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Evaluation of Link Adaptation Methods in Multi-User OFDM Systems with Imperfect Channel State Information

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Abstract: Link adaptation has shown to be a method of improving the wireless communication system throughput over quasi-static fading channels. Link adaptation, however, requires channel quality information (CQI) at the transmitter side, which is difficult to obtain accurately. Within the European WINNER project, a low complexity, near optimum, mutual information based adaptive coding and modulation (MI-ACM) link adaptation scheme was proposed. Previous work, however, only focused on evaluating this scheme with perfect CQI and without considering the potential signaling overhead introduced by this algorithm. In this paper, the performance of the MI-ACM algorithm is evaluated and compared to the link adaptation framework used in LTE. A more realistic multi-user scenario is studied by taking the channel prediction error and control signaling constraint into account. Simulation results show that the MI-ACM algorithm is useful only in a few types of scenarios, e.g., system with few users having low average SINR, low velocities with channels presenting substantial frequency selectivity.

Keywords: Link adaptation, channel prediction error, signaling overhead

1. Introduction

Link adaptation has been widely used in modern wireless broadband systems, e.g., Universal Mobile Telecommunications System (UMTS), Wireless Local Area Network (WLAN) and 3GPP Long Term Evolution (LTE), to boost the spectral efficiency. In particular, in frequency selective channels, an adaptive allocation of time and frequency resources based on users' channel quality can significantly improve the system throughput [1]. Link adaptation, however, requires certain degree of accuracy of channel quality information (CQI), namely the signal to interference and noise ratio (SINR), at the transmitter side. This is a challenge in real systems due to channel estimation errors, feedback delays, etc. Thus, link adaption performance is impeded by the imperfect CQI at the transmitter side when adapting the code rates and modulation schemes for the coming transmission slots. Channel prediction is an option to improve the accuracy of the knowledge of CQI at the transmitter side. Several different channel predictors have been studied in previous works [2]-[4]. Previous work, e.g. [5], showed that the use of channel prediction can improve the link adaptation performance.

A mutual information based adaptive coding and modulation (MI-ACM) algorithm proposed in [6], was chosen as the link adaptation candidate of the European Wireless World Initiative New Radio (WINNER) project [7]. Due to its near optimal performance and low complexity, the MI-ACM algorithm attracted considerable attention. It has been evaluated extensively within the WINNER project but most of the evaluations assumed a perfect CQI or constant CQI errors at the transmitter side [8]-[11]. This does not hold in general for user equipment (UE) having low SINR or high velocity. Reference [12] claimed that the MI-ACM algorithm outperformed the link adaptation scheme used in LTE. This work, however, did not consider the potential signaling overhead introduced by the MI-ACM algorithm.

In this paper, we evaluate the performance of the MI-ACM algorithm in a multi-user scenario with CQI values obtained by using a Kalman filter based channel predictor. With this approach, the prediction errors can be well modeled for UEs with different SINR and different velocities. In addition, we compare the performance of the MI-ACM algorithm with the link adaptation framework used in the LTE standard, including the impact of signaling overhead. Simulation results show that the advantage of the MI-ACM algorithm is limited to cases where only a small number of UEs are in the system, especially when they have low SINR, low speed in substantial frequency selective channels. On the other hand, the LTE link adaptation scheme is much more robust to channel prediction errors and in general has a better performance when taking the signaling overhead into consideration.

2. System model and problem statement

We consider the downlink of a point to multi-point system based on Orthogonal Frequency-Division Multiplexing (OFDM), as shown in Fig.1. A transmitter, which can be seen as the base station in a cellular network, is responsible for transmission, data packet processing, multi-user resource allocation and scheduling. The basic unit for resource allocation is a group of OFDM symbols and sub-carriers, denoted as resource block (RB) in the LTE standard. Perfect channel knowledge is assumed at the UE side and limited CQI is assumed at the transmitter side. A channel predictor is placed in each UE and the UEs feed back the predicted CQI to the transmitter for the next scheduling slot. The scheduler at the transmitter side determines the link adaption parameters and allocates the RBs to each of the UEs based on the CQI feedback.

