \cos^2\frac{\theta_{max}}{2}}{S+\, CQI_s\, \sin^2\frac{\theta_{max}}{2}} \tag{10}$$

C. Minimum mean square error precoding

MMSE pre-equalization [2] can also be used to maximize the signal-to-interference plus noise ratio. In this case, the precoding matrix is given as

$$W_{MMSE} = \widehat{H}^H(\widehat{H}\widehat{H}^H + \sigma^2 \times I)^{-1}\, \mathrm{diag}(\mathbf{p})^{1/2} \tag{11}$$

In this case, the BS also has to estimate the CQI for equal power allocation. The calculation is the same as ZF except for the precoding matrix.

V. PRACTICAL CONSIDERATIONS AND COMPLEXITY ISSUES

In a practical scenario, hardware complexity and feedback delay need to be taken into account. For the calculation for CSI feedback, the computational effort can be prohibitively large with a large number of subcarriers and users. To reduce the complexity we suggest the use of channel averaging as shown in [5]. In the following section we use a channel averaging of 72 subcarriers i.e., K = 72. Furthermore, this allows for reduced signaling overhead as less parameters need to be feedbacked.

We also consider the complexity reduction mentioned above, where for the recalculation we use the CQI index , PMI index, and θ_{max} which is known based on the codebook structure.

VI. SIMULATION RESULTS

In this section we provide link level simulation results to evaluate the performances of the precoding schemes presented in this paper. We also evaluate the performance of CQI and precoding recalculation schemes. For our simulations we use the LTE-A simulator released by Vienna University of Technology [8]. The main simulation parameters are summarized in Table I.

TABLE I. LINK SIMULATION PARAMETERS

Parameter	**Value**
Transmission bandwidth	1.4MHz
NFFT	128
Number of subcarriers	72

Antenna configuration	2×1 (2 users) 4×1 (4 users)
Receiver	Maximal Ratio Combining
Channel model	SUI 1
Feedback granularity	whole bandwidth
Channel estimation	Ideal
Codebook	LTE
CQI feedback	4 bit

A. Unitary MU-MIMO

We first consider a 2 user MU-MIMO transmission using the CQI and PMI feedbacked by the user without any recalculation. Figure 2 shows the ideal case that no interference exists between users, which means that the 2 user channel vectors are orthogonal to each other, and so do the precoding vectors. The red line is the 2 user MU-MIMO case and the blue line is our reference single user MIMO (SU-MIMO) case using transmit diversity, i.e. both antennas from the base station transmit the same data to the user. As expected, the BS can transmit at almost double throughput in the MU-MIMO case compared to SU-MIMO when no interference is present. When the user channel vectors are not orthogonal to each other, the selection of a precoding vector from the codebook results in interference among users, with a throughput degradation as shown in figure 3 (low interference case).

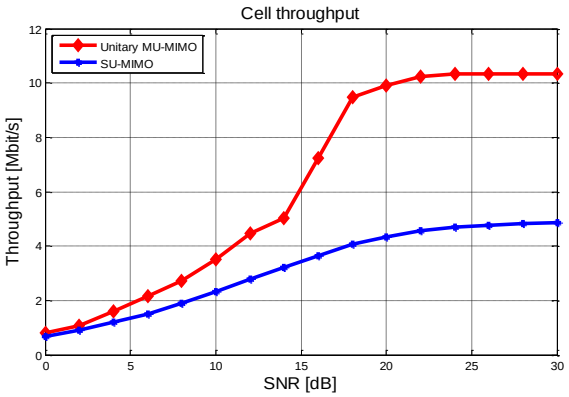

Fig. 2. MU-MIMO transmission with 2 users with orthogonal channel vectors, i.e. without interference

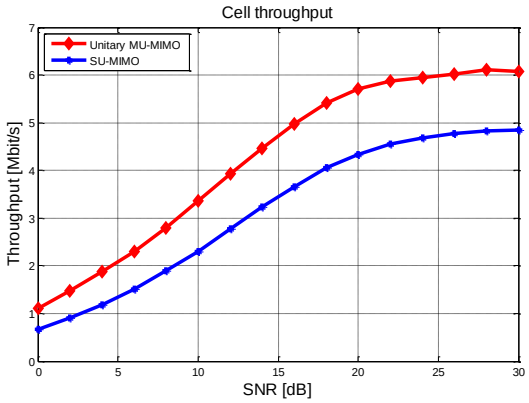

Fig. 3. MU-MIMO transmission with 2 users with random channels vectors, i.e. with low interference

In order to reduce the interference among users, CQI recalculation is needed. Here we adopt the recalculation method in section IV.A to improve performance. In figure 4 we can see that MU gain can still be achieved by CQI recalculation in medium and high interference scenarios.

