An Energy Efficiency Evaluation of MIMO Based LTE RANs with DTX Operation

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Abstract

This paper presents a system level evaluation of the energy consumption of a 4G LTE radio access network RAN when upgrading the access base stations from SISO to MIMO base stations. A macro only cell deployment scenario is evaluated, and the power consumption of the base stations is estimated by a parametric power consumption model. The impact of the discontinuous transmission feature (DTX) on the energy consumption of 2x2 and 4x4 MIMO radio access network with reference to the SISO radio access network is analyzed. A non-full buffer FTP traffic model is used in the analysis. Our results show that, without DTX, the 2x2 MIMO deployment consumes the least amount of energy. No energy savings are observed when more than 2 transmit antennas is used. When DTX is enabled, and at high values of offered traffic, the 4x4 MIMO deployment becomes the most energy efficient deployment option among the SISO and 2x2 MIMO deployments.

Keywords: Energy Efficiency**,** MIMO radio access networks, Energy Consumption Gain, Power consumption model, DTX**.**

1 Introduction

Multiple-In-Multiple-Out (MIMO) techniques are used in RANs to enhance cell capacity through spatial multiplexing or cell coverage through spatial diversity, without increasing the channel bandwidth or the RF transmit power. However, the power consumption of a MIMO base station increases due to the need for more signal processing and more RF chains when compared with a Single-Input-Single-Output (SISO) base station. The question of whether deploying MIMO base stations in a RAN is more energy efficient than SISO base stations or not is addressed in this paper. The energy consumption of SISO and MIMO RANs is evaluated when the base station circuit power consumption is considered and when more realistic non-full buffer FTP traffic model is used. The impact of enabling the fast DTX on the RAN energy consumption is also assessed.

Many previous publications have investigated the issue of MIMO energy efficiency. The authors of [2] have evaluated the MIMO energy efficiency in wireless sensor networks (WSNs) employing Alamouti diversity. Contra to the widely held view that MIMO systems would be more energy efficient than SISO ones, the authors concluded the opposite when the overhead circuit energy consumption was considered. Their research demonstrated that in short-range applications, SISO WSNs can be more energy efficient than MIMO WSNs.

The energy consumption ratio (ECR) measured in J/bit has been investigated for both SISO and 2x2 MIMO Alamouti schemes in [3], for both the Round Robin (RR) and Proportional Fair (PF) scheduling algorithms. When only the RF transmit power is considered, the authors concluded that the 2x2 MIMO transmission mode (i.e. the Alamouti space frequency block code) is both more spectrally and energy efficient than SISO in both the urban micro and urban macro cell deployment scenarios. Similarly, the authors of [4] investigated the

MIMO energy efficiency for different cell types and have observed that a significant SINR improvement can be obtained with MIMO (e.g. 7.1 dB for a 2×2 configuration) independent of the cell type. However, an increase in base station power consumption is observed due to the increased complexity of the transceiver circuitry, and the additional signal processing needed. The authors of [5] have evaluated the MIMO energy efficiency at the link level and have shown that MIMO does not provide any energy efficiency gain when more than two transmit antennas are used if the circuit overhead power consumption is included in the analysis.

In [6], the energy consumption of MIMO and SISO RANs under the same coverage and average traffic load conditions were compared. The results demonstrated that although a single MIMO base station consumes more energy than its SISO counterpart when transmitting at full power, the MIMO RAN can be more energy efficient as smaller number of MIMO base stations than SISO ones is needed to offer the same capacity.

Most of the previous publications considered only the case a full buffer traffic model, which unrealistically assumes that there is always data to be sent. In this paper, the authors compare the energy consumption of MIMO and SISO RANs for a bursty traffic model. Such a non-full buffer traffic model enables the energy efficiency to be investigated as a function of cell offered average traffic load. In addition, the impact of fast discontinuous transmission (DTX) at the base station is included to the analysis [7, 8]. Furthermore, the process of modelling the power consumption of a radio base station is described by adopting the same model developed in [9]. A system level MATLAB simulator of 4G LTE RAN was developed by the authors to determine the RAN average traffic load, and average throughput with users capable of operating in SISO and MIMO modes.