This setup can be applied both in frequency division duplex (FDD) systems and time division duplex (TDD) systems. Potentially the channel predictor can be placed at the transmitter side in a low interference TDD system. The computational burden, however, will then be much higher, since the transmitter needs to track and predict each of the active links at the same time. In this paper, a TDD system is assumed for consistency with the simulation setup in [6]. The required prediction horizons for both the TDD and the FDD systems in the WINNER framework can be found in [13].

The difficulty in obtaining accurate CQI at the transmitter side can be partly alleviated by applying a channel predictor. Thus, two questions arise in this situation: How well does the MI-ACM algorithm perform in a multi-user system with imperfect CQI obtained by channel predictions? How much could we gain if we adapt both outer code rate and modulation schemes for each RB, as it is done in the MI-ACM algorithm compared to only adapting the outer code rate and use the same modulation scheme for all RBs assigned to the same UE, as is done in LTE, especially when taking the signaling overhead into consideration?

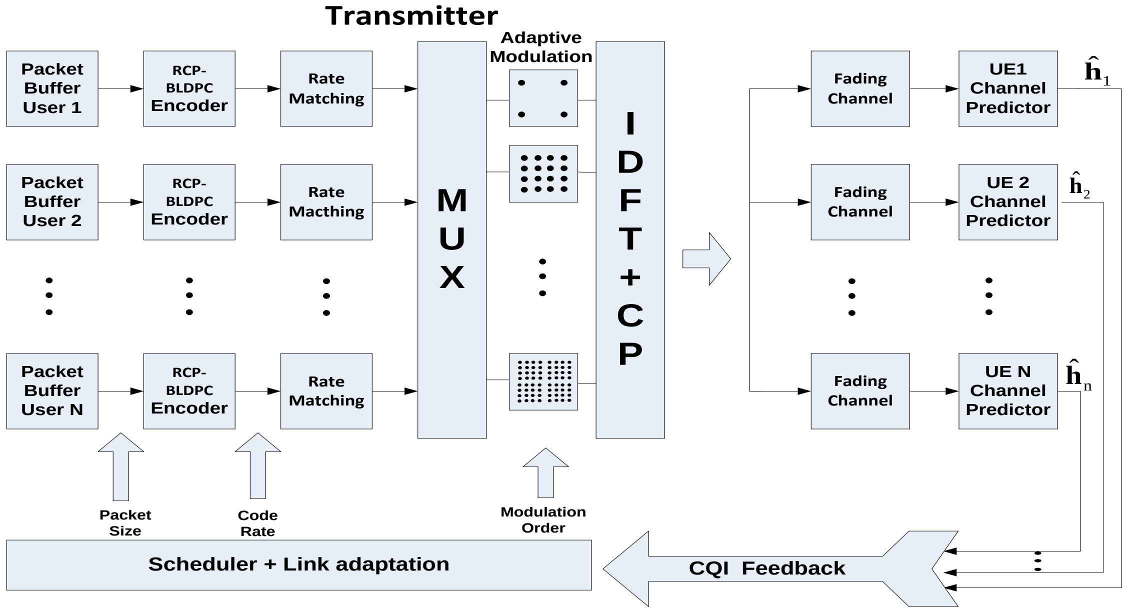

Figure 1: Block diagram of the single point to multi-point downlink OFDM based system.

3. Channel Prediction

As mentioned before, link adaptation and channel dependent multi-user scheduling require CQI at the transmitter side. The imperfect CQI can be modeled by using the Gaussian model based on [3], [14]. Studies in [9], [10] showed that this model can well reproduce the prediction errors for a complex base band channel, since both the correct variance and the probability density function of the prediction errors can be reproduced. The distribution of the predicted channel gain, the true channel gain and their conditional distribution can be found in [9].

The model is given as

$$\hat{H}_{t+L|t} = (1-\beta)H_{t+L} + w\sqrt{\beta(1-\beta)}\ ,$$

where H_{t+L} is the true channel coefficient, $\hat{H}_{t+L|t}$ is the predicted channel coefficient with a prediction horizon of L samples. w is a complex Gaussian random variable with zero mean and unit variance which is set to the same value for each RB. β is the normalized mean square error (NMSE) [9] defined as

$$\beta = E\left\{\left|\hat{H}_{t+L|t} - H_{t+L}\right|^2\right\}\Big/\sigma_h^2\ ,$$

where σ_h^2 is the mean channel power gain. The prediction accuracy depends on the velocity $v\,[m/s]$, the carrier wavelength $\lambda\,[m]$, and the prediction horizon $D = Lt_p\,[s]$ in time, where t_p is the time between channel samples. Furthermore, the prediction horizon l can be expressed in terms of the fractions of a wavelength via the relation $l = vD/\lambda$.

