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Abstract—**Ultra-reliable communications over wireless will open the possibility for a wide range of novel use cases and applications. In cellular networks, achieving reliable communication is challenging due to many factors, particularly the fading of the desired signal and the interference. In this regard, we investigate the potential of several techniques to combat these main threats. The analysis shows that traditional microscopic multiple-input multiple-output schemes with 2x2 or 4x4 antenna configurations are not enough to fulfil stringent reliability requirements. It is revealed how such antenna schemes must be complemented with macroscopic diversity as well as interference management techniques in order to ensure the necessary SINR outage performance. Based on the obtained performance results, it is discussed which of the feasible options fulfilling the ultra-reliable criteria are most promising in a practical setting, as well as pointers to supplementary techniques that should be included in future studies.**

I. INTRODUCTION

Today's wireless communication systems are designed for transporting a wide range of human-centric multimedia and data contents. However, it is expected that future wireless applications will be complemented by a wide range of machine-centered services that will have a big impact on society [1]. Machine-type communications (MTC) with ultra-reliable communication requirements is one of these new use cases attracting interest within the research community. By ultra-reliable, we mean applications requiring the transmission of a certain payload with low latency and high probability of success; e.g. 99.999%. Examples of applications within this category include vehicular communications for safety, tactile internet, industry automation, and energy management [1], [2], [3].

The signal quality outage performance is of key importance to satisfy stringent reliability requirements; in other words, it is essential that the target users perceive a signal quality above a certain value with high probability. In cellular networks, the signal quality is typically measured in terms of desired signal to interference-and-noise ratio (SINR). The SINR is, however, affected by many variable factors that are intrinsic for any wireless systems [4]. For instance, the desired signal power can be highly attenuated as a result of the fading nature of the wireless channel. Also, the received interference can be large due to the typical aggressive reuse of the time-frequency resources for maximizing system capacity in the network.

Studying the importance and potential techniques to combat these threats is the main focus of this paper. Diversity is a well-known technique used to deal with the fading channel. Diversity can be typically achieved in the space, time or frequency domain. An exhaustive review of the importance of spatial diversity in communication systems is presented in [5]. Appropriate combining of the multiple received signals has substantial importance on the SINR performance, and the most relevant approaches can be found in [6], [7]. Multi-cell cooperation techniques, such as joint transmission and coordinated scheduling, are presented in [8] as a way to improve spectral efficiency and data rates. The SINR outage probability of a joint transmission scheme is analysed in [9]. However, the evaluation in [9] is limited to a specific mobile terminal (MT) at a predefined position in the network. Recent work also evaluates diversity as one of the main enablers for ultra-reliable communication. As an example, [10] investigates utilizing multiple weak links instead of a single powerful link to ensure high availability in a wireless network; whereas [11] evaluates different multiple-input multiple-output (MIMO) antenna configurations to achieve ultra-reliable and low-latency communication. The studies are conducted for a single-user scenario, and hence effects of multi-user and multi-cell interference are not explicitly included in the analysis. Interference management is another complementary approach to improve the signal quality. There is a vast amount of work on interference mitigation and suppression techniques, ranging from static frequency reuse patterns to advanced receivers with interference suppression capabilities [7], [12], [13]. However, their potential to provide ultra-reliable communications requires more studies.

In this paper, we analyse the potential of a wide range of techniques for improving the downlink SINR outage performance in cellular networks. Particularly, spatial diversity techniques at the micro and macroscopic level, as well as interference management approaches, are evaluated. Our objective is to identify the required level of diversity and interference mitigation to achieve very low SINR outage probability as required for ultra-reliable communication. Compared to the studies in [10], [11], our work focuses on a multi-cell/multi-user scenario including diverse system aspects. The chosen evaluation methodology is system-level Monte-Carlo simulations, following the 3GPP-defined LTE simulation assumptions for a traditional macro case.