The paper is organized as follows: Section 2 describes the processes of modelling the power consumption of a radio base station. Section 3 evaluates the energy savings due to enabling the DTX in a radio base station. The MIMO channel capacity estimation is covered in Section 4. The analysis and network model are presented in Section 5, followed by the results and the discussion of the results in Section 6. Finally, Section 7 concludes the paper.

2 Radio Base Station Power Consumption

The radio base station (RBS) consumes the largest proportion of energy in a cellular network. In a homogeneous macro cell RAN, RBSs typically consume ~60 % of the total RAN energy [10]. Base station sites usually consist of seven common units identified as: the antennas and feeder cables; the power amplifier (PA); the RF transceiver; the baseband processing unit BBU; the backhaul unit; the cooling unit; and the AC/DC power supply unit. Figures 1 and 2 show these common units in SISO and 2x2 MIMO base stations. The enhanced Green Radio (GR) base station power consumption model which was developed in [9] is used to estimate the power consumption of a base station in this paper. This model predicts the power consumption of the base station versus the cell average traffic load at various number of radio chains (MIMO order).

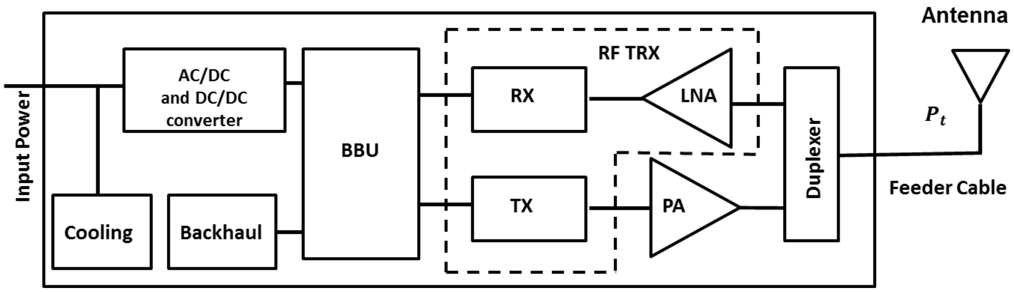

Figure 1: *The SISO radio base station simple architecture*

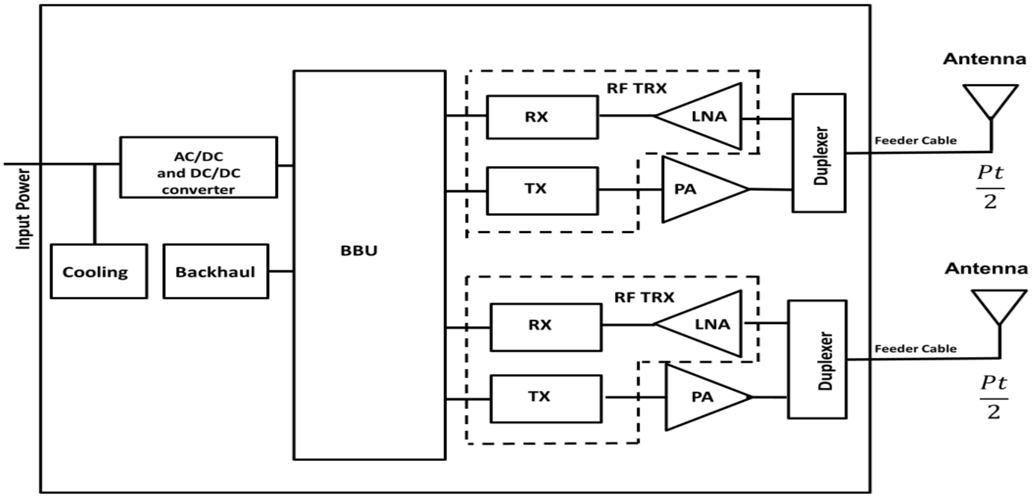

Figure 2: *The 2x2 MIMO radio base station simple architecture*

The average power consumption of a base station site is calculated by summing the power consumption of the base station units, as expressed in (1) and (2).

$$P_{site} = P_{cool} + P_{bh} + P_{bts} \tag{1}$$

$$P_{bts} = P_{rect} + n_s . n_t (P_{bb} + P_{trx} + P_{pa}) \tag{2}$$

In (1) and (2), the term in P_{site} represents the total base station site power consumption, P_{cool} denotes the cooling system power consumption, P_{rect} is the power consumed by the power supply unit, P_{bh} is the backhaul power consumption, and P_{bts} is the base transceiver station power consumption. The term P_{bb} is the baseband signal processing power consumption, P_{trx} is the RF transceiver power consumption, P_{pa} is the power consumed in the power amplifier, n_s is the number of sectors per site, and n_t is the number of transmit antennas per sector.

