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***Abstract*—In this paper we analyse the downlink performance of a rank adaptive multiple input multiple output (MIMO) system in a busty traffic cellular network. A LTE-Advanced system with multiple component carriers was selected as a study case. To highlight the advantage of using MIMO techniques, we used a single input multiple output (SIMO) system as a baseline for performance comparison. The gain mechanisms of the MIMO system over the SIMO system are investigated and their characteristic at different traffic load conditions are highlighted. The simulation results are used to verified our proposed model to predict the performance of the SIMO and MIMO systems in a bursty traffic network.**

I. Introduction

Applying multiple antennas at both ends of the transmission link has been shown as an effective way to improve the capacity of the system i.e. by spatial multiplexing [1] or the quality of the link i.e. by spatial diversity gain [2],[3]. Having such advantages, MIMO OFDM based cellular network has been recently standardized by 3GPP for UTRAN Long Term Evolution (LTE) system, [4], [5]. System level performances of MIMO reported in literature have confirmed the benefits from the deployment of MIMO in cellular networks, see for example [6], [7] among others. However, in most of the works the performance of downlink MIMO systems are evaluated based on a assumption of a full load traffic network with a fixed number of users. The performance of the downlink MIMO system is therefore evaluated in somewhat a worst case scenario where the users suffer from full inter-cell interference. This could be the reason for the low number of users that can really utilize the advantage of downlink MIMO i.e. receiving in multi-stream mode [6]. Therefore, one of the motivations of this paper is to evaluate and analyze the gain of the MIMO system in a bursty traffic cellular network where the arrival and departure of the users are modeled closer to what happens in practice. In this way the inter-cell interference at the users is also more realistically modeled i.e. the base station with no active user will not introduce interference to the users connected to other base stations.

As another solution to support very high user data rates in the downlink, carrier aggregation (CA) has been introduced in LTE-Advanced system, [8], [9]. By aggregating multiple component carriers (CC) much larger bandwidth is available to the user e.g. up to 100 MHz [10]. The data rates experienced at the users therefore increase linearly with the number of CCs they are assigned to. In a bursty traffic cellular network a higher bandwidth resource and a better user data rate by using MIMO technique mean a lower service time and therefore less number of active users in the system. The inter-cell interference level is reduced and the number of users that can be served in multi-stream mode will increase as a result. Thereby, MIMO and CA techniques naturally support each other in reaching the ultimate goal of improving the overall system performance. This is the motivation behind our interest in investigating the behavior of a cellular system where MIMO and CA techniques are coupled.

Motivated by these observations, in this paper we analyze the downlink performance of a rank adaptive MIMO system in a busty traffic cellular network. SIMO system is used as a baseline to illustrate the advantage of MIMO system. The performance of these two techniques are evaluated both on the traditional system with single component carrier per user and on the more advanced system with multiple component carriers per user. The simulation results are used to verified our proposed model to predict the performance of the SIMO and MIMO systems in bursty traffic network.

The paper is organized as follows. In Section II, we give a brief overview on the system level deployment of MIMO and CA techniques in LTE-Advanced downlink system. The model and assumptions used in the system level simulations are highlighted. In Section III we show the simulation results and provide some insights to the behaviors of the SIMO and MIMO systems in bursty traffic load conditions. The performance gain of the CA system over the traditional single component carrier system is characterized in the same section. In Section IV, we study the bursty traffic model and provide some analytical estimations on the average user throughput of the SIMO and MIMO system. The paper ends with conclusions in Section V.

II. System level model and assumptions

For a downlink MIMO system, to improve the system performance it is desirable to schedule as many UEs as possible in multi-stream mode. The mechanism to decide whether the UEs are scheduled in multi-stream mode or not is called rank adaptation and is done at both the UEs and the base station. The UE suggests its preferred precoding and receiving mode by feedback a precoding matrix indicator (PMI) and a rank indicator (RI) to the base station. Based on this information, the base station make a final decision on the receiving mode of the UEs. Basically the UE is to be scheduled in multi-stream mode if its estimated throughput in multi-stream mode is larger than the throughput it can obtain in single-stream mode [7]. This condition often implies that only UEs with good channel condition are capable of receiving multi-stream.