The rest of the paper is organized as follows: Section II provides a brief description of the studied techniques as well as the modelling of the system. The simulation assumptions are outlined in Section III. Performance results are presented in

Section IV. Section V discuss the implications of the evaluated techniques, and concluding remarks appear in Section VI.

II. System Model

Fig. 1 presents a generic cellular network scenario. Base stations (BSs) are strategically deployed to provide wide coverage to a certain area. In a typical scenario, each BS serves multiple MTs within their respective coverage area. From a MT perspective, the desired signal is contaminated with interference generated by neighbouring BSs. Both BS and MT can be equipped with multiple antennas in order to provide increased microscopic diversity. Additionally, various spatially-separated BSs can cooperatively serve the MT to provide higher order of macroscopic diversity and redundancy. Besides, the received interference at the MT can be reduced by applying interference mitigation or frequency reuse schemes. In the following, the models used to evaluate the performance of these different techniques are presented.

A. Microscopic Diversity

Microscopic diversity is an effective technique to mitigate the effects of multipath fading. Systems with multiple antennas at the transmitter and/or receiver can provide diversity gains as the multiple spatial transmitter-receiver paths can be coherently combined and decrease the overall probability of experiencing poor channel conditions. We consider a typical MIMO system consisting of T transmit antennas and R receive antennas. A closed-loop MIMO scheme is assumed, where the MT feeds back channel information to the serving BS that is used to determine the antenna transmitter weights (also known as precoding). As our focus in this study is on ultra-reliable communication, and therefore on the lower tails of the SINR distribution, only single-stream transmission cases are considered with maximal-ratio combining (MRC) at the receiver [6]. The R-dimensional received signal $\mathbf{r}_j$ by the user served by BS j is expressed as

$$\mathbf{r}_j = \mathbf{H}_j\sqrt{\Omega_j}\mathbf{w}_j^t s_j + \sum_{i=1}^{L}\mathbf{H}_i\sqrt{\Omega_i}\mathbf{w}_i^t s_i + \mathbf{n} , \quad (1)$$

where L is number of interfering signals, $\mathbf{H}_i$ is a RxT matrix whose (m,n)-th element represents the complex channel gain from transmit antenna n at BS i, to receive antenna m; $\mathbf{w}_i^t$ is the T-dimensional precoding vector at the i-th BS; s_i and Ω_i represent the transmitted symbol and the averaged received power from the i-th BS, respectively; for simplicity, $\|s_i\| = 1$; and $\mathbf{n}$ is a $Rx1$ zero mean Gaussian vector with variance σ^2 representing the noise at each receiving antenna. The received signal vector is weighted at the receiver as follows,

$$y = \mathbf{w}_j^r\mathbf{r}_j = \mathbf{w}_j^r\mathbf{H}_j\sqrt{\Omega_j}\mathbf{w}_j^t s_j + \sum_{i=1}^{L}\mathbf{w}_j^r\mathbf{H}_i\sqrt{\Omega_i}\mathbf{w}_i^t s_i + \mathbf{w}_j^r\mathbf{n} , \quad (2)$$

where $\mathbf{w}_j^r$ is the $1xR$ receive weight vector. For MRC, the optimal weights applied at the transmitter and receiving side are given by [6]

$$\mathbf{w}_j^t = \mathbf{u} , \quad (3)$$

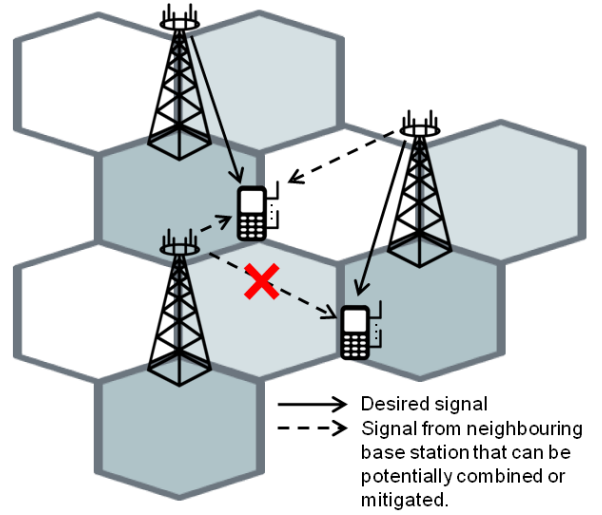$$\mathbf{w}_j^r = \mathbf{u}^H\mathbf{H}_j^H , \quad (4)$$