2.1 Power Amplifier

The power amplifier (PA) consumes the most power in a macro cell base station and its consumption depends on the average transmit RF power per antenna, the power amplifier efficiency η_{pa}, and the feeder cable losses σ_{feed} as shown in (3).

$$P_{pa} = \frac{\alpha \cdot P_{t,max}}{n_t \cdot \eta_{pa} \cdot (1 - \sigma_{feed})} \tag{3}$$

In (3), $P_{t,max}$ is the maximum transmitted RF power per sector while α denotes the normalised average offered load factor during a nominal observation time and has a value between 0 and 1. The value of the power amplifier efficiency η_{pa} at a specific transmit power can be estimated by using (4) [11], where $\eta_{pa,max}$ is the PA maximum efficiency corresponding to $P_{pa,max}$.

$$\eta_{pa} = \sqrt{\frac{\alpha \cdot P_{t,max}}{P_{pa,max}}} \cdot \eta_{pa,max} \tag{4}$$

2.2 RF Transceiver and Baseband Processing Unit

The RF transceiver TRX contains circuits for clock/carrier generation and distribution, modulators, mixers, filters, buffers, low noise amplifier and the analogue/digital converters. The RF transceiver power consumption per sector can be estimated by (5) as a function of the power consumption of a reference base station configuration [12].

$$P_{trx} = \frac{n_t \cdot B \cdot P_{trx,ref}}{B_{ref}} \tag{5}$$

In (5), the term $P_{trx,ref}$ is the RF transceiver power consumption at a reference bandwidth B_{ref} , assuming a single transmit antenna per sector. The baseband processing unit power consumption is usually modelled as being dependent on the number of transmit antennas and the system bandwidth. The base band power consumption is estimated by (6), where $P_{bb,ref}$ is the baseband unit BBU power consumption at a reference bandwidth B_{ref} , also assuming a single transmit antenna per sector.

$$P_{bb} = \frac{n_t \cdot B \cdot P_{bb,ref}}{B_{ref}} \tag{6}$$

2.3 Power Supply and Cooling Unit

The Power supply unit comprises the AC/DC and DC/DC converters. The power losses in this unit are usually modelled as a fixed percentage (10% to 15%) of the overall power consumption of the base station [13]. Site cooling is required at macro-cell sites to maintain a suitable operating temperature inside the base station cabinet. The power consumption of the cooling unit is estimated using (7) by calculating the amount of heat generated inside the cabinet in British Thermal Units (BTU) per hour. The feeder cable losses σ_{feed} are considered by subtracting the transmitted RF power per sector from the base transceiver station power consumption. The energy efficiency rating EER of a cooling unit indicates the number of BTUs per hour removed for each 1 W of consumed power, while the number 3.4121 is used to convert from BTU to watts.

$$P_{cool} = \frac{3.4121}{EER} \cdot \left(P_{bts} - \frac{n_s \cdot P_t}{1 - \sigma_{feed}}\right) \tag{7}$$

2.4 Overall Base Station Power Consumption

The overall base station site power consumption can be estimated as the sum of the power consumption of the base station subsystems in (1) and (2). Table 1 lists the parameters of the power model used to estimate the total power consumption of the macro base station sites for SISO and different MIMO schemes. These values are obtained from [14] while the PA efficiency values are estimated by (4).

Table 1: *Macro cell BTS power model*

Parameter	Macro 1x 40 W	Macro 2x20 W	Macro 4x10 W
Sectors	1	1	1
P_t/Antenna (dBm)	46	43	40
Feeder losses (dB)	3	3	3
PA Back-off (dB)	8	8	8
$P_{pa,max}$ (dBm)	57	45	51
$\eta_{pa,max}$	90%	90%	90%
η_{pa} at P_t	25.37%	25.37%	25.37%
Bandwidth (B_{ref}, MHz)	20	20	20
Transceiver Unit ($P_{trx,ref}$, W)	13	13	13
Processing Unit ($P_{bb,ref}$, W)	30	30	30

Figure 3 shows the macro cell base station site power consumption versus the average traffic load factor α. The average traffic load α refers in LTE to the frequency-time resource utilisation factor in the cell. When $\alpha = 1$, the base station transmits at full power which equals to 40 watts per antenna for a SISO base station, and 20 watts per antenna in case of 2x2 MIMO base station. Figure 3 shows also that reducing the macro cell average traffic load results in a decrease in the site power consumption.

