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Study of Spectral Efficiency for LTE Network

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Abstract

The efficiency with which spectrum is used in wireless communication systems is becoming increasingly important as a result of rapidly growing demands for bandwidth-intensive mobile broadband services and the finite nature of usable spectrum. Faced with ever-increasing cost pressures, it is significant for mobile network operator to make the most of spectrum investments. Therefore, this paper serves audience to better understand spectral efficiency, the factors that influence the efficient use of spectrum, the ways of measuring it and finally, what can be done to improve this wireless network performance metric.

Keywords: Wireless Network; LTE; SINR; CQI; Throughput; MIMO; Link Adaptation; Spectral Efficiency.

1. Introduction

The focus of this paper is firstly, to develop a better understanding around Spectral Efficiency for new generation wireless networks, namely for fourth generation mobile network – Long Term Evolution (LTE). Secondly, to comprehend what are the factors that affect this metric and lastly, how could we ameliorate it. Spectral Efficiency is a simple measure of wireless network Capacity. Common definition thereof is the raw bit rate in bits per second divided by the bandwidth in Hertz and it is expressed in bits/s/Hz, that is, throughput divided by bandwidth. It is important to keep in mind that there is a hard limit to how much data can be transmitted in a given bandwidth in accord with Shannon-Hartley theorem (Shannon’s Law):

$$C \approx n * B * \text{Log}_2(1 + S/N) \qquad (1)$$

C – Channel capacity (bits/s); n – number of transmit antennae; B – bandwidth (Hz); S/N – signal-to-noise ratio.

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This theorem defines the maximum rate at which information can be transmitted over a communications channel, over the air interface in our case, of a specified bandwidth in the presence of noise. It establishes a bound on the maximum amount of error-free information per time unit that can be transmitted with a specified bandwidth in the presence of the noise interference, assuming that the signal power is bounded, and that the Gaussian noise process is characterized by a known power spectral density [1].

2. SINR – Signal to Interference and Noise Ratio

In accordance with the equation (1) one can deduce that signal to noise ratio, that is, signal-to-interference-and-noise ratio as far as wireless cellular LTE network is concerned as long as inter cell interference comes into play is a very good indicator for signal quality and is one of the most important factor affecting the spectral efficiency. It is a common practice to use SINR as an indicator for network quality. It should be however noted that 3GPP specifications do not define SINR and therefore UE (User Equipment) does not report SINR to the network. SINR is still internally measured by most UEs and recorded by drive test tools. Unfortunately, UE chipset and RF scanner manufacturers have implemented SINR measurement in various different ways. While at first it may seem that defining SINR should be unambiguous, in case of LTE downlink this is not the case. This is because different REs within a radio frame carry different physical signals and channels each of which, in turn, see different interference level depending on inter-cell radio frame synchronization. For instance, in a frame-synchronized network SINR estimation based on synchronization signals (PSS/SSS) results in different SINR than SINR estimation based on Reference Signals, since in the latter case the frequency shift of the RS depends on the PCI plan. This is illustrated in Figure 1 and will be discussed in more details later on. Average subcarrier SINR can be defined as follows:

$$SINR = RSRP / (I + N) \qquad (2)$$

Where I is the average interference power and N is the thermal noise power. All quantities are measured over the same bandwidth and normalized to one subcarrier bandwidth. In OFDM own cell interference is often assumed to be negligible and consequently I is due to other cell interference only.

The RF quantities discussed in this paper are illustrated by the scanner measurement shown in Figure 1. The scanner location is roughly between two sectors of the same base station; note that the serving and neighbor cell RSRPs are within 2 dB of each other. In the beginning of the measurement, both cells are fully loaded (all subcarriers are utilized). After 85 seconds, the neighbor cell PDSCH utilization drops to 0%. At 165 seconds, also the serving cell PDSCH load drops to 0% [2].

The following observations summarize the main points in this section of the paper:

- RSRP is independent of own cell load and neighbor cell interference. It simply measures coverage similarly to CPICH RSCP in UMTS network.
- RSRQ reacts to load changes in both serving cell and neighbor cell.
- Since the radio frames are transmitted at the same frame timing in both cells, the Secondary

Synchronization Signals (SSS) overlap fully in time. Therefore SINR measured from SSS is continuously close to 0dB, independently of cell load. In TD-LTE all cells in the network are frame synchronized, which makes SSS SINR a simple and useful indicator for measuring physical RF dominance.

- Serving cell load does not impact serving cell RS SINR since PDSCH of the serving cell does not overlap with serving cell RS. On the other hand, neighbor cell RS SINR is reduced by serving cell load since serving cell PDSCH overlaps with neighbor cell RS.
- At the end of the measurement, where both cells are idle, serving cell RS SINR is about 15dB. Ideally, RS SINR should be much higher since the reference signals of the two cells do not overlap and only thermal noise limits RS SINR. The exact reason for the RS SINR degradation is unclear, but might be caused by neighbor cell PDCCH colliding with own cell RS. Note that SINR estimation method used was not documented by the scanner vendor [2].