Fig. 1. Example of typical network layout. The principles of micro and macroscopic diversity techniques, as well as interference mitigation or frequency reuse are also illustrated.

where $\mathbf{u}$ is the unitary eigenvector corresponding to the largest eigenvalue of the $\mathbf{H}_j^H\mathbf{H}_j$ matrix, and $[\cdot]^H$ denotes the Hermitian transpose. In order to emulate the limited feedback capacity of real systems, $\mathbf{u}$ is quantized and restricted to the predefined set of codewords as used in LTE [14]. The closed-loop transmit weight of each interfering link is randomly generated; this allows to decrease the execution time of the simulations with negligible impact on the performance results [15]. The resulting post-detection SINR expression is given by

$$SINR_j = \frac{\Omega_j\|\hat{\mathbf{u}}^H\mathbf{H}_j^H\mathbf{H}_j\hat{\mathbf{u}}\|^2}{\sum_{i=1}^{L}\Omega_i\|\hat{\mathbf{u}}^H\mathbf{H}_j^H\mathbf{H}_i\mathbf{w}_i^t\|^2 + \|\hat{\mathbf{u}}^H\mathbf{H}_j^H\mathbf{n}\|^2} , \quad (5)$$

where $\hat{\mathbf{u}}$ denotes the quantized version of the eigenvector $\mathbf{u}$.

B. Macroscopic Diversity

Macroscopic diversity is another technique for increasing the reliability. The idea is to have multiple BSs transmitting synchronously the same information, which is then combined at the receiver. Macroscopic diversity provides multiple benefits for achieving reliable communication; for example, it helps to combat shadowing effects, improves the diversity and redundancy of the system, and increases the total received power of the desired signal. However, this comes at the expense of using transmission resources for a single user at multiple BSs, which can have negative impact on the total network capacity. A simple soft-combining approach as known from 3G is assumed, where the received signal from each macroscopic branch is independently detected and combined [16]. The *SINR* after combining M macro branches is expressed as follows,

$$SINR = \sum_{j=1}^{M} SINR_j , \quad (6)$$

where $SINR_j$ is the SINR calculated according to (5), assuming the MT is connected to BS j. In a cochannel scenario, the best SINR performance is obtained by connecting to the M BSs with the highest received power. This is the approach applied in this study.

C. Interference Mitigation

The received interference from multiple BSs can be reduced in order to improve the SINR at the MT. Ideal cancellation of the signal received from the C ($1 \leq C \leq L$) strongest interfering BSs is assumed. This BS subset is denoted as A. The resulting SINR expression is as follows,

$$SINR_j = \frac{\Omega_j \|\hat{\mathbf{u}}^H \mathbf{H}_j^H \mathbf{H}_j \hat{\mathbf{u}}\|^2}{\sum_{i=1}^L \Omega_i \|\hat{\mathbf{u}}^H \mathbf{H}_j^H \mathbf{H}_i \mathbf{w}_i^t\|^2 \mathbf{1}_{\{i \in A^C\}} + \|\hat{\mathbf{u}}^H \mathbf{H}_j^H \mathbf{n}\|^2}, \tag{7}$$

where $\mathbf{1}_{\{i \in A^C\}}$ denotes the indicator function of the set A^C, and $[\cdot]^C$ denotes the complement; i.e. $\mathbf{1}_{\{i \in A^C\}} = 0$ if the received power from BS i is cancelled; otherwise $\mathbf{1}_{\{i \in A^C\}} = 1$.