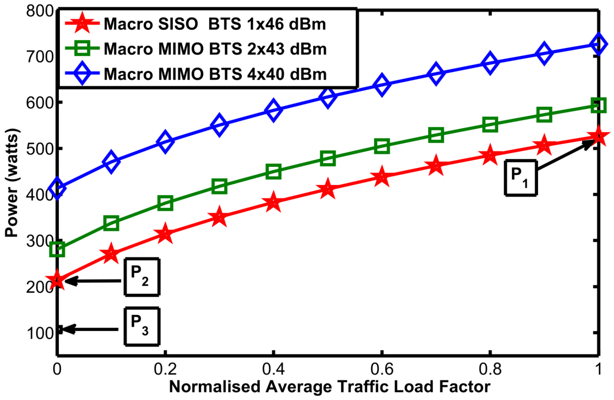

Figure 3: *Macro cell power consumption for various MIMO schemes*

3 Discontinuous Transmission (DTX)

Large energy savings can be achieved if some or all the base station subsystems are put into fast sleep mode during periods of low traffic intensity [15]. Under normal operation, an LTE base station transmits broadcasting, synchronization, and cell reference control signals, even when there is no traffic in the cell. This results in a small idle time to implement the DTX. One solution is to implement a fast DTX mechanism during the MBSFN (multicast and broadcast single frequency network) sub-frames. The LTE Rel-8 standards allow up to 6 MBSFN sub-frames to be transmitted per LTE frame. Each MBSFN sub-frame carries the CRS (cell specific reference) signal in the first LTE symbol. The sub-frame duration is 1 ms, which represent 10% of the frame duration, and consists of 14 LTE symbols, each symbol of 71.4 μs duration. By assuming a 30 μs sleep state transition time in the base station [7], the remaining available idle time for DTX is $(13 \times 71.4 - 30)$ μs. A maximum of 6 sub-frames can be configured in MBSFN. Therefore, the maximum percentage of idle time $\alpha_{DTX,max}$ in 6 sub-frames over one LTE frame is given by (8).

$$\alpha_{DTX,max} = \frac{6\times(1000-71.4-30)}{10000} = 0.5392 \tag{8}$$

When fast sleep mode is enabled, the cell may be in one of three states as follows: 1) transmitting at full power when there is a traffic present in the cell, thereby consuming P_{ON} (i.e. P_1 in Figure 3); 2) transmitting only the control signals, thereby consuming P_{OH} (i.e. P_2 in Figure 3) when there is no traffic in the cell; and 3) the base station is in DTX, thereby consuming P_{DTX} (i.e. P_3 in Figure 3). The P_{DTX} is expressed as a function of P_{OH} as shown by (9), where δ_{DTX} is the base station DTX factor.

$$P_{DTX} = \frac{P_{OH}}{\delta_{DTX}} \tag{9}$$

When DTX is not enabled, $\delta_{DTX} = 1$, and δ_{DTX} is greater than one when DTX is enabled. The larger the value of δ_{DTX}, the more amount of reduction in the power during the DTX. The intensity of the average traffic load in the cell determines the duration of the DTX period in the cell. If the cell average traffic load α_{ON} is known, then the proportion of DTX time in one frame is estimated by (10).

$$\alpha_{DTX} = \min\left(\left(\left\lfloor\frac{1-\alpha_{ON}}{0.1}\right\rfloor\right) \times 0.0899, \alpha_{DTX,max}\right) \tag{10}$$

The number "0.0899" equals the ratio of maximum idle time in one sub-frame to the LTE fame duration. The term in $\left\lfloor\frac{1-\alpha_{ON}}{0.1}\right\rfloor$ is equal to the number of idle sub-frames in one LTE frame. Let α_{OH} denote the ratio of the time spent transmitting the reference and control signalling to the total time duration of an LTE frame, as expressed in (11).