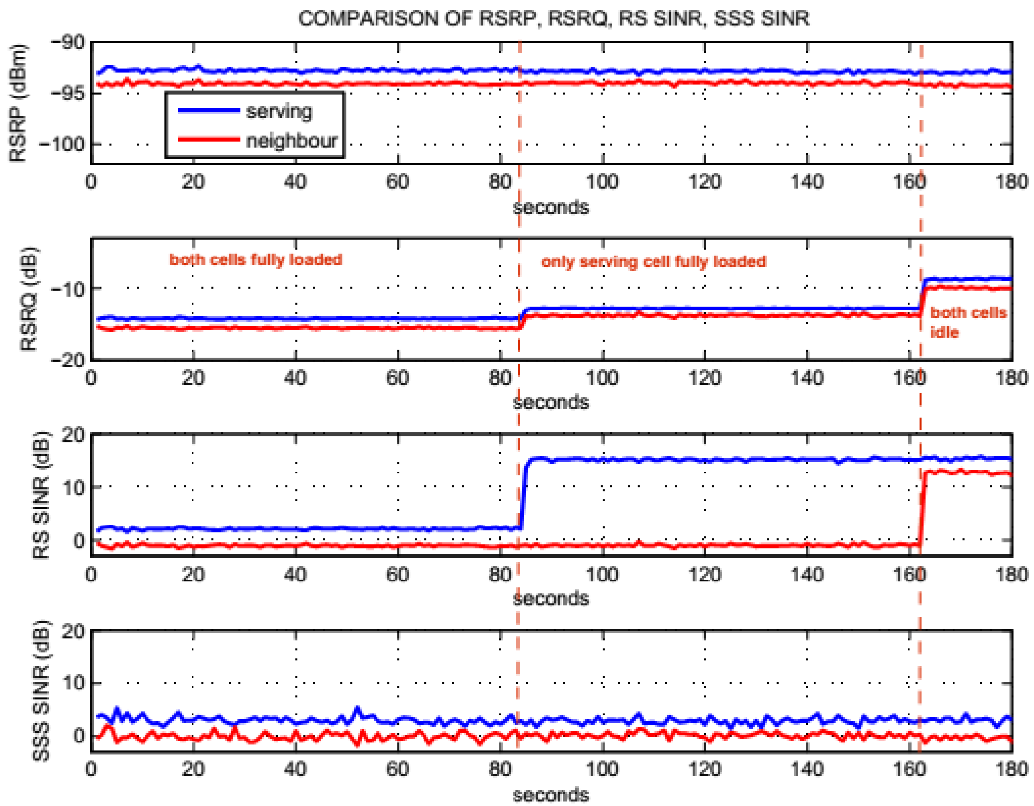

Figure 1: Comparison of RSRP, RSRQ, RS and S-SCH SINR in fading channel conditions. Serving cell PCImod3=0, neighbor cell PCImod3=2. Both cells have two transmit antennae

3. CQI – Channel Quality Indicator

CQI is another pivotal performance metrics that influence spectral efficiency. It is the information sent by UE on the uplink path to the eNB (LTE base station) as an indication of received channel quality and it is used by the packet scheduler for further scheduling purposes. The instantaneous SINR computed at a UE is mapped to a

CQI value and this process is referred to as SINR-to-CQI mapping. The SINR-to-CQI mapping with 10% BLER threshold is shown in Figure 2. A 10% Block Error Rate (BLER) threshold as recommended for LTE system [4] was set in this simulation. Within the BLER threshold, each CQI value corresponds to a specified Modulation and Coding Schema (MCS) index [5].