D. Frequency Reuse

With frequency reuse, the frequency resources are strategically distributed among the different BSs to reduce the cochannel interference and increase the SINR. Apart from the full frequency reuse scheme, a hard frequency reuse with 1/3 reuse factor is considered. This principle is illustrated in Fig. 1, where the resources used to serve MT within each sector are represented with different colours. Eq. (7) can also be used to represent the frequency reuse approach, with A corresponding to the set of BSs not utilizing the same frequency resources as the desired signal. Equal amount of resources per sector is assumed.

III. SIMULATION ASSUMPTIONS AND CONFIDENCE INTERVAL CALCULATION

A. Simulation Assumptions

The evaluation is carried out by analysing the downlink SINR distribution with different degrees of micro and macroscopic diversity, interference cancellation and frequency reuse schemes. A dense macro-cellular network composed of three-sector sites with an inter-site distance of 500 m is simulated, where MTs are uniformly distributed. All BSs are transmitting at full power (full load conditions) at a 2 GHz carrier frequency. A omnidirectional antenna pattern is assumed at the MT, whereas a three-dimensional antenna with horizontal and vertical patterns is assumed at the BS [17], including the effect of antenna downtilt. The propagation is modelled according to [17]. This includes distance-dependant pathloss, the effects of log-normal shadowing and fast fading. The fast fading is independent and identically distributed for each transmit-receive antenna pair, following a complex Gaussian distribution (i.e. the envelope is Rayleigh distributed).

For each MT, the models presented in Section II to calculate the experienced post-detection SINR for different techniques are applied. Effects of user mobility and handovers are not explicitly included in the simulations. However, the effect of handover hysteresis margins are implicitly model in the serving BS selection algorithm: each MT identifies the strongest received BSs that are within a certain *handover window*, as compared to the strongest BS. The serving BS for the MT is then randomly selected from the BSs within the *handover window*. This is a simple method for modelling the effect where not all MTs are served by their strongest BS due to the use of handover hysteresis margins in reality. Table I summarizes the simulation assumptions.

TABLE I.   SIMULATION ASSUMPTIONS

Parameter		Value
Network layout		3GPP macro case 1
BS transmit power		46 dBm
Carrier bandwidth and frequency		10 MHz @2.0 GHz
Pathloss		$128.1 + 37.6 \log 10(R[\text{km}])$ dB
Antenna pattern		BS: 3D with $12°$ downtilt
		MT: omnidirectional
Antenna gain		BS: 14 dBi. MT: 0 dBi
Shadowing	Distribution	Log-normal with $\sigma = 8$ dB
	Intra-site correlation	1.0
	Inter-site correlation	0.0
Noise	Power spectral density	-174 dBm/Hz
	Noise figure	8 dB
	Total noise power	-96 dBm
Handover window		3 dB
Fast fading		Rayleigh distributed; Uncorrelated among
		the different diversity branches
SINR outage target		0 dB at the 10^{-5}-th percentile

The generated SINR samples from all the users are used to form empirical cumulative distribution functions (CDF). For ultra-reliable communication, the key performance indicator is the SINR at the very-low percentiles, considering here the 10^{-5} level in line with [1]. Achieving reliable communication requires that the MT is able to correctly receive both the scheduling grant from the BS and the corresponding transport block with the actual data payload (i.e. information bits). Taking LTE as a reference, the scheduling grant is sent on the physical downlink control channel (PDCCH). Referring to the studies in [18], [19], the MT can decode the PDCCH with 10^{-2} error probability at -5 dB if the PDCCH is transmitted with the strongest coding format. However, in order to achieve truly error free PDCCH reception, an SINR of approximately 0 dB (or higher) is required, when including various imperfections. At 0 dB SINR, also the transport block with data on the physical downlink shared channel (PDSCH) can be correctly decoded if transmitted with QPSK and a conservative encoding rate[1] (e.g. 1/3) [20]. Hence, in this study we consider 0 dB SINR as the minimum threshold for a MT to have error free downlink reception, without relying on hybrid automatic repeat request retransmissions which further impacts the latency and reliability.

