MCS and Sub-band Selection for Downlink Interference Coordination in LTE-A Femtocells

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Abstract— **This paper proposes a decentralized algorithm for interference coordination in LTE-A networks, based on the exchange of information (pricing) at control plane level. In our approach, every user equipment (UE) report the maximum modulation and coding scheme (MCS) that can be used within several sets (sub-bands) of available resource blocks, along with a parameter (cost) that measures the MCS degradation due to the transmission from an interfering neighbor. Through the exchange of pricing messages, the higher costs are distributed to the dominant interferers; and the selection of the MCS and operational sub-band is based on the current link conditions along with the received pricing messages. We evaluate the algorithm in a cellular area covered by a macro base station (MBS) and multiple active femtocells. We also measure the degradation due to the quantization of the exchanged cost values. The results demonstrate significantly enhanced performance as compared to the non-coordinated case.**

Keywords- LTE-A, interference coordination, pricing.

I. INTRODUCTION

The growing interest in femtocell technology is explained by its great potential in terms of network capacity increase, energy saving, and the possibility of offering new services. Unlike conventional base stations, femto access points (FAPs) are installed in households by the end–user without precise network planning. A possible approach for distributed self-organizing operation is considering femtocells as selfish agents competing for the resources available in the common spectrum band. This approach comes, however, at the expenses of injecting undue interference to the whole system, lack of fairness and efficiency loss. An alternate method is based on the exchange of limited information among FAPs in the form of interference prices, which represent the interference cost at each receiver. This avoids performance degradation and yet gracefully scales under a massive deployment.

The idea of interference pricing was originally proposed in [1]. Other works have appeared later for single and multiple antenna transmitters and receivers, i.e., single input single output (SISO), multiple input single output (MISO) and multiple input multiple output (MIMO) case; either for maximizing overall transmission rate or minimizing overall transmit power [2-6]. Typically these schemes require the exchange of pricing information among neighbor transmitters including interference sensitivity and cross channels. Also, each receiver needs to report to the serving station the signal to interference and noise ratio (SINR) measured at each carrier. With this information, the power allocation per carrier is optimized.

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Despite the promising results of pricing schemes in femtocell deployments [5,6], applying them to current LTE-A standard is not straightforward due to some specific features imposed by the standard [7]:

- There is no downlink (DL) power control.
- There is no direct report of SINR. Instead, the user equipment (UE) reports the maximum modulation and coding scheme (MCS) supported in a group of resource blocks (RB)[1].
- All RBs allocated to one user within a scheduling period use the same MCS.

This paper presents a pricing based solution for FAPs where each transmitter-receiver pair selects the MCS and operational sub-band considering not only the current point-to-point link conditions but also the impact the own transmission will have on its neighborhood. Coordination with the MBS may be included as well. Different from other pricing approaches existing in the literature, our scheme has been designed to meet most LTE-A constraints. Therefore, we consider on/off transmission at each RB (no power control) and, instead of SINR, the UE reports the MCS supported in each one of the available sub-bands.

The paper is organized as follows. Section II presents the formulation of the problem, and a distributed solution is presented in Section III. Section IV describes how the scheme of section III can be extended to MISO settings, along with other practical considerations. Finally, Section V and VI present some simulation results and conclusions, respectively.

II. PROBLEM FORMULATION

We consider a set of N_F femtocells being served by FAPs operating on a set of common resources. Non-orthogonal access is considered among the different FAPs, meaning that a given resource can be used by several (even all) femtocells. Our goal is to provide a coordinated mechanism to maximize the sum of the MCSs (and equivalently the sum of transmission rates) within the set of FAPs. This mechanism could be employed to select the DL operational frequency for wideband channels (e.g. 5MHz) or the bandwidth part for

[1] In LTE-A a RB is composed by 12 subcarriers for a duration of 1 slot of 0.5 ms (7 OFDM symbols). The frequency granularity of the channel quality information reporting, in the form of supported MCS, is determined by defining a number of sub-bands, ech comprised of several contiguous RBs [7].

broadband channels (i.e. 10MHz, 15MHz or 20MHz)[2]. Also, given the operational frequency/bandwidth part, the same mechanism could be employed to select a portion of the channel bandwidth or a portion of the previously selected bandwidth part. In the following, we will use the term sub-band to refer to a set of RBs (either if they correspond to a wideband channel, a bandwidth part of a broadband channel, or portion of a channel or bandwidth part). We will adopt the following notation:

- S : Set of available sub-bands in the system.
- S_f : Set of available sub-bands for the f-th FAP.
- MCS_u^s : MCS reported by user u for the sub-band s.
- b_f^s : Equals 1 if the f-th FAP transmits in the s-th sub-band, and 0 otherwise. Notice that $b_f^s = 0,\ \text{if}\ s \notin S_f \subset S$.
- P_f : Transmission power per RB for the f-th FAP.
- $\left|h_{u,f}^{s,r}\right|$: Channel amplitude between the user u and the f-th FAP on the s-th sub-band, r-th RB, normalized by the square root of the noise power.
- $\mathbf{i}_u^s$: Vector containing the interference measured by user u in the N RBs of sub-band s, i.e, $\mathbf{i}_u^s = [i_u^{s,1},\ldots,i_u^{s,N}]^T$

To simplify notation, we consider that each FAP is serving one user, and we use $u(f)$ to denote the user connected to the f-th FAP. The SINR measured at the r-th RB of the s-th sub-band by the user $u(f)$ is:

$$SINR_{u(f)}^{s,r} = \frac{\left|h_{u(f),f}^{s,r}\right|^2 P_f}{1+\sum_{g\neq f}^{N_F} b_g^{s,r}\left|h_{u(f),g}^{s,r}\right|^2 P_g}. \tag{1}$$

We assume the SINR remains constant within each RB, but it might vary for other RBs. Since each user must use the same MCS over a set of RBs, the MCS should consider the different SINR values measured in those RBs. Different functions are commonly employed to map the set of SINRs to a single value of MCS for a required Block Error Rate (BLER) (see Appendix for one example). Hence, for the s-th sub-band, the user u uses a mapping function, m, to compute a MCS value based on the SINR measures for the N RBs in this sub-band:

$$MCS_u^s = m\left(SINR_u^{s,1},\ldots,SINR_u^{s,N}\right). \tag{2}$$

The problem consists in selecting the optimum MCS and operating sub-band for a set of N_F transmitters, under the goal of maximizing the sum rate. It can be written as follows:

$$\mathrm{P}_0: \quad \max_{\{b_f^s\}_{f=1,\ldots,N_F}} \sum_{f=1}^{N_F}\sum_{s\in\{S\}} b_f^s MCS_{u(f)}^s \tag{3}$$

$$\text{s.t.}\quad b_f^s = \{0,1\}\ \text{for}\ s\in S_f,\ f=1,\ldots,N_F, \tag{4}$$

$$b_f^s = 0\ \text{for}\ s\notin S_f,\ f=1,\ldots,N_F, \tag{5}$$

$$\sum_{s\in S} b_f^s = 1,\ \text{for}\ f=1,\ldots,N_F. \tag{6}$$

where we have imposed that each FAP will use one sub-band (by changing the last constraint in eq. (6), other options are possible, such us allocating more than one sub-band per FAP). Notice also that, if N_F =1 (uncoordinated problem), the solution is to select the sub-band with the highest reported MCS. However, in the general case, the solution depends on the strategy followed by the rest of transmitters, which results in a highly coupled problem. In next section, a pricing based approach provides a distributed solution to problem P_0.

III. A Pricing Based Mechanism for Coordinated MCS and Sub-band Selection

Due to the cross-interference, the MCS supported by a user connected to one transmitter will change if the other stations transmit or not in the user allocated sub-band. The interference measured at the r-th RB of the s-th sub-band by user $u(f)$ is

$$i_{u(f)}^{s,r} = \sum_{\substack{g=1\\ g\neq f}}^{N_F} b_g^s P_g \left|h_{u(f),g}^{s,r}\right|^2. \tag{7}$$

The variation of the interference at two time instances is:

$$\Delta i_{u(f)}^{s,r}(t) = i_{u(f)}^{s,r}(t) - i_{u(f)}^{s,r}(t-1) = \sum_{g=1,g\neq f}^{N_F} P_g \left|h_{u(f),g}^{s,r}\right|^2 \Delta b_g^s(t), \tag{8}$$

with $$\Delta b_g^s(t) = b_g^s(t) - b_g^s(t-1). \tag{9}$$

Let us use the following linear approximation for $MCS_{u(f)}^s$, where the dependence with t has been omitted for simplicity:

$$MCS_{u(f)}^s \approx MCS_{u(f)}^s\Big|_{\mathbf{i}_f^s(t-1)} + \sum_{r=1}^{N} \frac{\partial MCS_f^s}{\partial i_{u(f)}^{s,r}}\Bigg|_{\mathbf{i}_{u(f)}^s(t-1)} \Delta i_{u(f)}^{s,r}, \tag{10}$$

and define the interference sensitivity factor $\pi_{u(f)}^{s,r}$ as follows:

$$\pi_{u(f)}^{s,r} = -\frac{\partial MCS_{u(f)}^s}{\partial i_{u(f)}^{s,r}}\Bigg|_{\mathbf{i}_{u(f)}^s(t-1)}. \tag{11}$$