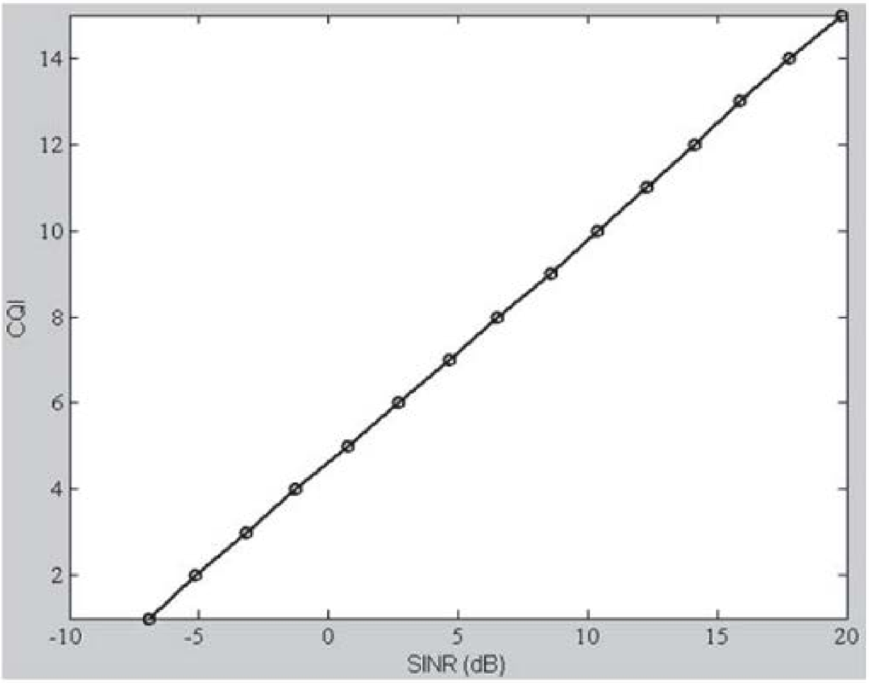

Figure 2: SINR-to-CQI mapping 10% BLER threshold

Besides making a scheduling decision, the CQI report is used to compute the data rate of a user for packet transmission. Based on the data rate, the efficiency of each RE can be determined. Table 1 shows the corresponding MCS and efficiency, in this case expressed in bits/RE, of each CQI category for 10% BLER threshold.

A PRB using normal cyclic prefix contains 168 resource elements (RE). Assuming that a PRB has 148 resource elements for 10% BLER threshold and 20 REs are used for control and signaling purposes [5] - instantaneous data rate can be computed based on the CQI look-up table in accord with the Table 1 and the total number of REs specified for downlink data transmission, the mathematical expression of the instantaneous data rate of each user is given below:

$$R(t) = Efficiency(t) * RE / TTI \qquad (3)$$

R is the instantaneous data rate at time t, Efficiency is the spectral efficiency in accord with Table 1at time t, RE is the total number of REs specified for downlink data transmission and TTI (Transmission Time Interval) represents the current scheduling interval.

Table 1: CQI look-up table considering 10% BLER threshold [6]

CQI	Range of SINR (dB)	MCS		Efficiency (Bits/RE)
		Modulation	Approximate code rate	
0	SINR<-6.936	Out of range	--	--
1	-6.936≤SINR<-5.146	QPSK	0.0762	0.1523
2	-5.147≤SINR<-3.18	QPSK	0.1172	0.2344
3	-3.18≤SINR<-1.253	QPSK	0.1885	0.3770
4	-1.253≤SINR<0.761	QPSK	0.3008	0.6016
5	0.761≤SINR<2.699	QPSK	0.4385	0.8770
6	2.699≤SINR<4.694	QPSK	0.5879	1.1758
7	4.694≤SINR<6.525	16 QAM	0.3691	1.4766
8	6.525≤SINR<8.573	16 QAM	0.4785	1.9141
9	8.573≤SINR<10.366	16 QAM	0.6016	2.4063
10	10.366≤SINR<12.289	64 QAM	0.4551	2.7305
11	12.289≤SINR<14.173	64 QAM	0.5537	3.3223
12	14.173≤SINR<15.888	64 QAM	0.6504	3.9023
13	15.888≤SINR<17.814	64 QAM	0.7539	4.5234
14	17.814≤SINR<19.829	64 QAM	0.8525	5.1152
15	SINR≥19.829	64 QAM	0.9258	5.5547

4. Study of RF Measurements effect on Spectral Efficiency by Analyzing Drive Test Data

This section of the paper presents the effect of LTE radio network measurements on spectral efficiency as well as their inter-dependence based on analyzing North America's one of the largest mobile operator's drive test (DT) data.

Figure 3 shows us the correlation of SINR, CQI and MCS index for 10 MHz channel at 700 MHz band. Dotted line represents the function of SINR to CQI relation expressed with the third order of polynomial equation, from where it can clearly be seen direct correlation between these two indicators – the better the SINR on DL (Down Link) the better is the UE (User Equipment) reported CQI.

Subsequently, the higher is CQI value the higher is MCS index chosen by the link adaptation entity of eNB. MCS index in turn, defines the size of transport block (TBS) with the duration of 1 ms TTI that is, number of transmitted bits, as a result it has an impact on system throughput as well as on spectral efficiency.

Below mentioned MCS and TBS index inter-dependence is defined in 3GPP 36.213 specification table 7.1.7.1-1 and table 7.1.7.1-1A [7] considering higher modulation order of 256 QAM.