B. Statistical Confidence Considerations

To guarantee high statistical confidence of the results, the confidence intervals are estimated using the normal approximation of the Binomial proportion [21]. The interval of a certain percentile $\hat{\gamma}$ is approximately $\hat{\gamma} \pm z_{\alpha/2}\sqrt{\hat{\gamma}(1-\hat{\gamma})/N}$, where N is the generated number of independent samples, $z_{\alpha/2}$ is the $100(1-\alpha/2)$-th percentile of the standard normal distribution, and α is the confidence level associated to the confidence intervals of the experiment. As an example, for a target of 95% confidence level in the estimate of $\hat{\gamma}$ within a $\pm 20\%$ interval we have

$$\frac{1.96\sqrt{\hat{\gamma}(1-\hat{\gamma})/N}}{\hat{\gamma}} < 0.2 . \tag{8}$$

For $\hat{\gamma} = 10^{-5}$, the required number of uncorrelated samples is then given by

$$N = \frac{1}{(0.2)^2}(1.96)^2 \frac{1-\hat{\gamma}}{\hat{\gamma}} = 9.604 \cdot 10^6 . \tag{9}$$

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[1]This is a fair assumption given the typically low data rates of use cases requiring ultra-reliablity.

We go beyond that limit and generate at least $N = 16 \cdot 10^6$ uncorrelated SINR samples for each of the simulated configurations.

IV. RESULTS

A. Microscopic Diversity

Fig. 2 shows the empirical CDF of the SINR distribution with different configurations of transmit and receive antennas. For each curve, the surrounding grey area represents the 95% confidence interval. At the 10^{-5}-th percentile, the SINR obtained with a single antenna configuration can be as low as -45 dB. This suggest that single transmit-receive antenna schemes are not appropriate for ultra-reliable communications. In contrast, the increased diversity order obtained with 2x2, 4x2 or 4x4 configurations results in steeper slopes and significantly better SINR performance, being the 4x4 antenna scheme only 6 dB away from achieving the 0 dB SINR target. It is worth mentioning that a 2x2 MIMO configuration is the most commonly used scheme in today's cellular systems such as LTE.

B. Macroscopic Diversity

Fig. 3 shows the SINR statistics of different macroscopic and microscopic configurations. The confidence intervals are no longer shown; however, the generated number of samples is kept the same, hence the curves have similar confidence as those shown in Fig. 2. It is observed that macroscopic diversity provides considerable gains in the SINR outage performance. By adding a secondary macroscopic link, more than 6 dB SINR improvement is obtained at the 10^{-5}-th percentile, which allows the 4x4 configuration to fulfil the 0 dB SINR requirement. The macroscopic gain comes mainly from the higher received power as well as the additional protection against shadow fading. The soft-combining is especially relevant for cell-edge MTs, which are likely to receive similar power from the M strongest BSs. Macroscopic diversity also minimizes the negative performance impact of the considered handover hysteresis window, since the probability of not being connected to the strongest BS is reduced.

C. Interference Mitigation

Fig. 4 shows the SINR distribution of 2x2 and 4x4 configurations assuming ideal cancellation of the C strongest interferers. As expected, cancelling the interference provides some SINR gains. However, the slope of the curve is not increased since the diversity order remains the same. Nevertheless, a 4x4 antenna configuration with ideal cancellation of the three strongest interfering links allows to fulfil the 0 dB SINR target with the desired outage probability.

