

Enhancing Data Rate in Cellular Multiple-Input-Multiple-Output Systems via Switched Micro-Macro Diversity

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Abstract—With the exponential growth of cellular users, a new generation of cellular networks is needed to enhance the required peak data rates. The co-channel interference between neighboring base stations inhibits peak data rate increase. To overcome this interference, multi-cell cooperation known as coordinated multipoint transmission is proposed. Such a solution makes use of multiple-input-multiple-output (MIMO) systems under two different structures: Micro- and macro-diversity. In this paper, we study the capacity and bit error rate in cellular networks using MIMO technology. We analyse both micro- and macro-diversity schemes and develop a hybrid model that switches between macro- and microdiversity in the case of hard handoff based on a cut-off range of signal-to-noise ratio values. We conclude that our hybrid switched micro-macro MIMO system outperforms classical MIMO systems at the cost of increased hardware and software complexity.

I. INTRODUCTION

W

ITH the evolution of mobile telecommunication technology, MIMO systems are being employed in cellular systems as a solution to the high demand for capacity in cellular networks in order to combat fading noise and improve the performance of these systems. MIMO systems are used in modern wireless standards, including IEEE 802.11n, 3GPP LTE, mobile WiMAX systems and mesh networks (e.g. Muni-wireless). LTE-advanced also aims to use 8x8 MIMO driven by 128-QAM modulation and promises to deliver 1 Gbits/s at fixed speeds and 100 Mbits/s to mobile users [1].

MIMO technology has many advantages: Large data rate, large spectral efficiency, large number of users, improvement in coverage and reliability, better interference suppression, better quality of service (QoS), low bit error rate (BER), and low transmission power. On the other hand, MIMO systems suffer from a number of disadvantages such

as software and hardware complexity caused by computationally intensive signal processing algorithms and the deployment of many antennas. MIMO systems also suffer from radio frequency (RF) interference and antenna correlation. In addition, the limited battery lifetime of mobile devices [1] and the classical thermal problems associated with the operation of

telecommunication equipment in general cause high power consumption in MIMO systems [2].

Technically, MIMO systems are characterized by spatial multiplexing and spatial diversity at the base station (BS) level where multiple signal paths of the transmitted information signal are combined at the receiving antennas. This is referred to as micro-diversity MIMO. To further improve the performance of cellular networks, macro-diversity MIMO is also used as a combination of cooperative multipoint (CoMP) transmitters [1]-[3].

II. MACRO- AND MICRO-DIVERSITY MIMO SYSTEMS

A. Macro-Diversity MIMO

When the BS and the mobile station are widely separated (each in a different cell), the system is called multi-cell MIMO cooperation or cooperative MIMO or macro-diversity MIMO system. In this case, the BS has multiple antennas and can serve a single user or multiple users. Multi-cell cooperation MIMO works when several BSs located in different cells are combined to send or receive multiple data streams from multiple users. This combination is called BS cooperation not only to share data but also to share control signals and user channel state information. In this scheme, the antennas are dispatched [2].

The cooperative MIMO scheme has a lot more advantages than disadvantages. In general, MIMO systems suffer from cochannel interference (CCI) caused by sharing common system resources and frequency reuse among adjacent cells. CCI can significantly reduce data rates and cause outages in cellular system. To solve this problem, the BSs in different cells coordinate with each other the transmission of signals to improve signal-to-interference-noise ratio (SINR) and throughput. By using distributed antennas, cooperative MIMO systems improve coverage, cell edge throughput and capacity by decorrelating the MIMO sub-channels. In addition to cancelling the inter-cell interference, the cooperative BS scheme also decreases the BER. The disadvantages of macroMIMO include an increase of system complexity and the large signaling overhead required for supporting device cooperation. For these reasons, macro-diversity MIMO employment is on the rise. One application is 3GPP LTE coordinated



multipoint transmission/reception (CoMP), where it is possible to send the same data to many mobiles in adjacent cells [2].