Using the linear approximation in (10), the cost function in (3) can be rewritten as follows:

$$\sum_{f=1}^{N_F}\sum_{s\in\{S\}} b_f^s\left(MCS_{u(f)}^s\Big|_{\mathbf{i}_f^s(t-1)} - \sum_{r=1}^{N}\pi_{u(f)}^{s,r}\left(\sum_{\substack{g=1\\ g\neq f}}^{N_F} P_g\left|h_{u(f),g}^{s,r}\right|^2 \Delta b_g^s\right)\right). \tag{12}$$

Notice that the terms for the f-th FAP depend on the other station variables, which results in a highly complex coupled problem. In order to derive a solution, we consider that, at a given time t, each transmitter optimizes its own variables, i.e. $\{b_f^s\}$ at time instant t, assuming the variables for the rest of the transmitters are fixed. Under this assumption, the terms in the cost function (12) that depend on $\{b_f^s\}$ are:

$$\sum_{s\in\{S\}} b_f^s MCS_{u(f)}^s + \sum_{\substack{j=1\\ j\neq f}}^{N_F}\sum_{s\in\{S\}} b_j^s\left(-\sum_{r=1}^{N}\pi_{u(j)}^{s,r}\left(P_f\left|h_{u(j),f}^{s,r}\right|^2 b_f^s\right)\right), \tag{13}$$

which are equal to:

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[2]The LTE physical specification is intended to allow operation in any sytem bandwidth from 6 RBs (1.08 MHz) to 110 RBs (19.8 MHz) [7].

$$\sum_{s\in\{S\}} b_f^s \left(MCS_{u(f)}^s - \sum_{\substack{j=1\\ j\neq f}}^{N_F} b_j^s \left(\sum_{r=1}^{N} \pi_{u(j)}^{s,r} P_f \left| h_{u(j),f}^{s,r} \right|^2 \right) \right), \qquad (14)$$

and the problem P_0 can be decomposed in sub-problems, where each FAP optimizes its own variables. For the f-th FAP the sub-problem is:

$$P_f: \max_{\{b_f^s\}} \sum_{s\in\{S\}} b_f^s \left(MCS_{u(f)}^s - \sum_{\substack{g=1\\ g\neq f}}^{N_F} b_g^s \left(\sum_{r=1}^{N} \pi_{u(g)}^{s,r} P_f \left| h_{u(g),f}^{s,r} \right|^2 \right) \right) \qquad (15)$$

$$\text{s.t.} \quad b_f^s = \{0,1\} \text{ for } s\in S_f, \qquad (16)$$

$$b_f^s = 0 \text{ for } s\notin S_f, \qquad (17)$$

$$\sum_{s\in\{S\}} b_f^s = 1. \qquad (18)$$

Assuming that other transmitters' variables are given, the solution to problem P_f in (15)-(18) is to select the sub-band, not with the highest reported MCS, $MCS_{u(f)}^s$, but with the highest difference between $MCS_{u(f)}^s$ and the pricing term

$$\text{price}_f^s = \sum_{g=1,g\neq f}^{N_F} b_g^s \left(\sum_{r=1}^{N} \pi_{u(g)}^{s,r} P_f \left| h_{u(g),f}^{s,r} \right|^2 \right). \qquad (19)$$

This pricing term measures the degradation of the MCS supported by the users connected to other transmitters due to the interference generated. For the g-th transmitter, the cost due to the transmission of the f-th FAP in the s-th sub-band is:

$$\text{cost}_{g,f}^s = b_g^s \left(\sum_{r=1}^{N} \pi_{u(g)}^{s,r} P_f \left| h_{u(g),f}^{s,r} \right|^2 \right). \qquad (20)$$

Notice that $\text{cost}_{g,f}^s$ is cero if b_g^s=0, i.e. if the g-th station does not use of the s-th sub-band. Otherwise, this cost is the sum, over the N RBs of the s-th sub-band, of the product of three terms:

- The term $\pi_{u(g)}^{s,r}$, which measures the sensitivity of the MCS reported by user $u(g)$ for the s-th sub-band due to the (total) interference in the r-th RB (see eq. (11)).
- The transmission power of the f-th station, P_f.
- The cross channel gain, in the r-th RB of the s-th sub-band, between the user $u(g)$ and the f-th station.