By concatenating several component carriers (CC) together the spectrum available for transmission in downlink LTE-Advanced system can be extended up to 100 MHz. The bandwidth of each CC defines the total number of operating CCs, N. This number can range for example from $N = 5$ CCs (20 MHz per CC) to $N = 10$ CCs (10 MHz per CC). In order to make the CA system backward compatible for LTE-Rel'8 UEs, it is decided that each CC will have an independent layer-1 transmission including the Hybrid automatic repeat request (HARQ) and Link Adaptation (LA) functionalities according to LTE-Rel'8 assumptions [11]. The assignment of the CC to the UEs is done at layer-3 where different load balancing mechanisms can be deployed. The layer-2 packet scheduling is responsible to schedule the UEs assigned at each CC. The scheduling can be done independently for each CC but also can be done across all CCs in order to improve the fairness among the UEs in the system. The readers are referred to [8], [9], for further detail information on CA and current development of CA in LTE-Advanced.

The MIMO and SIMO system performances are evaluated using a downlink multi-cell system level simulator with detail implementation of the layer 2 with packet scheduler, HARQ and LA functionalities as specified in [11]. The UE arrival rate ranges from 1.5 UEs/second/cell to 12 UEs/second/cell. The payload of each call is 4 Mbits and therefore the offered load corresponding to these UE arrival rates are within 6 Mbps to 48 Mbps range. We consider a CA system with $N = 2$ CCs, each with 20 MHz bandwidth. LTE-Rel'8 UEs is restricted to one CC and the CC is assigned to each UE in a round robin manner. In this way, we can make sure that the number of UEs in each CC is balanced. LTE-Advanced UEs are assigned to all CCs upon arrival. A proportional fair (PF) mechanism is used to schedule the UEs. The PF metric is estimated across all CCs to ensure the fairness as proposed in [14]. Table I summarized the main parameters used by the simulator.

TABLE I
BASIC SYSTEM PARAMETER USED IN THE SIMULATIONS

Parameters	**Setting**
Test Scenario	3GPP Macro cell case 1, 7 sites, 21 cells with wrap around and only interferences from cells with active UEs is considered
Carrier frequency	2 GHz
Carrier aggregation configuration	$N = 2$, 2x20 MHz contiguous CCs
Number of PRBs per CC	100 (12 subcarriers per PRB)
CQI, PMI group size	1 CQI, PMI per 6 PRBs
CQI reporting error	Log normal with 1 dB std
CQI reporting resolution	5 bits with 1.6 quantization step
CQI, PMI reporting delay	5 TTIs
Packet scheduling	Proportional fair for LTE-Rel'8 UEs Proportional fair across all CCs for LTE-Advanced UEs
1 st BLER target	20%
Traffic type	Bursty traffic, fixed buffer size per call of 4 Mbits and different Poisson arrival rates
Tx-Rx	2x2 MIMO and 1x2 SIMO
UE population	100% LTE-Rel'8 UEs; 100% LTE-Advanced UEs
Maximum number of UEs the system can serve	A=50 UEs

Fig. 1. Distribution of the UEs scheduled in dual-stream mode vs. the offered load for LTE-Rel'8 UEs (assigned with 1 CC) and LTE-Advanced UEs (assigned with 2 CCs).

III. Performance of MIMO system in bursty traffic

A. *Distribution of UEs scheduled in dual-stream mode*

Figure 1 shows the distributions of the number of MIMO UEs scheduled in dual-stream mode for LTE-Rel'8 UEs and LTE-Advanced UEs. To make a fair comparison we use the same user arrival rate for both scenarios. The probabilities of being scheduled in dual-stream mode of the UEs in both bandwidth settings decrease as the user arrival rate increases. At very low traffic load, up to 82% of the LTE-Advanced UEs are scheduled in dual-stream mode. Low inter-cell interference level and large bandwidth resource resulting from the low number of active UEs in the system are the main reasons for this very high probability of UEs scheduled in dual-stream mode. At very high traffic load where the system is closer to a full load condition, the probability of being schedule in dual-stream mode reduces to 17%, similar to values reported in [6].