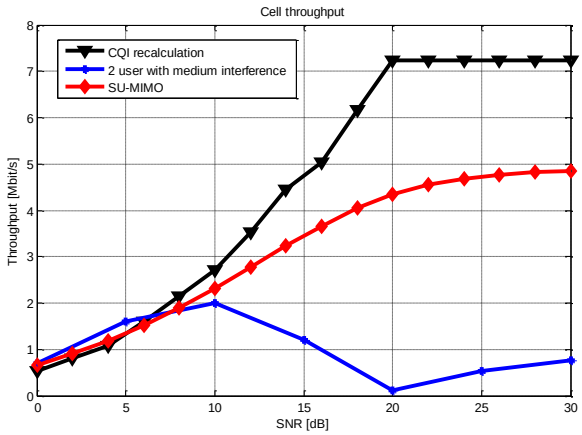

Fig. 4. MU-MIMO transmission with unitary precoding with medium interference

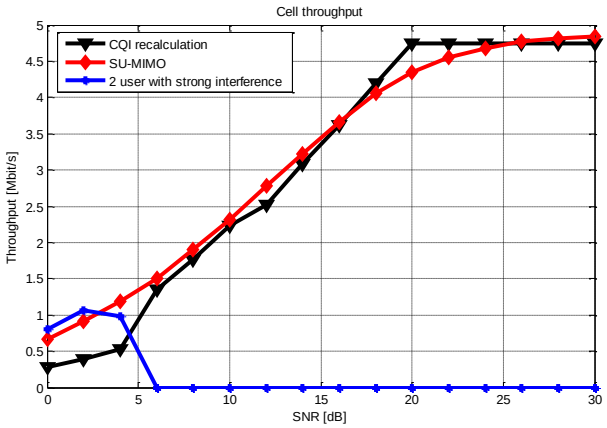

Fig. 5. MU-MIMO transmission with unitary precoding and high interference

As we increase the interference among users, the throughput degradation becomes severe as seen in figures 4 and 5. By adopting CQI recalculation we can improve performance with low and medium interference, but with high interference we can only achieve a similar throughput as SU-MIMO. Therefore, to achieve spatial diversity gain it is not practical to use unitary precoding. We turn then our attention to ZF and MMSE precoding schemes.

B. ZF MU-MIMO

In this case, the BS recalculates the precoding vector and the CQI as discussed in section IV.B. As we do not need CQI recalculation, we first evaluate the ideal case in which the BS knows exactly the users' channel vectors and then the realistic case where these channel vectors are mapped to the closest precoding vector from the codebook and feedbacked to the BS. In figure 6 we simulated the ideal case and we can observe that the throughput for the 2-user case is doubled compared to the SU case, and for the 4-user case it is almost four times.

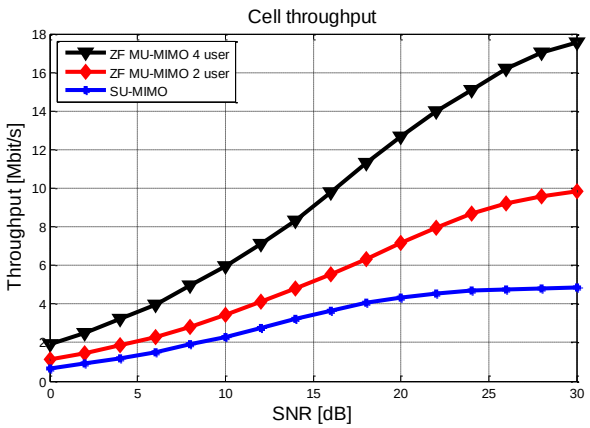

Fig. 6. Ideal channel feedback ZF MU-MIMO

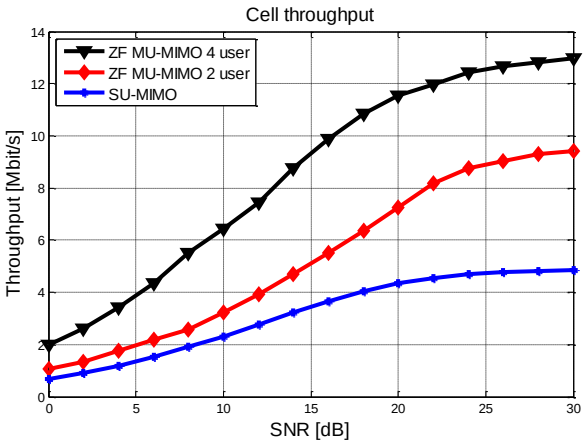

Fig. 7. Realistic channel feedback ZF MU-MIIMO

Using the precoding vectors instead of the exact channel vectors, the performance degrades as seen in Figure 7. However, in contrast to the unitary precoding, we can still achieve MU gain. The degradation is evidently larger for 4-user case since the interference increases with the number of users.