Instead of assuming constant β values for all users, as was done in [9], [10], a channel predictor based on a Kalman filter [4] is used to obtain the value of β in this work. Hence, the imperfect CQI can be better modeled, especially for UEs with different SINR and different velocities. The computational complexity for the Kalman algorithm mainly resides in updating the Riccati difference equations, but these updates only have to be carried out during a short initial transient phase, after which the computational complexity of the algorithm is considerably decreased.

4. The MI-ACM algorithm

The MI-ACM algorithm proposed in [6] is used as the link adaptation scheme in this work. The MI-ACM algorithm is inspired by the work in [15], which discussed the advantage of performing a per-RB based link adaptation. Simulation results from previous studies [6], [12] showed that the MI-ACM algorithm was capacity approaching and could attain comparable performance as the optimum Hughes-Hartogs algorithm but without power loading, given that the transmitter has access to the accurate CQI.

The MI-ACM algorithm is built on using a mutual information based link quality metric to maximize the throughput of a type-I HARQ system with a target code word error rate (CWER) of 0.01. It adapts both the code rate of the outer code and the modulation schemes of each RB. The difference between the MI-ACM algorithm and the link adaptation schemes used in LTE is that the LTE scheme only adapts the outer code rate but all RBs assigned to the same UE use the same modulation scheme. The original MI-ACM algorithm is based on a punctured block-circulant LDPC (RCP-BLDPC) code with a mother code rate of 1/2 and it can be easily extended to other channel coding schemes, e.g., dual binary turbo code [16].

Assuming interference free conditions, the modulation orders for each RB is based on the effective carrier to noise ratio (CNR) of the RB, given by

$$T_l = bf^{-1}\left(\frac{1}{n_f n_t}\sum_{i=1}^{n_f}\sum_{t=1}^{n_t} f\left(\frac{\left|H^l\left(i,t\right)^2\right|}{N_0}\right)\right) + \left(1-b\right)\min_{i,t}\frac{\left|H^l\left(i,t\right)^2\right|}{N_0},$$

where $0 < b \le 1$, $f\left(x\right) = \log_2\left(1+x\right)$, n_f and n_t are the number of sub-carriers in frequency and time domain of a RB, $H^l\left(i,t\right)$ is the channel coefficient of the $\left(i,t\right)$th subcarrier in the lth RB, N_0 is the noise power. The final CNR is a weighted sum of the average CNR and the CNR of the worst sub-carrier of that RB. Based on the results of [5], we choose b = 0.6. This gives a good balance of the CNR value between the average and the worst corner of each RB.

After determining the modulation order for each RB, the outer code rate is calculated as the weighted average of the local rates of each RB. Detailed thresholds of choosing local rate for each RB can be found in [6], [11] for different information block sizes.

5. Control signaling and resource allocation

Control signaling is an indispensable part of all communication systems. The control signaling includes the scheduling information, the addresses of the allocated RBs to each UE, the code rate and modulation schemes. The design of the control signaling is partly different in the LTE and the WINNER framework.

In LTE, the control signaling is unicast to each UE and distinguished by a unique scrambled CRC value. Hence, a balance between flexibilities and signaling overhead must be considered. To keep the RB addressing overhead low, while still achieving a certain degree of flexibility, three different types of RB allocation scheme are defined in LTE [17]. With these approaches, the control signaling in the LTE system can occupy up to the first 3 OFDM symbols, depending on the number of UEs, in each subframe of 12 or 14 OFDM symbols [18].

The WINNER frequency adaptive transmission framework only supports non-contiguous allocation of RBs over the entire available bandwidth. This achieves a maximum flexibility but generates extensive control signaling overhead [13]. Instead of unicasting the control information to each UE, the WINNER system groups the UEs into different control sets based on the number of active UEs, the required number of RBs needed by each UE and the UEs' channel conditions. Then, only a small common control signal is broadcast to all the UEs and UE specific control information, is multicast to each of the control sets. Studies in [13], [19] showed that the control signaling overhead in the WINNER framework can be kept below 24% while achieving full scheduling flexibility for up to 1280 UEs in a 100 MHz system bandwidth.