The probability of LTE-Advanced UEs scheduled in dual-stream mode is higher than that of LTE-Re'8 UEs by 2% to 9% depending on the traffic load. This illustrates the benefit of CA system as compared with the traditional single component carrier system. Having more bandwidth resource i.e. better user throughput, the serving time of the UEs in CA system is shorter than that of the UEs in a single component carrier system. This means the CA system has fewer active UEs than the single component carrier system does. Therefore, UEs at the CA system can benefit from the low inter-cell interference and more UEs can be scheduled in dual-stream mode as a result.

B. Performance gain of MIMO system over SIMO system

1) Number of active UEs in the system and the resource utilization: In a bursty traffic network, the number of UEs active in the system is varied along the time according to the system traffic conditions. It is the main difference from the full load traffic network model which often assumed a fixed number of UEs in the system. The traffic load condition is determined by the user arrival rate as well as the capability of the UEs in the system e.g being able to receive high/low data rate and therefore stay in the system in short/long period of time. To illustrate this in Figure 2 (first row), we show the average number of active UEs in one cell at different traffic load conditions for LTE-Rel'8 and LTE-Advanced UEs in SIMO and MIMO systems. It can be seen that, from low to medium traffic load there is almost no difference in the number of active UEs in the MIMO and SIMO systems. This means both MIMO and SIMO UEs are able to access to almost the same amount of bandwidth resources. In this case, the gain in the user throughput of the MIMO UEs over the SIMO UEs comes mainly from the spatial multiplexing and spatial diversity gains.

Fig. 2. Average number of active UEs per cell vs. the traffic load for MIMO and SIMO system (First row), Resource utilization for LTE-Rel'8 and LTE-Advanced UEs with SIMO and MIMO capabilities (Second row)

On the contrary, at high traffic load e.g. 36 Mbps to 48 Mbps the average number of active UEs in the SIMO system is significantly higher than that in the MIMO system e.g. from 20% to 200% for LTE-Rel'8 and from 25% to 125% for LTE-Advanced. This illustrates a fact that at a high traffic load, with spatial multiplexing gain and spatial diversity gain, MIMO UEs can quickly finish their transmissions. They leave the system after a shorter period of time than SIMO UEs and therefore the active UEs in the system can enjoy a better share of the bandwidth resource. It should be noted here that at this high traffic load, all MIMO UEs regardless of their channel conditions can benefit from the low number of active UEs in the system i.e. better bandwidth share and less inter-cell interference. As a result of better bandwidth resources, the number of active UEs in LTE-Advanced system is always lower than that in a LTE-Rel'8 system. This holds true for both SIMO and MIMO UEs.

The number of active UEs in the system determines how the system resource is utilized. Figure 2 (second row) shows the utilization of the system resource for LTE-Rel'8 and LTE-Advanced UEs with SIMO and MIMO capabilities. The resource utilization is calculated as the ratio of the used physical resource block (PRB) over the total available PRBs in the system. With the same traffic load condition, the system with lower resource utilization index will perform better as it can potentially server more users. As a result of better data rate MIMO UEs use less system resource than SIMO UEs in all traffic load conditions (from 2% to 15%). With the same reason, LTE-Advanced UEs also required less system resource than LTE-Rel'8 UEs (from 2% to 10%).

2) User throughput performances: Figure 3 illustrates the 5%-ile user throughput obtained in 2x2 MIMO system and its gain over that of SIMO system. The performance of both LTE-Rel'8 and LTE-Advanced UEs are shown on the same figure. From low to medium traffic load the gain in the 5%-ile is flat with an average value of 25% for LTE-Advanced UEs. For LTE-Rel'8 UEs, the gain is reduced from 25 % to 0%. A steady increase in the gain at higher traffic loads is observed for both types of the UE.

Fig. 3. 5%-ile (coverage) user throughput and the gain in the coverage throughput of MIMO UEs over that of SIMO UEs

The advantage of having MIMO UEs scheduled in dual-stream mode is that they can be served in very short period of time and quickly leave the system. Once leaving the system they release the occupied resources and make them available to the active UEs. This in return benefits the active UEs in the system as more bandwidth resources mean better data transmission rates. It appears from the results that from low to medium traffic load, the UEs scheduled in dual-stream mode has less effect on the performance of UEs at cell-edge. At this state, the spatial diversity gain dominates the gain of the MIMO system over the SIMO system. However, at higher traffic load e.g. from 36 Mbps to 48 Mbps, in additional to the spectral efficiency gain the MIMO UEs are also benefit from the low number of active UEs in the system i.e. better bandwidth resource, Section III-B1. This explains for a boost in the gain of the MIMO UEs over SIMO UEs at very high traffic load.