Fig. 1 depicts a macro-MIMO system where CoMP transmissions are combined at the BS sub-system [3].

where ρ is the ratio between the transmitted power and noise power and Q the signal covariance matrix. The capacity grows linearly with the number of antennas without using additional transmission power or spectral bandwidth. In the case where the channel state information (CSI) is not known, the transmitter selects ρ to maximize the channel capacity under worst-case statistics. In that case, the capacity becomes [2]

$$\log \det \left(I + \rho Q \right) \quad (3)$$

Chae et al. analyses a BS cooperative network with coordinated beamforming (N-CBF) systems [1]. The study consists of three BS and three MS in each cell. Each MS has one antenna at the transmitter and each BS has more than one antenna. The MS and BS cooperate perfectly with each other for transmit processing. This system can be considered as multi-user MIMO that have equal power allocation supporting the three studied users. Three contributions were done in the work of Chae et al [1]: Linear network coordinated beamforming, nonlinear network coordinated beamforming, and the role of the receiver antennas. The linear concept is divided into two: Full broadcast channel and clustered broadcast channel. The clustered broadcast channel, with a low complexity non iterative N -CBF algorithm has two of three users receiving the same data streams. Therefore, the BSs do not need to reduce the inter-user interference between these two users, which implies that each user with same data stream can use the same signal sent to the other user in order to increase the SNR. A generalized linear N -CBF algorithm is used for full broadcast channel (where each user receives its own independent data). The linear N -CBF algorithms are compared to the sum capacity (supports two users even if the BS has more than two antennas at the transmitter). What distinguishes the linear N -CBF from the nonlinear N -CBF is the improvement in BER performance at the expense of higher complexity for the nonlinear N -CBF algorithm in which each user can use any number of receiver antennas (this use is called dimensionality constraint). Two antenna selectionbased and equal gain combining algorithms are proposed for performance comparison. The proposed system needs to have the smallest largest Eigenvalue of the inverse of the effective matched channel matrix and the largest Frobenius channel norm of the effective channel. The impact of receiver antennas is also studied to show that the BER gap discussed before decreases as the number of receiver antennas increases. It is noted in the study that although each user can have any number of data stream, Chae et al. [1] only discuss one data stream. The linear N -CBF method aims at assuring that the received signal is interference-free and assigns this task to the BS.

where \mathbf{n} is the noise vector and \mathbf{H} is the channel matrix consisting of the transmitted information streams [3].

The information capacity is a fundamental measure which quantifies the maximum amount of information transferable across a channel reliably. When the channel state information is known for the BS and mobile user, the ergodic channel capacity of the MIMO systems is [2]

$$\max_{\mathbf{P}} \log \det \left(I + \mathbf{H} \mathbf{P} \mathbf{H}^H \right) \quad (2)$$

In the mentioned study, it is assumed that the channel (of size 3 and complex entries) is flat fading and realized with orthogonal frequency division multiplexing (OFDM). In the case of clustered broadcast channel, the received symbol at the user can be expressed as

$$y_k = \sqrt{p_k} x_k + \sum_{i \neq k} \sqrt{p_i} x_i + n_k, \quad (4)$$

where $\sqrt{p_k} x_k$ is the desired signal and $\sum_{i \neq k} \sqrt{p_i} x_i$ is the interference, p_k is the transmitted power for the symbol with x_k , P is the total transmit power at the BS, x_k is the transmit symbol and n_k is the AWGN vector with variance σ^2 per entry observed at the user, w_k is the unit-norm transmit beamforming vector, and

v_k is the unit-norm receive combining vector. When $w_k^H v_k = 1$, the signal received at each user after combining is interference-free.

The received symbol at each user can be expressed as

$$y_k = \sum_{i=1}^K w_i^H v_k x_i + n_k, \quad (5)$$

$$y_k = \sum_{i=1}^K w_i^H v_k x_i + n_k, \quad (6)$$

$$y_k = \sum_{i=1}^K w_i^H v_k x_i + n_k, \quad (7)$$

in (5)-(7) is the total transmitted power with the assumption of equal power allocation at each symbol (P/K for and K).