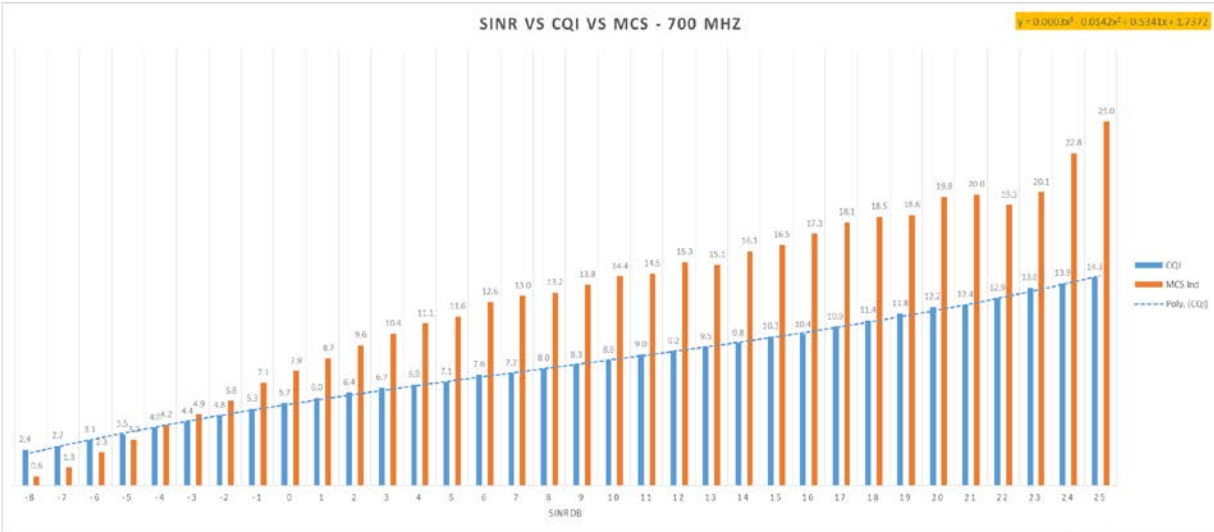

Figure 3: SINR – CQI – MCS correlation

Table 2: MCS to TBS index mapping table

MCS Index I_{MCS}	Modulation Order Q_m	TBS Index I_{TBS}
0	2	0
1	2	2
2	2	4
3	2	6
4	2	8
5	4	10
6	4	11
7	4	12
8	4	13
9	4	14
10	4	15
11	6	16
12	6	17
13	6	18
14	6	19
15	6	20
16	6	21
17	6	22
18	6	23
19	6	24
20	8	25
21	8	27
22	8	28
23	8	29
24	8	30
25	8	31
26	8	32
27	8	33
28	2	reserved
29	4	
30	6	
31	8	

As far as transport block size is concerned, it depends on TBS index and allocated number of PRBs. Their distribution is also defined in 3GPP 36.213 specification table 7.1.7.2.1 [7].

As a logical continuation of the subject, Figure 4 presents SINR, CQI and DL UE Throughput correlation for the same 700 MHz channel. It shows us the degree of UE throughput increase that is, number of transmitted bits per second, in line with the signal quality improvement. At the same time, it is worth mentioning that given values of throughput also depend on the load of serving cell of eNB. The higher the number of active connected UEs the less is the figure of throughput.

Table 3: TB size determination

I_{TBS}	N_{PRB}									
	1	2	3	4	5	6	7	8	9	10
0	16	32	56	88	120	152	176	208	224	256
1	24	56	88	144	176	208	224	256	328	344
2	32	72	144	176	208	256	296	328	376	424
3	40	104	176	208	256	328	392	440	504	568
4	56	120	208	256	328	408	488	552	632	696
5	72	144	224	328	424	504	600	680	776	872
6	328	176	256	392	504	600	712	808	936	1032
7	104	224	328	472	584	712	840	968	1096	1224
8	120	256	392	536	680	808	968	1096	1256	1384
9	136	296	456	616	776	936	1096	1256	1416	1544
10	144	328	504	680	872	1032	1224	1384	1544	1736
11	176	376	584	776	1000	1192	1384	1608	1800	2024
12	208	440	680	904	1128	1352	1608	1800	2024	2280
13	224	488	744	1000	1256	1544	1800	2024	2280	2536
14	256	552	840	1128	1416	1736	1992	2280	2600	2856
15	280	600	904	1224	1544	1800	2152	2472	2728	3112
16	328	632	968	1288	1608	1928	2280	2600	2984	3240
17	336	696	1064	1416	1800	2152	2536	2856	3240	3624
18	376	776	1160	1544	1992	2344	2792	3112	3624	4008
19	408	840	1288	1736	2152	2600	2984	3496	3880	4264