Figure 4 shows the absolute value of the average user throughput experienced at the MIMO UEs in LTE-Rel'8 and LTE-Advanced systems vs. the offered load. The gain of the MIMO system over SIMO system corresponding to different offered loads is also shown in the same figure. The gain first decreases as the offered load increases as expected. It somehow saturates at the medium offered load and steadily increases at high load. The boost in the gain of the MIMO system over SIMO system at high traffic load is due to the larger bandwidth resource available for the MIMO UEs as described in Section III-B1.

Fig. 4. Average UE throughput and the gain in the average throughput of MIMO UEs over that of SIMO UEs

From Figures 3, 4 it is observed that, in terms of user throughput LTE-Advanced system outperforms LTE-Rel'8 system in all traffic load conditions. The gain of the LTE-Advanced system over LTE-Rel'8 system is highest at low load and gradually reduces at high traffic loads. This behavior can be explained as follows. At low load, the bandwidth available for LTE-Advanced UEs is N times higher that of LTE-Rel'8 UEs. Having more bandwidth to transmit the data, LTE-Advanced UEs outperform LTE-Rel'8 UEs in the experienced data rate. This can also happen at higher traffic load although the chance for an UE being simultaneously scheduled on N CCs gradually becomes lower. On top of that as the number of UEs increases with the offered load, more UEs are multiplexed over a fixed amount of bandwidth. At this state, the difference in the allocated bandwidth resource to LTE-Rel'8 UEs and LTE-Advanced UEs becomes smaller. Therefore, both systems will give almost the same performance when the traffic is closer to full load condition.

IV. Bursty traffic model and average user throughput estimation

In this section we present some analytical results where the performance of a SIMO and MIMO systems in a bursty traffic cellular network is modeled. The bursty traffic in cellular system can be modeled as a birth-death process [12]. The "birth" is the process where a new user arrives and thereby the total number of users in the system is increased by 1. The "death" is the process where a user finishes its transmission and leaves the system. We list in Table II the notations which are used in the modeling of the bursty traffic network.

TABLE II
Notations in bursty traffic model

Parameters	Meaning
S_k	System state with k UEs being served
λ_k	UE arrival rate in state k, user per second per cell
μ_k	Service rate in state k, $1/\mu_k$ will be the average service time
A	Maximum number of user the cell can server
F	The user buffer size in Mbits

In a cellular network, the admission of a new user equipment (UE) in the system is decided by the admission control unit. Due to practical constraints, there is a limitation in the number of the UEs the system can serve: A. Therefore when the system has reached its limitation, no new UEs will be admitted in the system and we have the following rule for the simulated arrival rate

$$\lambda_k = \begin{cases} \lambda, & 0 \le k \le A; \\ 0, & k > A. \end{cases} \quad (1)$$

Using a proportional fair packet scheduler in the frequency domain leads to average cell throughput enhancement. According to [13], the gain can be modeled as a logarithmic function of the number of active users. Here we use the same simplification calculation as in [14] to estimate the gain in the average cell throughput

$$G_k = \begin{cases} 1, & k \le 1; \\ 0.11ln(k) + 1.1, & 1 < k \le 13; \\ 1.38, & k > 13. \end{cases} \quad (2)$$