$$\alpha_{OH} = 1 - \alpha_{ON} - \alpha_{DTX} \tag{11}$$

If the values of δ_{DTX}, α_{ON}, α_{DTX}, α_{OH}, P_{DTX}, P_{OH} and P_{ON}, are known, the base station site power consumption during DTX mode can be calculated by (12).

$$P_{site} = \alpha_{ON}.P_{ON} + \alpha_{OH}.P_{OH} + \alpha_{DTX}.P_{DTX} \tag{12}$$

By substituting (9) into (12), the base station power consumption during the DTX mode is given by (13).

$$P_{site} = \alpha_{ON}.P_{ON} + P_{OH}\left(\alpha_{OH} + \frac{\alpha_{DTX}}{\delta_{DTX}}\right) \tag{13}$$

Figure 4 shows the P_{site} versus the cell average traffic load and DTX factor δ_{DTX} for a SISO macro base station. The curves show that enabling DTX gives significant power savings at low traffic loads. While higher values of δ_{DTX} lead to more savings in the base station power consumption.

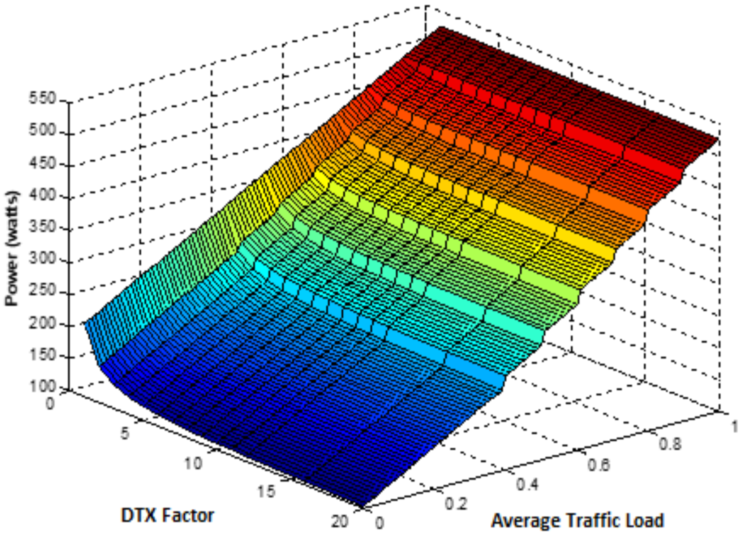

Figure 4: *The power consumption of a SISO macro base station with DTX*

4 MIMO Channel Capacity

Two MIMO operating modes are considered in this paper: 1) a spatial multiplexing MIMO mode with channel state information at the receiver (CSIR); and 2) a spatial diversity MIMO mode based on dominant eigenmode beamforming. The bit/s/Hz channel capacity of an N_t x N_r single user CSIR MIMO scheme, with N_t transmit antennas and N_r receive antenna, is given by (14) [16], where H is the MIMO channel matrix.

$$C_{CSIR} = \log_2\left[det\left(I_{N_r} + \frac{SNR}{N_t} \cdot HH^H\right)\right] \tag{14}$$

In (15), the CSIR MIMO channel capacity is expressed as the sum of N_t channels in terms of the eigenvalues λ_i of HH^H, where SNR represents the signal to noise ratio at the receive antennas.

$$C_{CSIR} = \sum_{i=1}^{i=N_t} \log_2\left(1 + \frac{SNR}{N_t} \cdot \lambda_i\right) \tag{15}$$

For dominant eigenmode beamforming, only one information stream is transmitted, and all the power is allocated to the channel which has the largest eigenvalue λ_{max}. The channel capacity in this case is given by (16).

$$C_{eig} = \log_2(1 + SNR \cdot \lambda_{max}) \tag{16}$$

Figure 5 shows the channel capacity versus SINR of the SISO and the two MIMO schemes. The MIMO channels are modelled as unit variance Gaussian Independent and Identical Distributed zero mean complex processes.