D. Frequency Reuse

Fig. 5 shows the SINR statistics when applying a fixed frequency reuse scheme of 1/3 and different orders of macroscopic diversity. Similar to the performance observed with interference cancellation, the applied technique does not provide any additional diversity order. But, substantial gains are achieved in the very low percentiles of the SINR distribution due to the drastic reduction of the interference. The 0 dB SINR
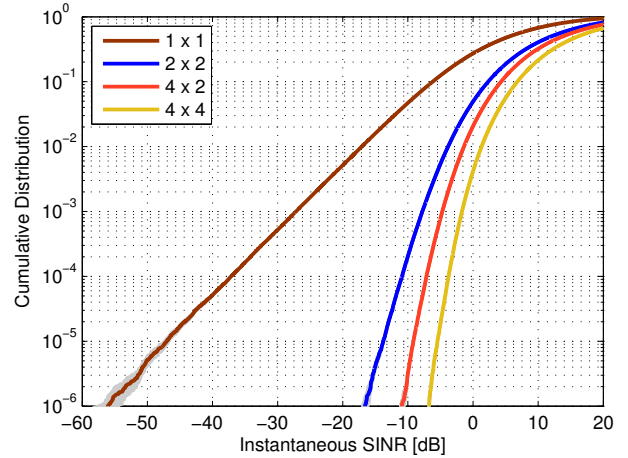

Fig. 2. SINR performance with different MIMO antenna configurations. The legend indicates Number of transmitting antennas x Number of receiving antennas. For each curve, the surrounding grey area represents the confidence interval at the 95% confidence level.
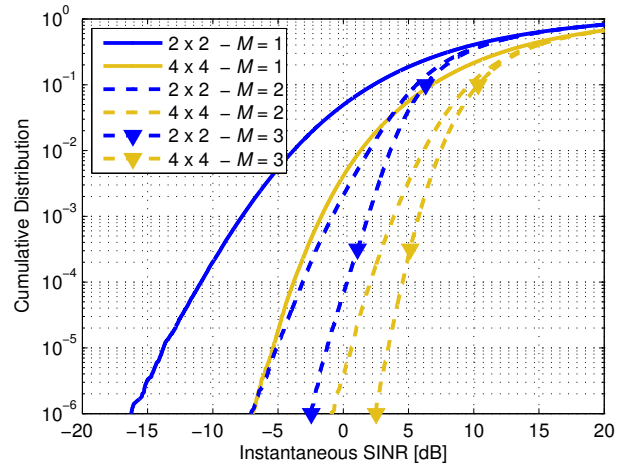

Fig. 3. SINR performance with different levels of macroscopic diversity applied to a 2x2 and 4x4 MIMO antenna configurations.

target can be achieved by using a 2x2 MIMO scheme together with $M = 2$ macroscopic links. Notice that the macroscopic diversity gains are slightly larger than those obtained with the full frequency reuse scheme (see Fig. 3). In this case, the multiple BSs serving a certain user are likely to be using different frequency resources therefore not interfering with each other.

V. SUMMARY AND DISCUSSION

Fig. 6 presents a summary of the achieved SINR at the 10^{-5}-th percentile for 2x2, 4x2 and 4x4 microscopic antenna schemes together with diverse configurations of macroscopic diversity and interference management techniques. The plotted configurations are selected according to the attained performance and deployment feasibility. The 0 dB SINR target is represented with a horizontal dashed line. Among the various configurations shown in Fig. 6, a 4x4 antenna scheme with $M = 2$ macroscopic links seems to be the most feasible configuration for achieving the ultra-reliability target. Similar
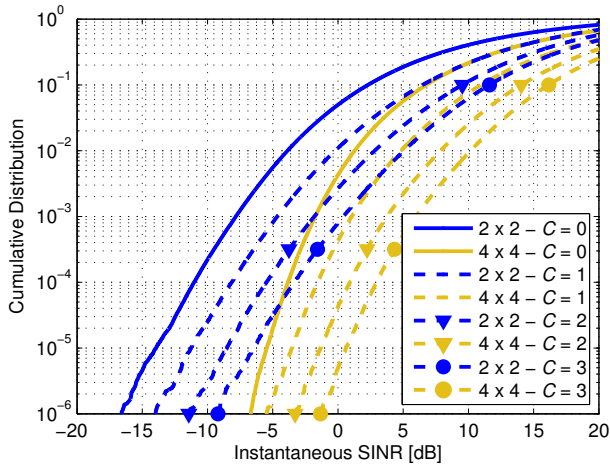
Fig. 4. SINR performance assuming ideal cancellation of the *C* strongest interfering signals.