The required standard enhancements for the UE measurement and reporting of costs, along with the exchange of these costs among transmitters, have been proposed in [8].

IV. EXTENSION TO MISO SETTINGS AND OTHER PRACTICAL CONSIDERATIONS

The described algorithm can be easily extended to the MISO case. Due to the lack of space, details are omitted, but the basic idea is the following. For different number of transmit antennas, LTE-A allows transmission with a beamformer selected from a predefined set. The UE will report a MCS per sub-band and per each one of the beamformers the serving station can use. Also, for each dominant interferer, the UE needs to report a cost value for each one of the beamformers the interferer can use. Then, a bidimensional selection in both frequency (i.e. sub-band, s) and space (i.e beamformer, w) is carried out:

$$(\hat{w},\hat{s}) = \max_{w\in\{W_f\}, s\in\{S\}} \left(MCS_{u(f)}^{w,s} - \text{price}_f^{w,s} \right) \qquad (21)$$

where $\{W_f\}$ denotes the set of available beamformers to the serving station. If the f-th FAP has only one antenna, $\{W_f\}$ contains one single element.

With the proposed approach, each transmitter updates its resource allocation strategy (MCS, sub-band and transmit beamformer) assuming other FAPs' variables are given. In practice, several approaches are possible, i.e., the transmitters may perform synchronously or asynchronously (either at random time instances or sequentially). In order to speed up convergence, we will consider that all the stations may update the resource allocation at each frame. When all the stations update their strategy simultaneously a problem that may happen is that they go back and forward on the same sub-bands. To avoid this problem, we can use some memory for the update of pricing values. For the n-th frame, the pricing values are computed as follows:

$$\text{price}_f^{w,s}(n) = \alpha \text{price}_f^{w,s}(n-1) + (1-\alpha) \sum_{\substack{g=1\\ g\neq f}}^{N_F} b_g^s \text{cost}_{g,f}^{w,s}, \qquad (22)$$

with α taking values between 0 and 1.

A last issue to consider is the need for the quantization of the costs exchanged between transmitters. As the cost for the unused sub-bands is zero (see eq. (20)), one possibility is to use for each sub-band a variable number of bits. A first bit will indicate if the cost is 0. If the cost is different from 0 (first bit equals 1), then R additional bits will follow to encode the cost value for the sub-band (and beamformer).

V. SIMULATION RESULTS

This section provides performance results of our LTE-A adapted pricing approach. We have applied the pricing policy to the deployment shown in Figure 1 with one FAP dual-strip area, with a random number of active FAPs. The number of floors in the area varies also randomly between 1 and 6.

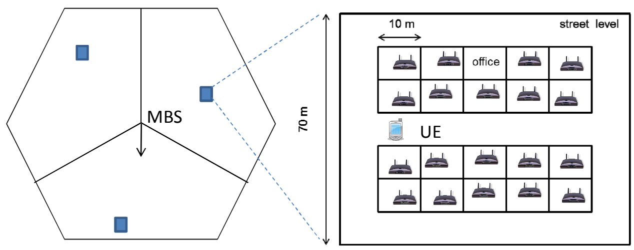

Figure 1. Deployment scenario

The MBS operates as another FAP but with a privileged role: while the FAPs have to take into account the cost values originated by the MBS, the MBS do not consider the cost values generated by the FAPs. In this way, we capture the fact that UEs connected to the MBS (MUEs) have a higher priority than the UEs connected to a FAP (FUEs). Other parameters are: channel bandwidth of 100 RBs (aprox. 20MHz) and 25RBs per sub-band (aprox. 5MHz); 1 FUE per FAP; 2 MUEs served by the MBS and placed in the FAP area (the MBS will allocate these 2 MUEs in two separate sub-bands, each one of 25 RBs). Cost values are only sent to dominant interfering FAPs. A FAP is considered a dominant interferer if the average signal strength from this FAP is between 0 and 15 dB below the signal strength from the serving station.

Figure 2 shows the time evolution of the average throughput per FAP for a scenario with 6 active FAPs. Using pricing, the total FAPs throughput gain after convergence is aprox. 2Mb/s. Figure 3 depicts the cumulative density function of the MCS supported by the FUEs in the allocated sub-band. 100 independent scenarios have been simulated with an average of 6 active FAPs per scenario. The use of pricing allows 90% of the FUEs to support the highest MCS. This value is reduced to 70% when pricing is not used.