The received SINR for each user is given by

$$\text{SINR}_k = \frac{|w_k^H v_k x_k|^2}{\sum_{i \neq k} |w_i^H v_k x_i|^2 + \sigma^2}, \quad (8)$$

$$\text{SINR}_k = \frac{P}{3\sigma^2} |w_k^H v_k|^2, \quad (9)$$

$$\text{SINR}_k = \frac{P}{3\sigma^2} |w_k^H v_k|^2, \quad (10)$$

For full broadcast channel, the received symbol at each user

$$y_k = \sum_{i=1}^K w_i^H v_k x_i + n_k, \quad (11)$$

$$y_k = \sum_{i=1}^K w_i^H v_k x_i + n_k, \quad (12)$$

$$y_k = \sum_{i=1}^K w_i^H v_k x_i + n_k, \quad (13)$$

The received SINR for each user is given by

$$\text{SINR}_k = \frac{P}{3\sigma^2} |w_k^H v_k|^2, \quad k = 1, 2, 3. \quad (14)$$

In the non-linear network coordinated beamforming, the BS removes the inter-user interference using a precoder (a matrix inversion of H , being the effective channel matrix). The transmitted symbol is given by

$$x = H^{-1} y, \quad (15)$$

where H is the effective channel matrix. The received signal at user is given by

$$y_k = w_k^H H x + n_k, \quad (16)$$

The received SINR for the user is given by

$$\text{SINR}_k = \frac{|w_k^H H x_k|^2}{\sum_{i \neq k} |w_i^H H x_i|^2 + \sigma^2}, \quad (17)$$

The largest eigenvalue of $H^H H$ is given by

$$\lambda_{\max}(H^H H) = \Lambda, \quad (18)$$

The sum rate is expressed as

$$R = \sum_{k=1}^K \log_2(1 + \text{SINR}_k) \text{bps/Hz}. \quad (19)$$

In another study, Zhang proposed a base transceiver station (BTS) coordination strategy with clustered linear precoding for the downlink of a cellular multi-user MIMO system [2]. This coordination strategy decreases the interference and provides a greater sum rate gain to increase the available spatial degrees of freedom (minimum number of transmitter and receiver antennas). Full intra-cluster coordination and limited inter-cluster coordination are considered. Precoding across BTSs in the same cluster gives the intra-cluster coordination. The inter-cluster coordination or intercell scheduling is used to pre-cancel interference for the users at the edge of neighboring clusters. The precoding technique used in this work is the block diagonalization that allows for each user to have an interference free channel and helps to increase the sum rate of the system. It is noted in this work that cell planning is not needed since the universal frequency reuse is applied. To define the inter-cluster coordination area, a tradeoff is done between sum rate and fairness.

The BTSs and mobile users in this work are considered to have multiple antennas. In order to do the coordination strategy, three assumptions were made: (1) The BTSs know everything about the users located in the same cluster and at the edges, (2) The BTSs in the same cluster can fully share CSI and user data and BTSs in different clusters can also exchange traffic information, and (3) BTSs in the same cluster are synchronized in time and phase and any propagation delays from BTSs to mobile users are recovered. BTSs within a cluster serve interior users and neighboring clusters coordinate with each other to serve edge users.

The selection of a cluster (named *home cluster*) by an edge user is based on the channel state, and the neighboring clusters (act as *helpers*) are used for data transmission, while the other clusters are named *interferer clusters*. To serve the edge users, the number of users within a cluster must be reduced, yielding a tradeoff between reducing interference for edge users and maximizing the whole throughput. While serving this edge user, neighboring clusters have to reduce the number of degrees of freedom for their own users in order to give it for the edge user in the other cluster. The inter-cluster coordination deals with two important parameters: coordination distance and cluster size. The coordination distance helps with the grouping of the users in the clusters between interior users and edge users. Interior users are served with intra-cluster coordination (multi-cell BD). To classify if the user is cluster interior user or cluster edge user, the coordination distance (distance between interior and edge user) is studied. The user is a cluster edge user if the distance of the user to the cluster edge is no larger than .