Fig. 5. SINR performance when applying a frequency reuse scheme of 1/3 with different macroscopic and microscopic diversity configurations.

performance can also be achieved by e.g. cancelling the received power from the three strongest interferers. However, in practice, full non-linear interference cancellation of three interferers is most likely not possible [22], so the performance obtained with this configuration should be regarded as an upper bound. A 2x2 microscopic diversity scheme on its own is not able to provide the required performance to achieve ultra-reliable communications. The results suggest that such configuration must be complemented with significant reduction of interference by e.g. applying a frequency reuse scheme and having at least two macroscopic links, in order to fulfil the required SINR target. As expected, the 4x2 antenna configuration attains a performance in-between the 2x2 and 4x4 schemes. With 4x2, the 0 dB SINR target can be achieved by adding an additional macroscopic link, compared to what is needed for 4x4 schemes. This configuration is relevant for small devices (e.g. sensors and actuators in wireless-automated industries) where it might be difficult to accommodate a high number of antennas in the MT. The obtained results further motivates relevance of 5G research focusing on cases with at least 4x4 MIMO and various interference suppression techniques [22], [23].

Macroscopic diversity is clearly an important technique to increase the reliability, providing increased diversity against both fast and slow fading, and more transmit power towards the user. Furthermore, macroscopic diversity offers robustness towards BS failures, as well as additional mobility robustness during handovers from one BS to another. However, compared to microscopic diversity, macroscopic diversity consumes resources for a single user at multiple BSs, which can have negative impact on the total network capacity. Secondly, tight coordination and low latency communication between the BSs involved in macroscopic transmission are needed. Thus, in line with basic communication theory, achieving ultra-reliable communications comes at a cost in terms of reduced average spectral efficiency [4].

The performance results for frequency reuse 1/3 show significant improvements in the SINR performance. In this respect, it is worth noticing, that if applying channel and interference aware frequency domain packet scheduling (as e.g.
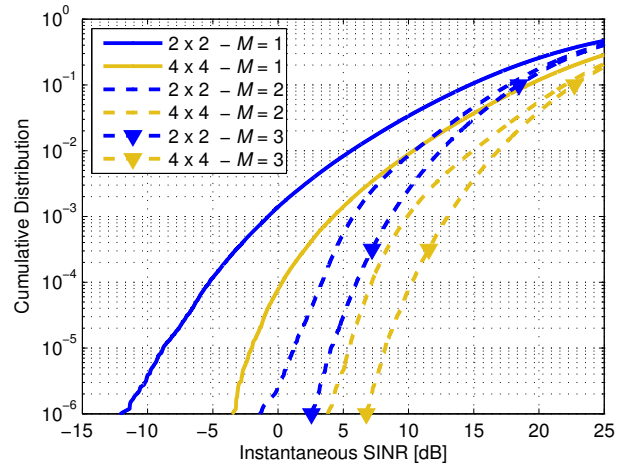
supported in LTE), then the system converges to an equivalent frequency reuse pattern depending on the offered traffic [20]. Hence, the performance results for frequency reuse 1/3 are equivalent to the performance that would be experienced under fractional load conditions, where each BS only utilize 33% of the available frequency domain resources.

Although the interference mitigation techniques do not improve the distribution (i.e. diversity order) of the desired signal, improvements in the SINR outage performance are still visible. In this study, only ideal non-linear interference cancellation has been considered, although other techniques are also of interest. Among others, it is suggested to conduct further research on other candidate techniques like linear interference-rejection combining (IRC) and more sophisticated proactive or reactive network based interference coordination techniques. As compared to existing studies of network-based interference coordination techniques (see e.g. [13]), the optimization target to have ultra-reliable communication would likely lead to slightly different solutions. Similarly, addition of small cells at strategically chosen locations to enhance reliability is another future research direction [23]. See also [4] for additional pointers to 5G enhancements for ultra-reliable communication.