6. Simulation results

In order to keep consistency with the original MI-ACM algorithm in [6], the simulation setup is based on the WINNER II Microcellular TDD mode of 1:1 asymmetry [13]. This can be easily extended to the FDD case, by using the corresponding bandwidth and prediction horizon. An information block size K = 2304 is used for the MI-ACM algorithm. The LTE simulation is based on [20] by changing the turbo code to the same BLDPC code that is used in the MI-ACM algorithm in [6] in order to diminish the influence of different coding schemes. A carrier frequency of 5 GHz is assumed and the FFT bandwidth is 100 MHz within which the signal bandwidth is 89.84 MHz. The subcarrier distance is 48828.125 Hz and the useful symbol duration is 20.48 μs. Each RB contains 15 OFDM symbols and 8 subcarriers and is 0.3456 ms long in the time domain, which includes a duplex guard time of 8.4 μs and 390.62 kHz in the frequency domain.

The channel models used in this work are the WINNER II B1 Urban micro-cell NLOS channel and WINNER II B2 Bad Urban micro-cell NLOS channel [21]. The B2 channel presents more frequency selectivity than the B1 channel, since the B2 channel models the case of multipath energy from distant objects being received at some locations. A Kalman filter based channel predictor is used to obtain the NMSE values for the channel predictions. We use four pilot symbols spaced 12 OFDM symbols and 4 subcarriers apart in each RB for channel prediction. The prediction horizon is set to D = 0.6912 ms according to the WINNER II TDD system specifications. A full buffer traffic model is assumed for each UE.

For the LTE simulation, every five RBs have been grouped together, which corresponds to the type 0 resource allocation scheme in [17] with a slight modifications due to the increment of the bandwidth, and allocated to the UEs by using the classical proportional fairness (PF) scheduler. Since how to determine the code rate and modulation scheme is not a part of the LTE standard but left to be decided by equipment manufacturers, we make the following assumption: the modulation scheme is chosen as the average modulation order of the RBs that are assigned to a given UE and the code rate is chosen as the weighted sum of the highest supported code rate of each RB. For the WINNER system, we allocate all the available RBs to all the active UEs by using the same PF scheduler as in LTE. The control signaling is simulated based on [18] for LTE and [13] for the WINNER system.

Fig. 2, 3 and 4 show system throughput of the MI-ACM and the LTE link adaptation (LTE-LA) scheme using the B1 channel at average UE SINR of 5 dB, 15 dB and 25 dB. Fig. 5 and 6 show the system throughput of the MI-ACM and the LTE-LA scheme using the B2 channel at average UE SINR of 5 dB and 15 dB. Fig. 7 is the corresponding CWER of Fig. 6.

From the simulation results we can see that the link adaption scheme used in LTE has in general better performances. As shown in Fig. 4, 5 and 6, the MI-ACM algorithm is useful only in a few types of scenarios such that system with few users having low average SINR, low velocities with channels presenting substantial frequency selectivity, i.e., in the region of 1 to 5 users in Fig.4 and solid green and red in Fig. 5 and 6. This is mainly due to the fact that if the variation of the channel is not so big, the supported code rate and modulation scheme of all the assigned RBs tend to be similar. Also, as the number of UEs in the system increases, the scheduler tends to assign RBs with similar CNR values to a given UE. In these cases, the signaling overhead introduced by MI-ACM will overshadow its gain.

On the other hand, if the variation of the channel is very big, the MI-ACM can better exploit the benefit of the channel variation. The LTE-LA scheme, in this case, tends to be more conservative, due to the fact that all the RBs need to use the same modulation scheme. From Fig. 7, we can see that the PF scheduler used in the LTE-LA scheme tends to underutilize the system quite much, since the CWER is much lower than the set target, which is 0.1 in the LTE standard. Thus, small prediction errors in the CQI can actually facilitate the scheduler to be a bit more aggressive and achieve a better throughput.