In yet another study, Heath considers an interference aware link adaptation strategy that requires limited coordination between BS [3]. The research studies two interfering cells and two possible spatial transmission modes which are spatial multiplexing and statistical beamforming. In spatial multiplexing, the user demultiplexes a symbol of data stream across all the transmit antennas to achieve higher data rates. The interfering signals and the desired signal are assumed to be Gaussian. The mutual information determines the value of adapting to different interference scenarios. There are several steps that allow us to determine the interference-aware link adaptation. Mobile users estimate their sensitivity to interference and acknowledge it to its BS. The users in other cells know the spatial mode used by the interferer when the BS exchange spatial transmission plans and inform each other about their transmission schedule. Each user knows the spatial mode being used by any interfering BS because the BS broadcast an interference mode allocation summary vector to all mobile users. Each mobile user estimates its sensitivity to different kinds of spatial interference and its effective rate. Thus the

sensitivity to interference can significantly impact the achieved rate. This proposed approach gives SNR improvements with a single interferer, and it is proven that this approach also works with multiple number of interferers.

Also in another study [4], Shim proposes an enhancement to block diagonalization that mitigates the effect of the other-cell interference (OCI) and maximizes the system capacity. By using the OCI plus noise covariance matrix at the transmitter, and in the presence of OCI for a given receiver structure, the proposed method is realized. One assumption is made: The transmitter has full CSI for all users in the cell and knows the interference plus noise covariance matrix for each in-cell user (estimated at each user). To verify the performance of this technique, an analysis of the asymptotic sum capacity (maximum sum rate per antenna in the limit of a large number of antennas) must be done. The asymptotic sum capacity technique is achieved by assuming two cases: (1) no interference, and (2) OCI. The asymptotic sum capacity technique is the maximum sum rate/antenna in the limit of a large number of antennas. The system model is assumed to have users, antennas for the BS, receiver antennas for the t th user, flat fading channel, and orthogonal frequency division multiplexing (OFDM) modulation. Using OCI plus noise covariance matrix at the transmitter, the capacity is maximized and the effect of OCI is reduced in the system. In case of interference-heavy environment, the interfering power at each user can be considered as a white noise and the sum rate becomes a function of each user's SINR. In the case where the SINR is high, the loss of capacity due to OCI is calculated by the sum of the single-user MIMO capacity at each user with interference-noise ratio (INR) instead of SINR. The sum rate of MIMO-BD using interference plus noise covariance matrix is limited to the amount of INR even at only high SINR. But the MIMO-BD sum rate with OCI when the SINR is low is determined by the sum rate of a noise-limited MIMO-BD with reduced degrees of freedom. The latter corresponds to the case where the number of interferers is less than the number of receiver antennas.

In an important study [5], it was established that in the case of two transmitters located at the same distance, when one of them starts to come closer to two receivers (BS), the system capacity decreases [5]. The SNR saturates when the distance of the transmitter is not large, which means near the two receivers. The received power increases, but the introduced noise also increases because they are proportional.

This causes a decrease in the system ergodic capacity.

In a recent study [6], the ergodic capacity of macrodiversity in flat Rayleigh fading channel was studied with no CSI at the transmitters. The ergodic sum capacity is expressed as

$$\log \quad \text{---} \quad , \quad (20)$$

where γ is the SNR of the system. At $\gamma = 10$ dB, the ergodic capacity is approximately 4 bits/s/Hz when the network has 3 users and approximately 5 bits/s/Hz when the network has 6 users and 6 antennas.

The application of multi-user detection (MUD) that can mitigate the CCI is studied by Sun and Zhang [7]. The proposed solution was BS coordination, where the BSs get the CSI either by uplink channel estimation or feedback channel. The BSs are connected by high-speed wired backbones to guarantee the reliability of the information. Despite strong interference environment, the mobile users can communicate with the BS in adjacent cells. The interference is transformed into constructive signals by the BS coordination which gives the system a huge performance gain. The BS coordinated MUD schemes studied in this work are ZF COMP, MMSE COMP, ZF-SIC COMP, and MMSE-SIC COMP. These schemes were proven to significantly decrease the BER, improve the performance of the system, and mitigate the CCI. The schemes were compared in multi-cell environment and single-cell with and without interference. The Bell Labs Space-Time architecture is the spatial multiplexing technique used to improve the spectral efficiency of the system. Successive interference cancellation are done and combined with MMSE and ZF. Simulations of BER vs. SNR were done for 1x1 MIMO and 4x4 MIMO in interference environment and interference free environment. The results showed that the single cell processing failed to detect the required signals, and that both ZF and ZF-SIC have a constant BER throughout for different values of SNR. Coordination with other cells gave an impressive result for ZF COMP and ZF-SIC COMP. MMSE-SIC COMP gave the lowest BER among all other schemes.