I_{TBS}	N_{PRB}									
	91	92	93	94	95	96	97	98	99	100
0	2536	2536	2600	2600	2664	2664	2728	2728	2728	2792
1	3368	3368	3368	3496	3496	3496	3496	3624	3624	3624
2	4136	4136	4136	4264	4264	4264	4392	4392	4392	4584
3	5352	5352	5352	5544	5544	5544	5736	5736	5736	5736
4	6456	6456	6712	6712	6712	6968	6968	6968	6968	7224
5	7992	7992	8248	8248	8248	8504	8504	8760	8760	8760
6	9528	9528	9528	9912	9912	9912	10296	10296	10296	10296
7	11064	11448	11448	11448	11448	11832	11832	11832	12216	12216
8	12576	12960	12960	12960	13536	13536	13536	13536	14112	14112
9	14112	14688	14688	14688	15264	15264	15264	15264	15840	15840
10	15840	16416	16416	16416	16992	16992	16992	16992	17568	17568
11	18336	18336	19080	19080	19080	19080	19848	19848	19848	19848
12	20616	21384	21384	21384	21384	22152	22152	22152	22920	22920
13	23688	23688	23688	24496	24496	24496	25456	25456	25456	25456
14	26416	26416	26416	27376	27376	27376	28336	28336	28336	28336
15	28336	28336	28336	29296	29296	29296	29296	30576	30576	30576
16	29296	30576	30576	30576	30576	31704	31704	31704	31704	32856
17	32856	32856	34008	34008	34008	35160	35160	35160	35160	36696
18	36696	36696	36696	37888	37888	37888	37888	39232	39232	39232
19	39232	39232	40576	40576	40576	40576	42368	42368	42368	43816
20	42368	42368	43816	43816	43816	45352	45352	45352	46888	46888
21	45352	46888	46888	46888	46888	48936	48936	48936	48936	51024
22	48936	48936	51024	51024	51024	51024	52752	52752	52752	55056
23	52752	52752	52752	55056	55056	55056	55056	57336	57336	57336
24	55056	57336	57336	57336	57336	59256	59256	59256	61664	61664
25	57336	59256	59256	59256	61664	61664	61664	61664	63776	63776
26	66592	68808	68808	68808	71112	71112	71112	73712	73712	75376

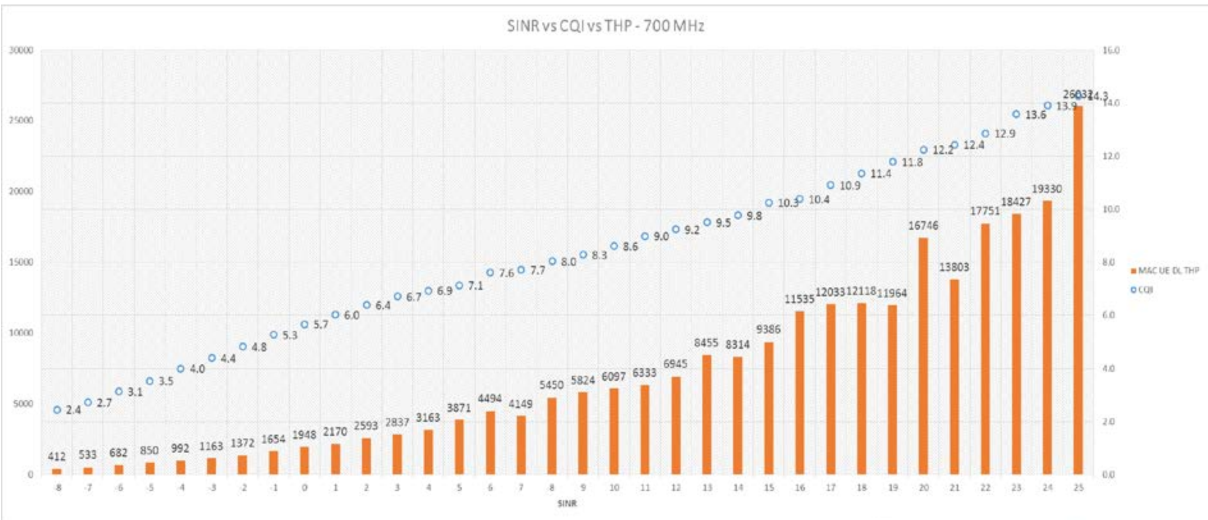

Figure 4: SINR – CQI – UE Throughput (Kbps) correlation

Figure 5 shows us the correlation of SINR, CQI and BLER (block error rate) for the same 700 MHz channel. The chart demonstrates conservative and protective operation of link adaptation mechanism of eNB which is explained by the BLER values that are less than 10% (this value is taken during LTE system design as the error probability at physical and MAC layers); moreover, BLER value is around 6.2% at 21 dB SINR. In other words, there is unnecessary redundancy in the channel coding process – protection bits which reduces effective coding rate and number of real data bits. Consequently, it has a negative impact on spectral efficiency. However, it is also worth mentioning that this function of link adaptation mechanism, in most of the cases, cannot be influenced by parameter change rather it depends on internal settings and algorithms developed by the vendors of the equipment.