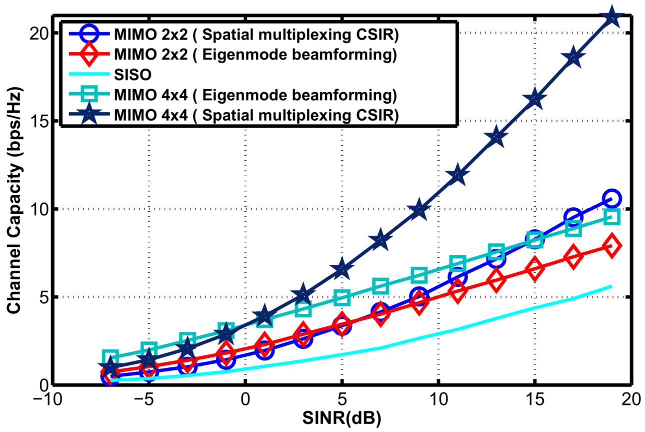

Figure 5: *SISO and MIMO channel capacities*

5 Energy Analysis and Network Model

5.1 Energy Efficiency Analysis

The average site power consumption P_{site} is estimated by the presented power model in Section 2 as a function of the number of transmit antennas and the cell average traffic load factor. The consumed energy in the base station site is given by (17), where T_{OH} is an observation time.

$$E = T_{OH}.P_{site} \tag{17}$$

We determine the energy efficiency using the energy consumption gain (ECG) [9], which defined as the ratio of the energy consumption E_{SISO} of a reference RAN, here comprised of *N* SISO base stations, to the energy consumption E_{MIMO} of a test RAN, here also comprised of *N* MIMO base stations as shown in (18).

$$ECG = \frac{E_{\text{SISO}}}{E_{\text{MIMO}}} \tag{18}$$

The ECG is evaluated at user arrival rates per cell ranging from 0.5 to 1.5 arrivals per second, whereby each user is considered to download a 2 MB file and then departs the network. The user arrival rate is an indication of the average offered traffic per cell. For example, 0.5 arrivals per second is equivalent of $0.5 \times 2 \times 8 = 8$ Mbit/s. The ECG is estimated for the various considered MIMO RANs with reference to a SISO RAN comparing a DTX enabled sites with the disabled case.

5.2 The Network Model

A homogeneous multicell, multiuser RAN with a hexagonal cell layout and omnidirectional base station antennas is simulated in the developed MATLAB simulator. Performance statistics are collected only from the centre cell. The SINR values are calculated by considering only the six first tier of interfering cells. A static system level simulator is used to estimate the users' average throughput as well as the cell average traffic load for the SISO and MIMO RANs. A non-full buffer FTP traffic model with a variable arrival rate, described in 3GPP document 36.814 is adopted. Users dynamically select between spatial multiplexing or diversity modes to achieve a maximum user throughput. Performances between SISO and MIMO schemes are compared for same values of offered traffic and same number of base stations.

6 Results and Discussion

6.1 RAN Energy Efficiency Without DTX

Table 2 lists the main configuration parameters used in the RAN simulation. The cell average traffic load values for the various deployment schemes, given in Table 3, are used to determine the macro cell RAN power consumption for different cell average offered traffic values. The ECG is calculated by (18) for 2x2 and 4x4 MIMO RANs with the SISO RAN as a reference and plotted in Figure 6 for the non-DTX case. The ECG versus the cell average offered traffic of the 2x2 MIMO RAN is nearly always greater than unity. That means, though the SISO RAN can meet the offered traffic requirement, the 2x2 MIMO RAN meets the same offered traffic requirement while expending less energy. This is not the case for the 4x4 MIMO RAN which exhibits an ECG less than unity for all offered traffic values.

Table 2: *Simulation parameters*

Parameter	Omni Macro Cell
Frequency (MHz)	2000
Site Range (km)	Macro 0.5
Antenna Gain (dBi)	15
Wall Penetration loss (dB)	20
Traffic Model	FTP (2MB file)
User Distribution	Uniform
Resource allocation	Round Robin
Observation Time	100000 TTIs
Path loss model	3GPP Uma

Table 3: *Cell average traffic load*

Arrival Rate Per Second Per Cell	Cell Average Offered Traffic (Mbit/s)	Cell Average Load α_{ON}		
		SISO	MIMO 2x2	MIMO 4x4
0.50	8	0.357	0.174	0.100
0.75	12	0.609	0.299	0.172
1.00	16	0.635	0.316	0.182
1.25	20	0.776	0.399	0.232
1.50	24	0.850	0.490	0.295