The capacity of the MIMO system was studied by Choi and Andrews from the perspective of intercell scheduling in multiantenna selection [8]. The DPC multicell is very useful for performance bound but demands a high amount of information exchange. To reduce inter-cell interference, inter-scheduling was proposed, where neighboring BSs schedule their transmission either dynamically or based on a certain sequence. The multiuser diversity gain grows by a factor of $\log_2 2$, and when the BSs cooperate, the growth factor increases to $2\log_2 2$, taking into account the shadow fading and geometry of the mobile. It was concluded in that study that inter-cell scheduling has higher capacity than frequency reuse, with a capacity value of 1 bits/Hz for 2x2 MIMO and 2 bits/Hz for 4x4 MIMO. That is, inter-cell scheduling gives an extra 1 bit/Hz than frequency reuse.

IV. A HYBRID SWITCHED MICRO-MACRO MIMO SCHEME

A. Comparison between Macro- and Micro-MIMO

We first conduct a number of simulations using MATLAB to analyze the capacity of a MIMO system in general versus the SNR in a Rayleigh fading channel for a different number of transmitter and receiver antennas. Fig. 3 illustrates the capacity vs. SNR for 2, 3, and 4, and compares it to the Shannon capacity. We notice that the digital bandwidth efficiency (in bits/Hz) increases with the number of antennas and exceeds the Shannon capacity.

Fig. 3 Capacity vs. SNR for different number of antennas

Next, we conduct simulations to compare the capacity and BER of micro-diversity and macro-diversity MIMO in the case of soft handoff. Assuming 2x3 MIMO, Rayleigh fading channel, block diagonalization technique, and MMSE receiver, the capacity (in bits/Hz) and BER are plotted as a function of the SNR (in dB) in Figs. 4 and 5, respectively. We note that the capacity of macro-diversity MIMO exceeds that of micro-diversity MIMO for all values of SNR, and that the capacity expectedly increases with an increasing SNR. We also note that the BER of macro-diversity MIMO is lower than that of micro-diversity MIMO for all values of SNR, and that the BER expectedly decreases with an increasing SNR.