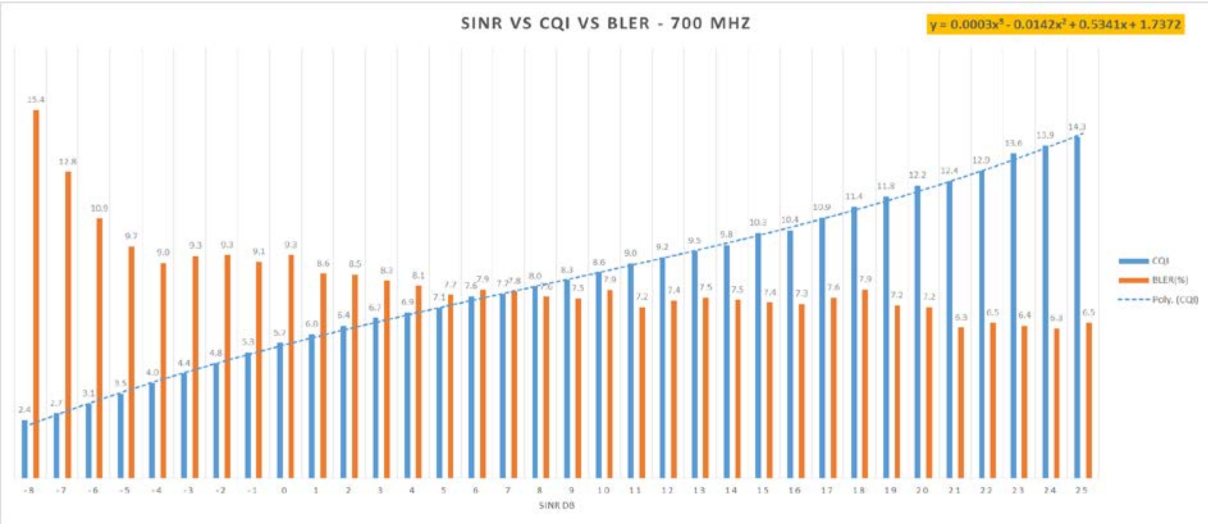

Figure 5: SINR – CQI – BLER correlation

According to the equation 1 another component that is capable of having significant effect on spectral efficiency is number of spatial layers of transmit antennae, that is MIMO (multiple input multiple output) and its usage. Figure 6 shows the correlation of SINR, CQI and MIMO spatial multiplexing utilization for the same 700 MHz channel. Dotted line represents the function of SINR to MIMO usage (RI-2 – rank indicator 2 which stands for 2 spatial layers) relation expressed with the third order of polynomial equation, from where it can clearly be seen direct correlation between these two indicators – the better the SINR on DL the higher is the MIMO RI-2 utilization. By increasing the number of spatial layers we significantly boost number of transmitted information bits which in turn, improves system throughput and spectral efficiency.

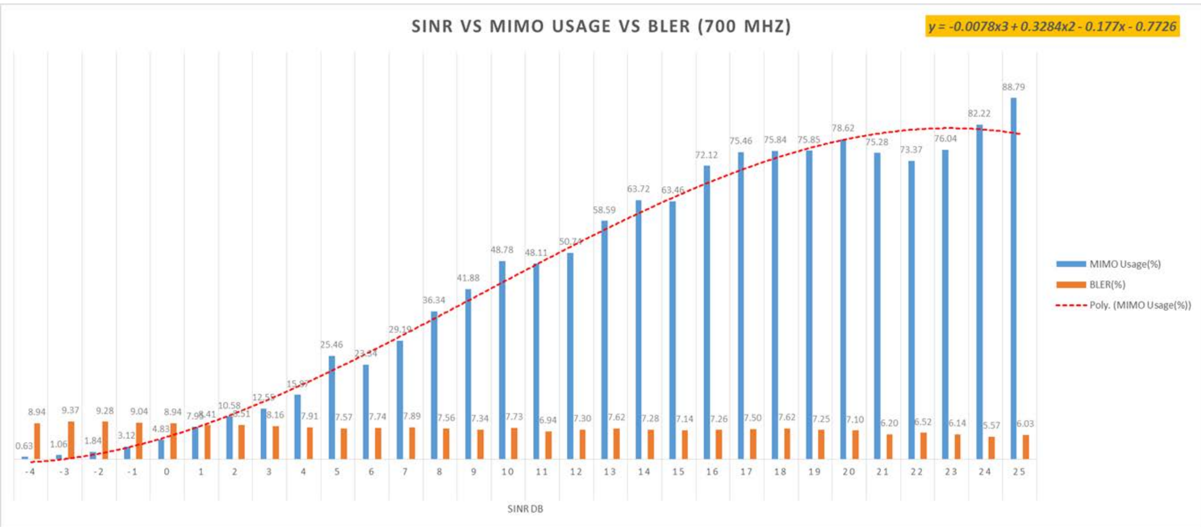

Figure 6: SINR – CQI – MIMO Usage correlation

Let's elaborate a bit more on MIMO utilization. Hence, Figure 7 presents the correlation of SINR and CQI with MIMO spatial multiplexing and transmit diversity modes for the combined 10 and 20 MHz channels at 700 and 1900 MHz bands respectively. Rank indicator determines the selection of transmission layers on DL and it is applicable for open and closed loop transmission modes. RIs can be transmitted either on PUCCH or PUSCH channels on UL from UE to eNB. In case of 2x2 MIMO with two transmit and two receive antennae – RI-1 represents TX diversity and RI-2 spatial multiplexing modes. Red and amber dotted curves show the number of samples per rank indicator.