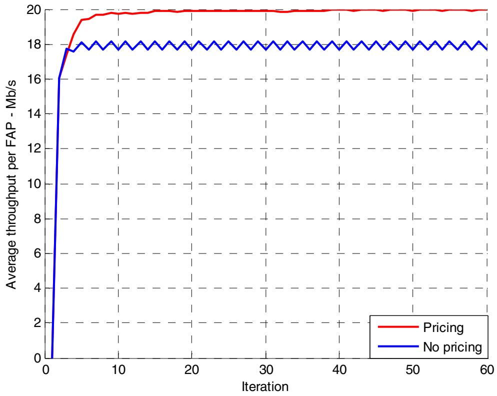

Figure 2. Time evolution of the average FAP throughput (Mb/s); 6 active FAPs.

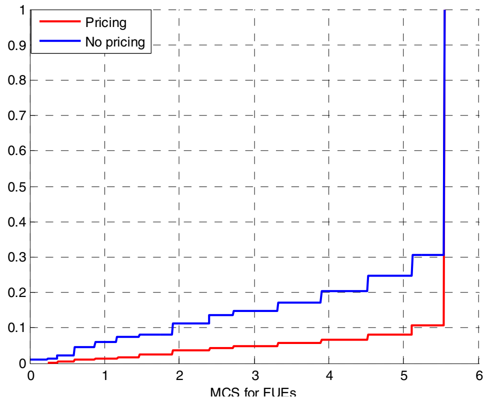

Figure 3. MCS for FUEs; 6 (average) active FAPs

The throughput achieved depends on the number of active FAPs. Figures 4 and 5 show the average FAP throughput and the MBS throughput respectively versus the average number of active FAPs. SISO mode and MISO settings are considered. For the MISO case (1 antenna per UE, 2 antennas per FAP, and 4 antennas for the MBS), LTE-A beamformer codebooks have been used. Furthermore, the effect of the quantization of the cost values has been measured. 3 bits at most are considered for each sub-band and beamformer. The first bit indicates if the cost is 0. If the cost is different from 0, 2 bits are used to encode its value. The highest level for the cost reported is 5.55, i.e. aprox. the highest MCS. For low FAPs densities, it is expected to receive cost values from a low number of neighbors and for a low number of sub-bands. It may happen that a FAP decides to use a sub-band with a worse MCS if the difference between the MCS and the received cost is greater. The computed costs are pessimistic approximations of the degradation of the MCS in a neighbor FAP, but the decision regarding the use of a sub-band is binary. It may happen that the error due to quantization compensates the pessimism of the approximation, resulting in a better decision. As the FAPs density grows, however, costs will be received for all the sub-bands from an increased number of neighbors. Therefore, despite the costs transmitted are still approximations, detailed information helps to sort the sub-bands appropriately to make a better decision for the one that deteriorates less the performance of the neighbors and therefore the total sum-rate. Both effects are observed in the next figures. For the average FAP throughput, there is a slight variation due to quantization, while for the MBS throughput a small degradation is noticeable when the density of FAPs increases.

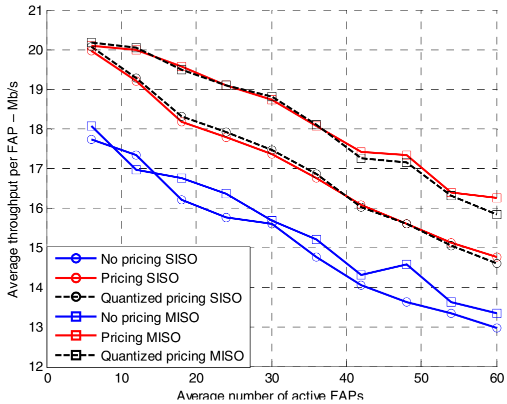

Figure 4: Average FAP throughput (Mb/s) vs. average # of FAPs

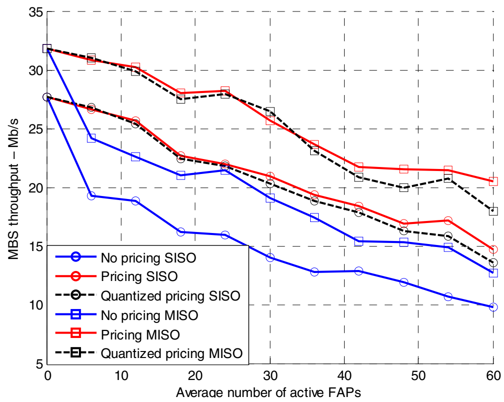

Figure 5: MBS throughput (Mb/s) vs. average # of FAPs.