UEs with high average SINR, can always choose the highest code rate and modulation order. The signaling overhead introduced by the MI-ACM schemes will lower the throughput compared to the LTE-LA scheme. Fig. 4 show the simulation results of the B1 NLOS channel with an average user SNIR = 25 dB. Similar results are obtained for the B2 NLOS channel. As the number of UEs increase, the throughput decreases due to the padding loss when less RBs are allocated to each UE. In both MI-ACM and LTE-LA, an integer number of code words need to be transmitted in one scheduling slot, and the remaining symbols will be padded with zeros. Furthermore, for more than 20 UEs in the LTE-LA case, 2 OFDM symbols in each subframe are used for signaling instead of 1, which also decreases the throughput.

A modified version of the MI-ACM is proposed in the final stage of the WINNER project [22]. It uses a subset of the modulation and coding scheme of the original MI-ACM scheme in order to better combat the imperfect CQI with a sacrifice of the system throughput. It, however, still requires the similar levels of signaling information. Thus, the potential gain of it is foreseeable limited. Another point that needs to be mentioned is that the way of determining the code rate and the modulation scheme for our LTE-LA simulation is not optimal. This can be partly seen from the simulation results, i.e., Fig. 5 and 7, since it cannot fully take advantage of the multi-user scheduling gain. The way of feeding back the CQI to the transmitter defined in the LTE framework limit the optimal decision of choosing the code rate and modulation scheme, since the UE only feeds back the preferred code and modulation scheme for each RB instead of the actual CQI. Thus, we foresee that a better-designed scheduler with a careful choice of code and modulation scheme can further improve the LTE system throughput.

7. Conclusion and future work

We presented the performance of the MI-ACM algorithm in a single point to multi-point system with CQI obtained by a Kalman filter-based channel predictor. Moreover, we compared it with the link adaptation framework used in the LTE standard. Simulation results show that the MI-ACM algorithm is useful only in a few types of scenarios, e.g., system with few users having low average SINR, low velocities with channels presenting substantial frequency selectivity. The LTE-LA scheme, however, attains a generally better performance than the MI-ACM algorithm when taking the signaling overhead into consideration. Thus how to minimize the control signaling is a very interesting topic for future studies.

Furthermore, in this work, only a full buffer traffic model is assumed for each UE. The evaluation of both schemes on a mixed traffic model scenario with different quality of service constraints could provide insights for the design a good scheduler, which could further improve the system throughput.