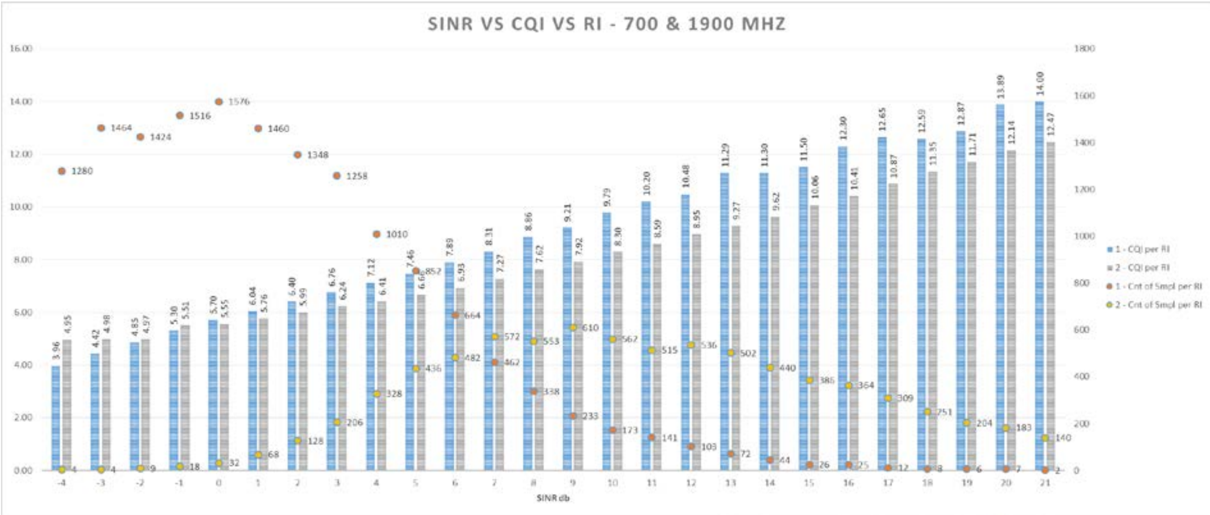

Figure 7: SINR – CQI – RI correlation

According to Figure 7 it is interesting to underline better CQI values reported for RI-1. It can be explained by the nature of transmit diversity operation which increases the signal to noise ratio at the receiver instead of directly increasing the data rate. Each transmit antenna transmits essentially the same stream of data and so the receiver gets replicas of the same signal. A suitable signal combining technique reduces fading variation and increases the signal to noise ratio at the receiver side.

Therefore, the robustness of data transmission is achieved especially in fading scenarios. An additional antenna-specific coding is applied to the signals before transmission to increase the diversity effect. Transmit diversity is only defined for 2 and 4 transmit antennas and one data stream in LTE. Transmit diversity is applied using Space-Frequency Block Coding (SFBC) and Frequency Switched Transmit Diversity (FSTD) [8].

Figure 8 presents correlation of SINR and MCS with MIMO spatial multiplexing and transmit diversity modes for the same combined 10 and 20 MHz channels at 700 and 1900 MHz bands respectively. Red and amber dotted curves show the number of samples per rank indicator. It is worth pointing out better MCS indexes for RI-1 that can be interpreted by better CQI values reported by UEs and at the same time, by protective behavior of eNB’s link adaptation mechanism.

Figure 9 also substantiates conservative operation of LTE base station’s link adaptation entity. The chart shows us MCS index and BLER correlation with MIMO rank indicators for 20 MHz channel at 1900 MHz band. It is observed that MCS index as well as BLER values are better for RI-1 as opposed to RI-2 – the difference is around 3 index in MCS and 1.64% in BLER.