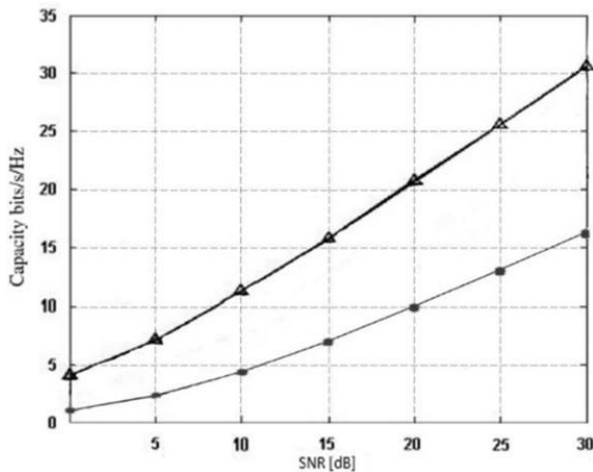


Fig. 4 Capacity vs. SNR for micro- and macro-diversity MIMO with soft handoff

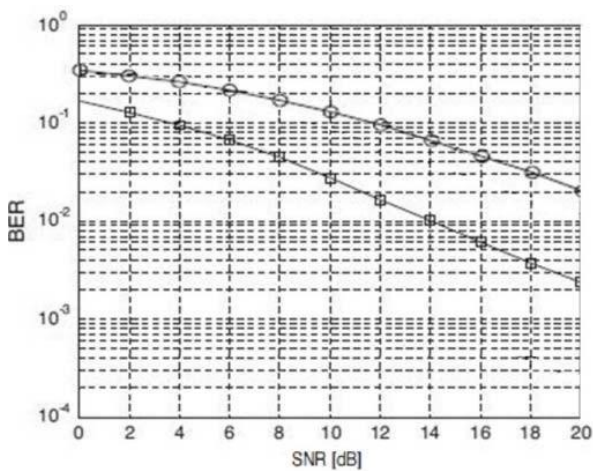


Fig. 5 BER vs. SNR for micro-diversity and macro-diversity MIMO with soft handoff

B. The Hard Handoff Case

We now consider the case of *hard handoff*, also known as *break-before-make*. In this scenario, different frequency ranges are used in adjacent channels to minimize the interference. When the MS moves from cell to cell and needs to communicate with another BS, the communication with the first BS is terminated because different frequencies are used. In the case of a call setup, the MS keeps track of the communicating cells and choose the cells that fall above the handoff threshold. The advantages of hard handoff are low cost because it requires only one channel to operate and the user does not feel an interruption in the call because it is a fast handoff. We choose this type of handoff in our developed hybrid scheme as detailed below.

C. Hybrid Model

In this hybrid micro-macro MIMO scheme, switching is conducted between macro- and micro-diversity MIMO

schemes and vice-versa. In a cellular network, the MS receives signals from the BS located in the same cell and from adjacent BSs. Receiving signals from other BSs increases the spectral efficiency of the cellular network and improves the data rates for the edge users. In the case of two BSs and one MS in each cell, if the first MS is communicating with the BS in the same cell, the other BS located in a different cell will be the interfering one. But the interfering BS also sends signals to this MS, so the signals from the interfering BS and serving BS arrive at the MS at the same time and they are synchronized. The overall capacity is higher when there is cooperation between the BSs, i.e., macro-diversity, than the capacity of a single cell. But it was shown in previous work [1]-[8] that in some instances the user's capacity (and BER) with no cooperation is better than the capacity (and BER) under cooperation. Therefore, a switching must be conducted in those instances and a hybrid micro-macro MIMO scheme could be deployed to decide whether to use cooperation or not.

D. The Switching Algorithm

For macro-diversity, the capacity is given by

$$\log \left(1 + \frac{\text{SINR}}{\gamma} \right) \quad (21)$$

and for micro-diversity, the capacity is given by

$$\log \left(1 + \text{SINR} \right) \quad (22)$$

where γ is the gap between the simulated and theoretical limit of the signal-to-noise ratio.

To define whether to operate under a micro-diversity or macro-diversity scheme, the capacities and SNRs are compared. First the channel information is determined for the serving BS and the neighboring BS that will do the cooperation. OFDM modulation is applied at the transmitter having two antennas, and linear coordinated beamforming technique is applied at the receiver having three antennas. Then, the capacities and SINR are calculated. If the SINR of the micro-MIMO is low (less than 0 dB) and the SINR of the macro-MIMO is much greater, then the macro-diversity scheme is chosen. Figs. 6 and 7 illustrate the switching technique for both BER and capacity versus the SNR in dB, respectively.

The SNR saturates when the transmitter is near the receivers, and as the received power increases, so does the power of the introduced noise because it is proportional to the received power. This causes a decrease in the system ergodic capacity. We can conclude from Figs. 6 and 7 that as the hybrid model is applied and switching occurs from macro- to micro-MIMO and vice-versa over a cut-off range of SNR values, an improvement (decrease) in the BER occurs at the cost of a deterioration in the capacity

(decrease) and viceversa over the same range of SNR values.