VI. CONCLUSIONS

In this study, we have evaluated the potential of diversity and interference-management techniques to achieve ultra-reliability in the 3GPP-defined macro cellular scenario. Micro and macroscopic diversity techniques have been shown to be one of the main enablers of ultra-reliable communications. The evaluated spatial techniques not only provide high diversity to combat the fast fading in the wireless channel, but also increase the robustness of the communication. For a 10^{-5} desired SINR outage, a 4x4 MIMO scheme with second order macroscopic diversity is considered as the most feasible configuration when taking practical implementation considerations into account. Mitigating the interference by either network-based or terminal-based techniques has been identified as a promising complementary solutions to improve the SINR outage performance. Although such techniques do not increase the diversity of the desired signal component, up to 10 dB
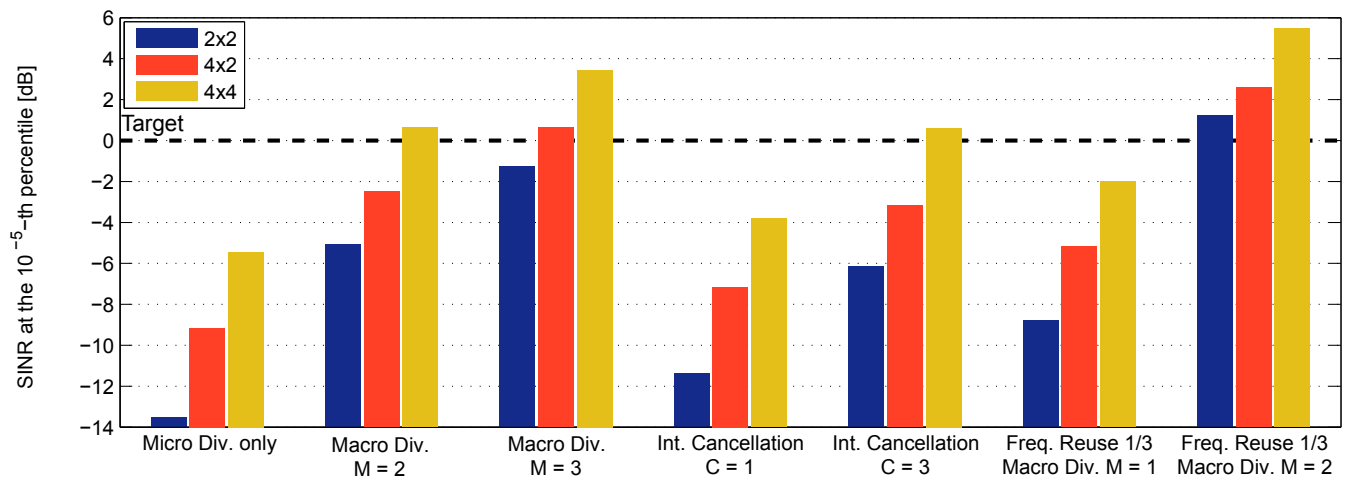
Fig. 6. Achieved SINR at the 10^{-5}-th percentile for several diversity and interference management configurations.

gain in the outage SINR is achieved by cancelling multiple interferers or applying a 1/3 frequency reuse scheme in the studied scenario.

Future work must further consider the imperfections present in real systems such as non-ideal channel estimation, correlation among the multiple antennas, and more realistic modelling of interference mitigation techniques. Extending the evaluation to include wideband systems with frequency-selective fading channels is also of interest. On a further note, evaluations for other scenarios in addition to the generic 3GPP cases are also recommended. For instance, analysis of scenarios based on data from real network deployments to further assess the degree of reliability that can be supported.

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