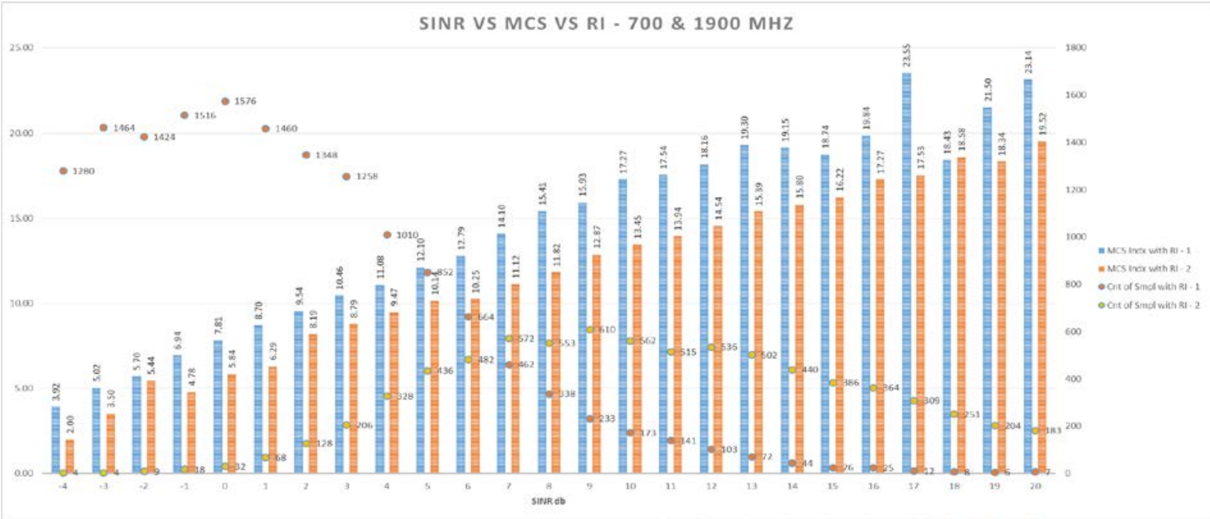

Figure 8: SINR – MCS – RI correlation

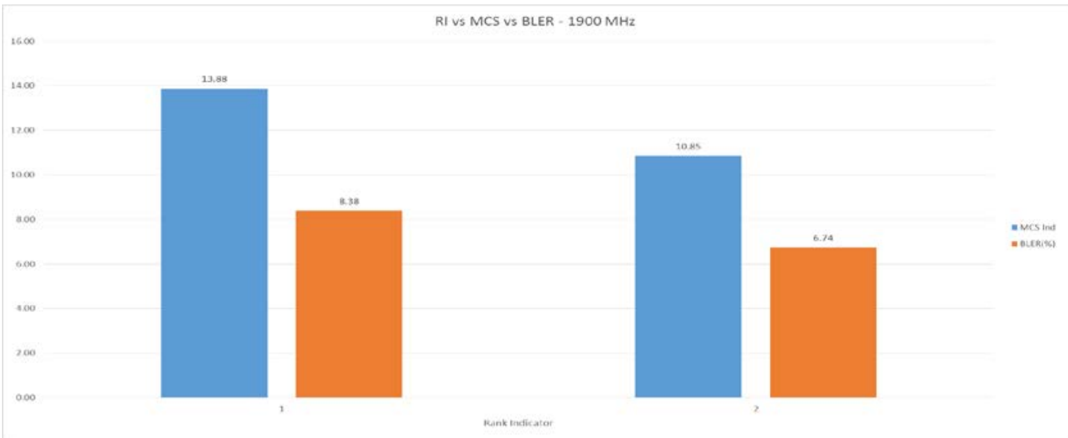

Figure 9: MCS – BLER - RI correlation

5. Conclusion

The focus of this paper is to expound spectral efficiency for fourth generation wireless LTE network, explore the factors affecting it and the possible ways of improving this metric. It is observed from the study and analysis that SINR is one of the most important measurements that influences spectral efficiency directly. Based on SINR, UE calculates CQI value that is reported back to LTE base station, subsequently eNB's link adaptation entity chooses relevant MCS index which is mapped to corresponding TBS index according to which the size of transport block, that is number of transmitted bits is determined on DL path. The more bits are transferred per transmission time interval, the higher is system throughput and the better is the spectral efficiency.

Another important component affecting spectral efficiency is MIMO and usage of its spatial layers. In other words, the number of transmit antennae that significantly increases the amount of transmitted information bits per TTI, subsequently enhancing spectral efficiency considerably.

6. Recommendations

The author also underlines in the paper the importance of LTE base station’s link adaptation mechanism and its optimal operation in order to maximize spectral efficiency. Hybrid link adaptation entities can further be investigated to achieve higher spectral efficiency. Forward error correction (FEC) rate, power levels, modulation and coding rate and power adaptation intervals can be exploited by link adaptation mechanism. The choice for adapting these parameters is dependent on dynamically changing channel parameters such as the instantaneous channel gains, the root mean square (RMS) delay spread of the channel, Doppler frequency spread and average signal to noise ratio (SNR). The term Hybrid is used because not only the bit and power is being adapted but also the adaptation framework could be adapted for achieving higher spectral efficiency with optimal resolution of adaptation [10].

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