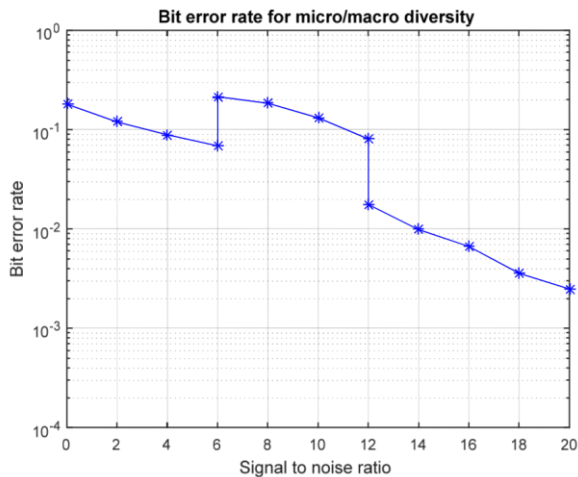


Fig. 6 BER vs. SNR of the hybrid macro-micro MIMO scheme

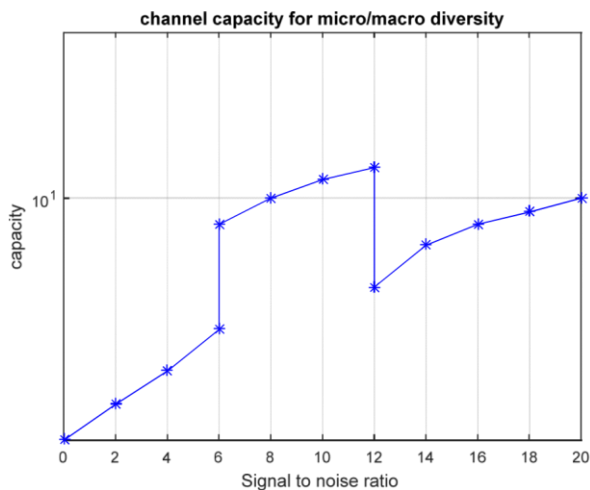


Fig. 7 Capacity vs. SNR of the hybrid scheme macro-micro MIMO scheme

V. CONCLUSIONS AND FUTURE WORK

MIMO technology is adopted in 3G and 4G mobile communications because it increases the reliability and channel capacity of wireless channels. This technology has greatly contributed to the expansion of cellular networks and the improvement of its performance. In this paper, we studied the capacity and BER in cellular networks using MIMO technology. We first analysed both micro- and macro-diversity schemes in the case of soft handoff and observed that macrodiversity outperforms micro-diversity MIMO in terms of capacity in bits per Hz and BER. Results also showed that the capacity grows linearly with the number of antennas at both the BS receiver and mobile user transmitter of a cellular network.

A number of recent research [1]-[8] concluded that in some instances the user's capacity and BER of systems with

no cooperation (micro) is better than the capacity and BER of systems with cooperation (macro). This drove us to study if switching between micro- and macro-systems can be conducted in the case of hard handoff and to test a proposed hybrid micro-macro MIMO scheme that will decide whether or not cooperation should be used.

To define whether to operate under a micro-diversity or macro-diversity scheme, the capacities and SNRs need to be compared. Then, a hybrid model can be deployed to switch between macro- and micro-diversity based on a set of predetermined cut-off range of SNR values. As the hybrid model was applied and switching occurred from macro- to microMIMO and vice-versa over a cut-off range of SNR values, we observed an improvement (decrease) in the BER at the cost of a deterioration in the capacity (decrease) and vice-versa over the same range of SNR values. As a result, we can conclude that our developed hybrid system outperforms classical MIMO systems as it switches between micro- and macro-diversities. The cost of this performance improvement is an increase in system's cost due to much higher hardware and software complexities.

In order to further enhance the capacity of the system, we need to maximize the SNR. SNR maximization is done using maximum ratio combining (MRC), and hence our hybrid micro-macro-MIMO scheme could be applied under MRC combining for optimal SNR and capacity results. Since MRC requires complicated CSI estimation techniques (in terms of fading amplitude and phase), this proposed scheme is left for future work along with the deployment of optimal CSI estimation schemes [9]-[20], subject to the development of advanced stochastic models for fading noise [21]-[36]. Such CSI-driven MRC scheme will constitute a sub-system within our proposed hybrid MIMO model.

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