A. Average throughput of UEs with SIMO setting

In [14] the authors provided a model that can approximately estimate the average throughput of SIMO UEs in a bursty traffic network. In the model, the service rate was shown to be a function of the cell throughput C when the cell is fully loaded, the user buffer size and the packet scheduling gain. The service rate was calculated for the case where all cells are assumed to experience full inter-cell interference. To generalize the analysis, here we introduce the interference reduction gain IR in the calculation of the service rate. This IR gain accounts for the gain in the cell throughput of the system with dynamic inter-cell interference i.e. the interference level at the UEs varies according to the status of the neighbor base stations active/inactive, over that of the system with full inter-cell interference C. As indicated in Section I, the status of the base stations is defined by the number of active UEs in the system. The IR gain is therefore dependent on the user arrival rate λ. When λ is low, only few base stations are activated and we have a high $IR(\lambda)$ gain. When λ increases, the probability of having inactive base station becomes lower and the $IR(\lambda)$ gain approaches 1. In fact, when $IR(\lambda)$ is 1, the system returns to the state of full inter-cell interference. The generalized version of the service rate can be calculated as

$$\mu_k = \begin{cases} 0, & k = 0; \\ \frac{C}{F}\frac{G_k}{G_\infty} IR(\lambda), & 0 < k \le A; \\ \text{undefined}, & k > A. \end{cases} \quad (3)$$

Following the same steps as in [14] we have the probability of being in state S_k (k active UEs per cell) as

$$P_k = \begin{cases} P_o \prod_{i=0}^{k-1} \frac{\lambda_i}{\mu_{i+1}} = P_o \left(\frac{\lambda F}{IR(\lambda)C}\right)^k \prod_{i=1}^{k} \frac{G_\infty}{G_i}, & 1 \le k \le A; \\ 0, & k > A. \end{cases} \quad (4)$$

With a condition that the sum of the probabilities in all states should be 1 we can derive the probability for the system in state S_0 (no active UEs in the cell) as follows

$$\begin{aligned} P_o = & \left(1 + \sum_{k=1}^{A} \prod_{i=0}^{k-1} \frac{\lambda_i}{\mu_{i+1}}\right)^{-1} \\ = & \left(1 + \sum_{k=1}^{A} \left(\frac{\lambda F}{IR(\lambda)C}\right)^k \prod_{i=1}^{k} \frac{G_\infty}{G_i}\right)^{-1} \end{aligned} \quad (5)$$

From (4) and (5), the average user throughput can be approximated as the weighted mean of the average user throughput at each state S_k

$$TP_{UE-SIMO}(\lambda, F, C, A) = \frac{IR(\lambda) \sum_{k=1}^{A} \frac{CP_k}{k} \frac{G_k}{G_\infty}}{1 - P_o} \quad (6)$$

B. Average throughput of UEs with MIMO setting

The performance of the MIMO system can be estimated from the performance of a SIMO system if we know the distribution of the MIMO UE scheduled in spatial multiplexing mode (multi-stream) and spatial diversity mode (single-stream) as well as the spectral efficiency gain corresponding to each mode. For the MIMO UEs scheduled in multi-stream mode, the theoretical maximum spectral efficiency gain over SIMO UEs is min(N_r,N_t) where N_r and N_t is the number of receiving and transmitting antenna respectively. The spatial multiplexing gain in practice is often smaller due to the limitation in the user signal to noise ratio and the modulation and coding order. For those MIMO UEs scheduled in the single-stream mode, the spatial diversity gain can translate into the enhancement of the user data rate by means of higher modulation and coding order. Due to the spatial multiplexing gain and the spatial diversity gain the service rate of the MIMO system is expected to be higher than that of the SIMO system. From eq. (3) the service rate of a MIMO system can be calculated as

$$\mu_k = \begin{cases} 0, & \text{k=0;} \\ \frac{CG_k IR(\lambda)(P_{MT}(\lambda)SM_G + (1-P_{MT}(\lambda))SD_G)}{FG_\infty}, & 0 < k \le A; \\ \text{undefined}, & k > A. \end{cases} \quad (7)$$

where $P_{MT}(\lambda)$ is the probability of the UEs being scheduled in multi-stream mode and (1-$P_{MT}(\lambda)$) is the probability of the UEs being scheduled in single-stream mode; SM_G is the spectral efficiency gain of the MIMO system over the SIMO system due the spatial multiplexing; SD_G is the spectral efficiency gain of the MIMO system over the SIMO system due to the spatial diversity. Applying μ_k defined in eq. (7) to eq. (4) and eq. (5) and following the same procedure as for the SIMO system we can derive the average user throughput of the MIMO system

$$TP_{UE-MIMO}(\lambda, F, C, A) = \frac{IR(\lambda)\left(P_{MT}(\lambda)SM_G + (1 - P_{MT}(\lambda))SD_G\right) \sum_{k=1}^{A} \frac{CP_k}{k} \frac{G_k}{G_\infty}}{(1 - P_o)} \quad (8)$$