Finally, Figure 6 shows the average number of dominant interfering FAPs. Notice that this number is less than 2 for FUEs (even in the case of very high FAPs densities). The value is greater for the MUEs deployed within the simulated area, due to the lower signal strength received from the MBS compared to FAPs. Each UE must report one cost value, corresponding to the operational bandwidth part, per dominant interferer (and beamfomer). Using 3 bits to quantize each cost value every frame (10 ms) results in an average traffic for pricing information exchange equals to 600 bps (SISO case) per FUE, and up to 6 kbps (SISO case) per MUE in the case of very high FAPs densities.

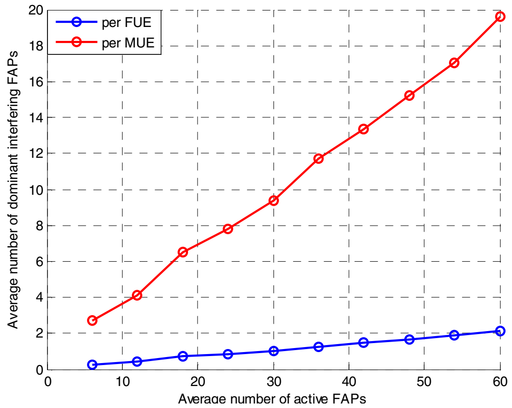

Figure 6. Average number of dominant interferer FAPs detected per FUE and MUE.

VI. CONCLUSIONS

A pricing based algorithm has been proposed for coordinated MCS and sub-band selection that meet LTE-A constraints (no power control, MCS reporting for a set of RBs, etc). Our scheme also requires that every UE reports the MCS cost of interfering transmissions, and that the serving station distributes the greater cost values to the dominant interferers. Therefore, some enhancements in future LTE releases are still needed in terms of control plane communication between BS. Our results demonstrate, however, significantly improved performance as compared to the non-coordinated case, justifying the investment.

VII. APPENDIX

As described in section II, when all the subcarriers allocated to one receiver are modulated using the same MCS, a compression function to map the instantaneous values of SINRs to one single MCS value is required. Furthermore, this function is needed to measure the interference sensitivity factors, $\pi_{u(f)}^{s,r}$, defined in eq. (11), required to compute the cost values. Despite there are different possibilities, the EESM (Exponential Effective SINR Mapping) has shown to yield an accurate estimation of the AWGN-equivalent SINR (usually referred to as 'effective SINR') for frequency selective channels, so we used this metric for the simulations. The EESM method estimates the effective SINR using the following formula:

$$SINR_{eff} = EESM(\gamma, \beta) = -\beta \ln\left(\frac{1}{M}\sum_{i=1}^{M} e^{-\frac{\lambda_i}{\beta}}\right) \qquad (23)$$

where the λ_i's are the per sub-carrier SINR values, and β is the parameter to be determined for each MCS level. This value is used to match the actual BLER and the predicted BLER from the effective SINR in the AWGN channel. For the simulation results we have considered the MCSs available in LTE-A (15 values ranging from 0.1523 to 5.5547), along with the effective SINR and β values provided in [9], obtained through extensive simulations using the LTE codes. For each MCS value, the effective SINR is the effective SINR required for a BLER less than 10% when using the MCS value. As shown in figure 7, the relationship between the MCS and the required effective SINR (red points) can be approximated by the following empirical SINR-to-MCS mapping function (solid blue line), with k=1.2213:

$$MCS\left(SINR_{eff}\right) \cong k \cdot \ln\left(1 + SINR_{eff}\right) \qquad (24)$$

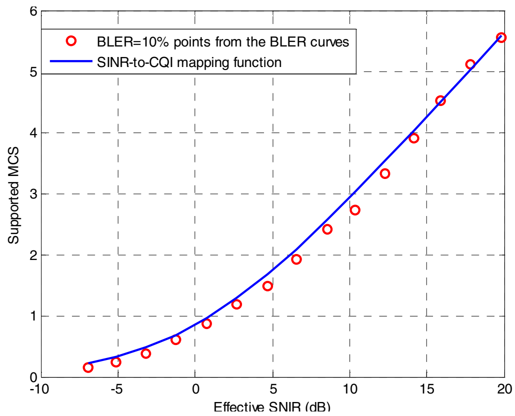

Figure 7. MCS mapping.

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