C. *MMSE MU-MIMO*

Finally we evaluate the MMSE case, and also simulated in both ideal and realistic cases as shown in figure 7 and 8, respectively. As expected, the throughput performance is similar to ZF case when the noise power is limited. However, by increasing the noise, we can see that MMSE outperforms ZF precoding scheme as shown in figure 10 and 11 for both 2 user and 4 user case. However, for MMSE the statistical noise information should be feedbacked from the user.

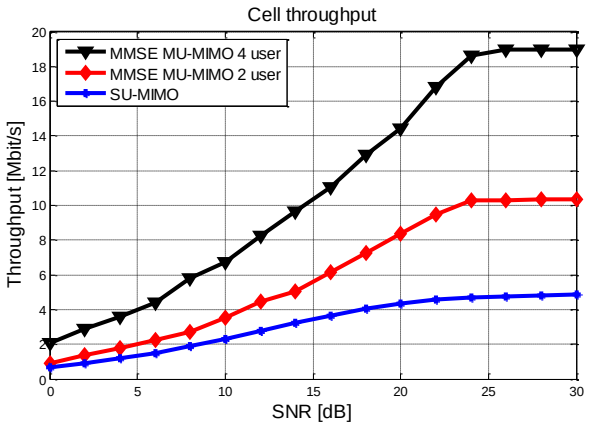

Fig. 8 Ideal channel feedback MMSE MU-MIMO

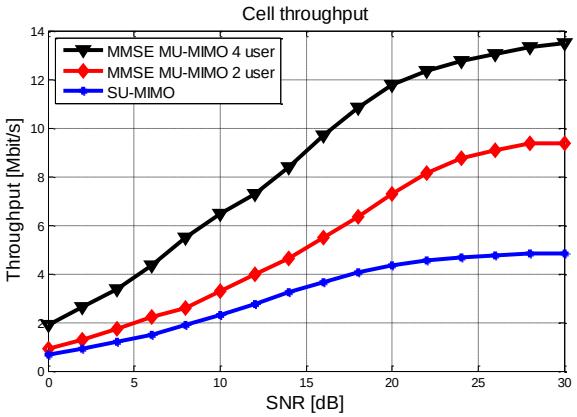

Fig. 9. Realistic channel feedback MMSE MU-MIMO

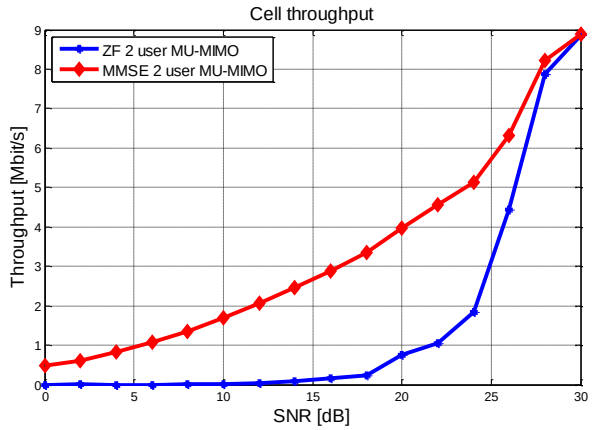

Fig. 10. Two-user throughput comparison for ZF and MMSE with high

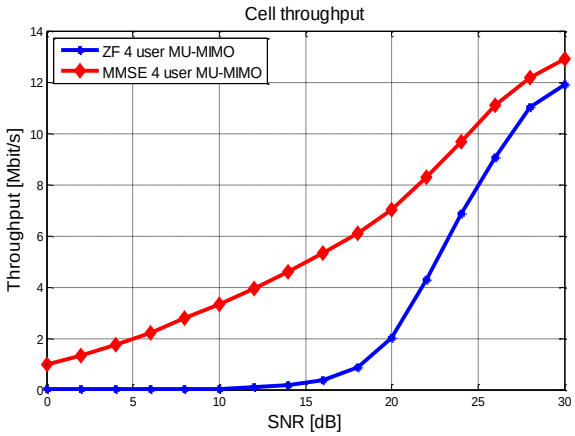

Fig. 11. Four-user throughput comparison for ZF and MMSE with high noise power

VII. CONCLUSIONS

Three different MU-MIMO precoding schemes with SU feedback are presented in this paper. In particular, CQI and precoding recalculation are derived for each case using rank-one feedback. We also discuss the practical complexity issues and suggest channel averaging and CQI recalculation lower bound to reduce complexity. Through our simulations we show that unitary MU-MIMO precoding can achieve multi user gain in low interference scenarios when CQI recalculation is used. In medium and high interference scenarios, multi user gain can still be achieved by using ZF and MMSE precoding schemes that require an extra pre-equalization step before transmission, with MMSE outperforming ZF with high levels of noise power. This is especially evident in intermediate SNR range since ZF scheme does not take noise into account, while MMSE scheme balances noise and interference.

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