C. Analytical results

In this section we illustrate some analytical results with the input parameters taken from the simulation results presented in Section II. Due to the space limit, here we only show the results for MIMO and SIMO systems with CA. With the parameters presented in Section II, the simulated maximum achievable cell throughput for a fully loaded, full inter-cell interference 1x2 SIMO system is in the order of 49 Mbps. Therefore, we use this value as input for the busty traffic model $C = 49$ Mbps in eq. (6). The maximum number of UEs the system can serve is set to the same value used in the simulation $A = 50$. We then need to fine tune the interference reduction $IR(\lambda)$ parameter for SIMO system described in Section IV-A . It appears that by using $IR(\lambda)$=[3.0,2.8,2.5,2.1,1.8,1.5,1.1,1.0] we can obtain a close match between the average user throughput from the simulation and from the analytical model. The $IR(\lambda)$ was derived by a nonlinear least squares fitting with a condition that the interference reduction factor is set to 1 for very high traffic load as all the base stations are assumed to be active in this state.

It should be noted here that the same $IR(\lambda)$ factors are used for the estimation of the average user throughput in MIMO system. These spatial multiplexing gain SM_G and the spatial diversity gain SD_G are derived by means of simulation. Due to the space limitation, the simulation parameters and the detail procedures to derive these gains from the simulation results are not presented here in this paper. It was found that the SM_G and SD_G gains of the 2x2 MIMO system over the 1x2 SIMO system are 160% and 110% respectively. The probability of the UEs being scheduled in dual-stream mode $P_{MT}(\lambda)$ is obtained from Figure 1. Applying these values in eq. (8) we can then obtain the average user throughput of the MIMO system.

In Figure 5 we compare the user throughput performance obtained from the simulation and from the analytical results. There is a good match between the analytical and simulated results. The difference between the analytical user throughput of the MIMO system and the simulated one is in the order of 10% only. These discrepancies could be due to the limitations in the modeling of the bursty traffic network as well as the simplification in estimating the average user throughput e.g. eq. (6) and eq. (8). Nevertheless, it is shown that the analytical model is capable of capturing the principle behaviors of SIMO and MIMO systems in a bursty traffic network.

Anal_Sim_resutls_SIMO_MIMO.eps

Fig. 5. Simulation and analytical results on the average user throughput of SIMO and MIMO systems

V. Conclusions and Remarks

In this paper we have illustrated the advantage of the MIMO system under practical traffic conditions. The obtained results are significantly different from previous research works where the performance of a MIMO system is often evaluated under an assumption of closed loop traffic with full buffer for each call. We showed that in a cellular network, MIMO techniques do not only boost the user throughput at low traffic load but also at high traffic load conditions. Most of the gain is obtained by allowing multi-stream transmission to the UE when its channel condition is good enough. In addition, spatial diversity gain also contributes to the overall gain of the MIMO system when multi-stream transmissions is not favorable. Simulation results of the 2x2 MIMO system show a significant performance gain over the 1x2 SIMO system. However, this gain is heavily dependent on the traffic model and the system load. It degrades as the traffic load increases from low to medium levels. When the system gets close to full load condition, an interesting behavior is observed where there is a boost in the gain of the MIMO system over SIMO system. This behavior is a result of both the spectral efficiency gain of MIMO technique over SIMO technique and the open loop traffic model. MIMO UEs with high throughput will leave the system fast and MIMO UEs left in the system will benefit from having more bandwidth resource. Independent of the implemented multiple antenna transmission techniques, LTE-Advanced system outperforms LTE-Rel'8 system in most of the traffic load conditions. The gain is due to the higher bandwidth resource for UEs capable of operating in multiple component carriers. The gain deceases as the traffic load increases and becomes negligible when the traffic gets closer to a full load condition. We also tried to predict the performance of SIMO and MIMO systems in an analytical form. Although some fine tunings need to be done due to the complexity of the simulated system, the analytical results show a fairly good match with those obtained from simulations.

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