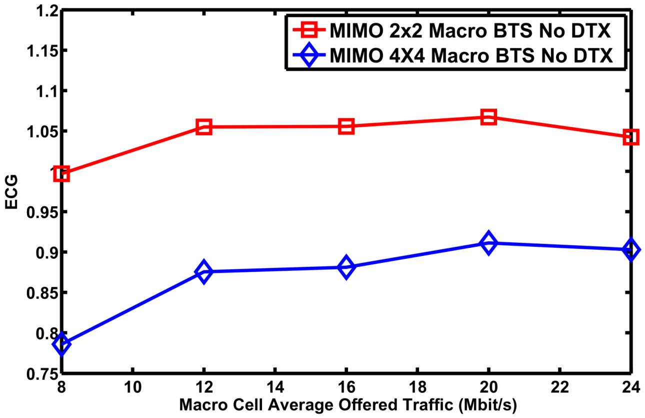

Figure 6: *ECG of 2x2 and 4x4 MIMO macro cells*

The trends in Figure 6 is attributed to the decrease in the cell average traffic load when increasing the number of transmit antennas. While the reduced load factor saves energy, the increase in number of RF chains consumes more energy. An optimum trade-off occurs for the 2x2 MIMO RAN. Thus, from an operator's perspective, upgrading from SISO to 4x4 MIMO cannot be justified on the basis of energy consumption alone.

These observations contradict the widely held view that adaptive MIMO muting techniques always improve the RAN energy efficiency [17]. When measured by the ECG figure of merit, our results illustrate that switching from a 2x2 MIMO mode to SISO degrades the RAN energy efficiency. Also, the curves in Figure 6 show that the use of more than 2 transmit antennas at the base station degrades the energy efficiency. As mentioned earlier, the above results correspond to the non-DTX base station mode of operation

6.2 RAN Energy Efficiency With DTX Enabled

When DTX is enabled, the optimum trade-off between the cell average traffic load and the number of transmit antennas shifts to a new position. Figure 7 plots the curves of ECG versus cell average offered traffic for the same SISO and MIMO schemes with DTX enabled. The reference scheme is a SISO RAN without DTX enabled.

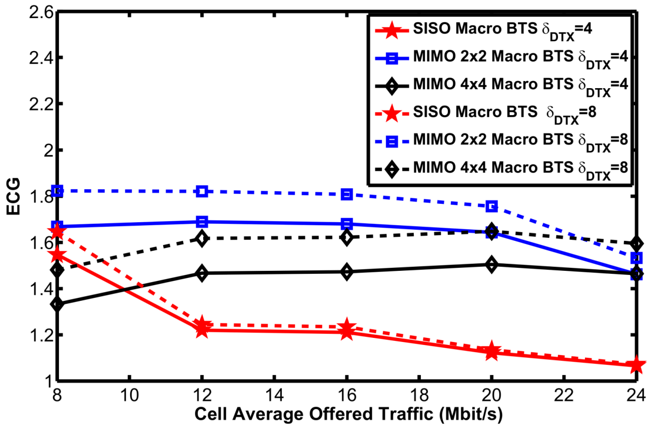

Figure 7: *ECG of SISO and MIMO RANs with DTX enabled*

The curves show that all the DTX cases save energy. At low cell average offered traffic values, the 2x2 MIMO RAN is the most energy efficient scheme whereas at very high offered traffic, the 4x4 MIMO RAN becomes the most energy efficient. Increasing the DTX factor δ_{DTX} from 4 to 8 leads to more energy saving in MIMO RANs than in SISO RANs which illustrates the benefits of DTX in MIMO schemes.

7 Conclusion

A system level evaluation of the energy efficiency of LTE based MIMO RANs was presented in this paper. Two MIMO schemes were considered: 2x2 and 4x4 MIMO with both the diversity and spatial multiplexing gains included in the evaluation. A non-full buffer FTP traffic model was used to model the cell average traffic load variation and to observe the model's impact on the RAN energy consumption. Moreover, the process of modelling the power consumption in radio base stations with DTX either disabled or enabled was presented. The key findings of this paper show that for macro cells, the 2x2 MIMO RAN can provide greater energy efficiency than SISO for the same offered traffic when DTX is disabled. When DTX is enabled, both the 2x2 and 4x4 MIMO RANs are more energy efficient than the SISO RAN.

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