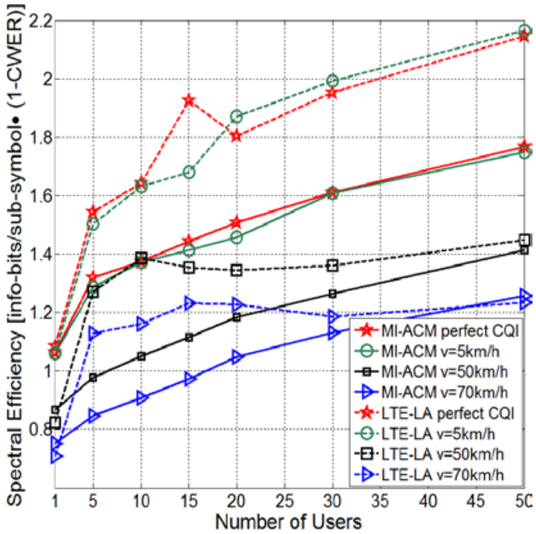

Figure 2: System Throughput, B1 NLOS, average user SINR=5dB

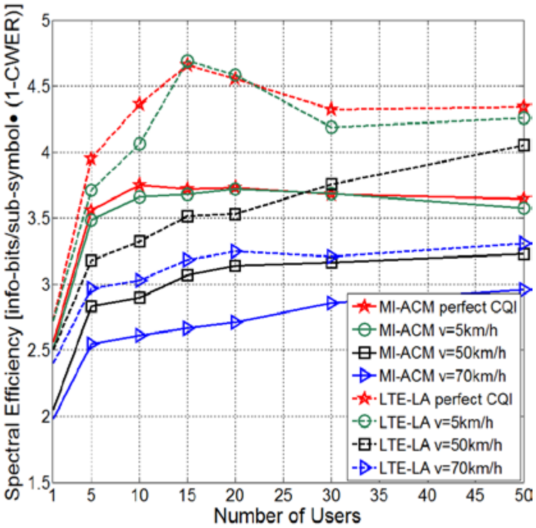

Figure 3: System Throughput, B1 NLOS, average user SINR=15dB

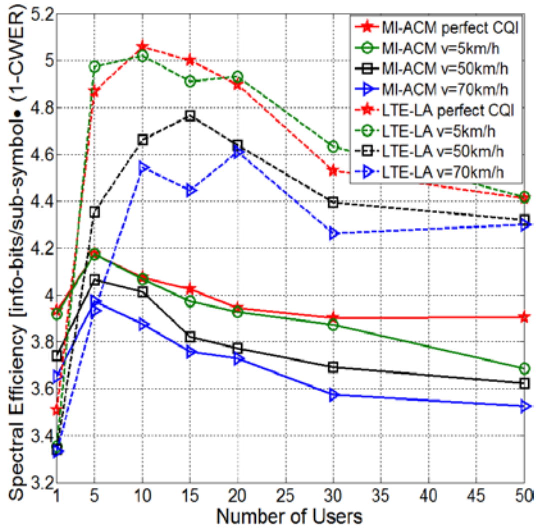

Figure 4: System Throughput, B1 NLOS, average user SINR=25dB

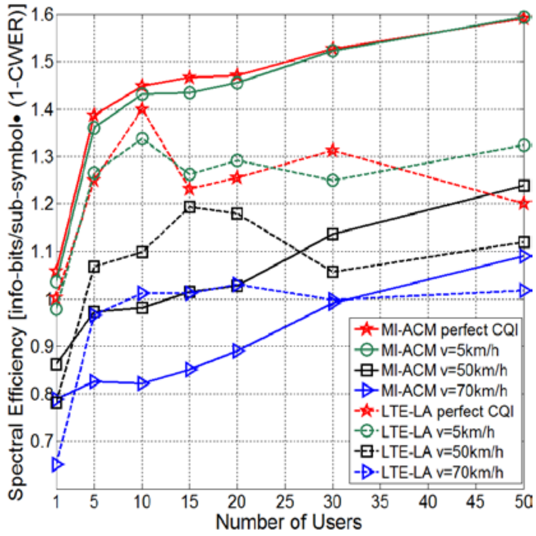

Figure 5: System Throughput, B2 NLOS, average user SINR=5dB

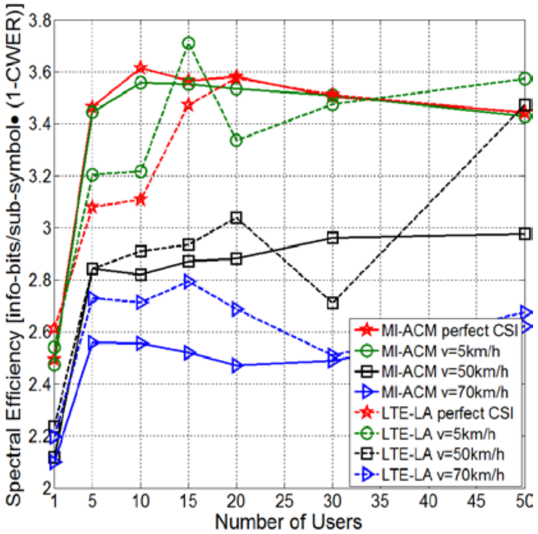

Figure 6: System Throughput, B2 NLOS, average user SINR=15dB

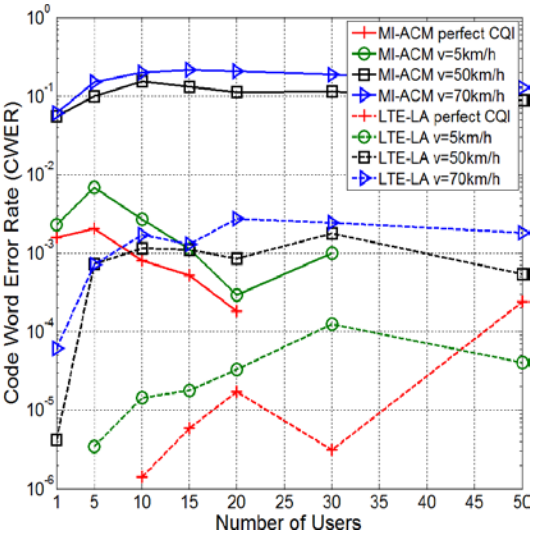

Figure 7: CWER, B2 NLOS, average user SINR=15dB

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