LTE Uplink Performance with Interference from In-Band Device-to-Device (D2D) Communications

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***Abstract*—Direct device-to-device (D2D) communications between mobile terminals in cellular networks allows operators to offload proximity traffic from the Radio Access Network (RAN) and permits out-of-coverage terminals to maintain peer-to-peer communications. In this study, we consider D2D communications in the context of the Long Term Evolution (LTE) RAN and, in particular, the scenario in which D2D communications share LTE uplink resources. Specifically, we evaluate the performance degradation of the cellular LTE uplink in the presence of interference from in-band (underlay) D2D communications. Through physical layer simulations, we quantify the increase in signal-to-noise ratio (SNR) needed to maintain a certain data rate or coverage criterion as a function of the induced noise rise and under various multipath channel conditions. The results can be used to develop physical layer models for network-layer analyses of D2D and cellular network performance.**

***Index Terms*—Device-to-device; Long Term Evolution; public safety.**

I. INTRODUCTION

Cellular networks are continuing to evolve away from the traditional "hub-and-spoke" Radio Access Network (RAN) architecture consisting of high-power base stations communicating with a large population of user equipment (UE). As cellular traffic goes from being dominated by data rather than telephony, following the trend of wired networks a decade ago, the RAN architecture is changing in order to meet the resulting demand for increases in capacity and coverage expansion. The introduction of lower power base stations, i.e., small cells, is an example of this type of transformation [1].

Another, more recent, development is the recent surge of interest in technologies to enable Device-to-Device (D2D) communications [2]. While D2D communications will be possible with or without assistance from an enhanced Node-B (eNB) (i.e., base station), unassisted communication is of particular interest to the public safety community because it enables small groups of public safety personnel to communicate in emergency situations even if they are out of coverage of any eNBs or relay nodes [3]. However, networks of D2D UEs that operate as an underlay without coordinating with any nearby RANs can interfere with those networks if some D2D UEs are located outside but close to a cell's coverage area. How close a D2D network can be to a cell's coverage area is thus an important architectural question.

In this paper, we characterize the performance of the LTE uplink in the presence of co-channel interference from D2D transmitters. We define several performance metrics that a network operator can use to determine the severity of the D2D network's effect on the cellular network, and we use Monte Carlo simulation to obtain values for these metrics.

II. D2D SCENARIOS AND ASSUMPTIONS

A variety of scenarios are possible for the implementation of D2D communications in an LTE band. Among the design considerations are whether to reuse the uplink, downlink, or both, and whether D2D usage will be permitted for users who are out of coverage of the LTE radio access network (RAN), in network coverage, or both. This section discusses each option and the assumptions made in this paper.

A. Uplink vs. Downlink Reuse

Assuming the LTE RAN uses frequency division duplex (FDD), a key design choice for a D2D system is whether it shares the uplink band, downlink band, or both bands of the LTE RAN. In the case of uplink reuse (Fig. 1(a)), the potential victims on the infrastructure network are the eNBs. Sources of interference to the D2D links are user equipment (UE) connected to the LTE RAN and communicating with the eNB. Furthermore, if the cellular system is uplink-limited, as is often the case, the interference power from an out-of-coverage D2D link, I_{D2D}, shown in Fig. 1(a), will be no stronger, on average, than the uplink received signal power from a cellular UE, S_{CUE}. Hence, the signal-to-interference ratio (SIR) at the eNB due to a single out-of-coverage D2D emitter is lower-bounded by 0 dB (i.e., $SIR_{eNB} = S_{CUE}/I_{D2D} > 1$).

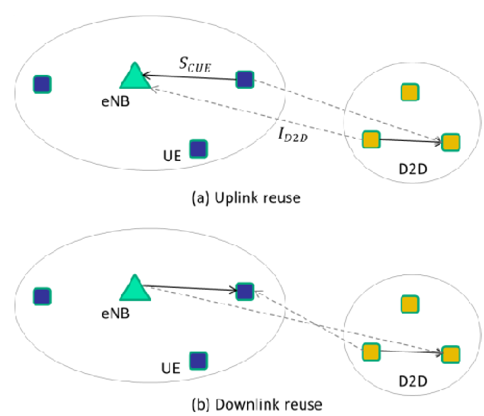


Fig. 1: Interference in uplink and downlink reuse scenarios

In the case of downlink reuse (Fig. 1(b)), the potential victims on the infrastructure network are UEs, and eNBs are the sources of interference to D2D links. Unlike the uplink reuse case, no immediate conclusions can be made on the SIR at the cellular UEs or D2D receivers. However, Doppler et al. [4] report that uplink interference to D2D communications from cellular UEs is much lower than downlink interference from eNBs and conclude that reusing downlink resources is therefore more challenging. In addition, as summarized by Qianxi et al. [5], a recent contribution to 3GPP on the D2D interference issue [6] also found that the interference seen by cellular UEs from D2D UEs transmitting on the downlink can be greater than the interference seen by eNBs from D2D UEs transmitting on the uplink, and that downlink interference is harder to control. The authors in [6] also note that allowing D2D UEs to transmit on the downlink requires adding an additional transmitter to the UE if FDD is being used, and that there may be regulatory obstacles to allowing D2D UEs to use the downlink. For these reasons, we consider the uplink reuse scenario in this paper.

B. In-coverage vs. Out-of-coverage

Another aspect of the D2D system is whether the UEs in the D2D networks are all in coverage of the RAN, out of coverage, or a mixture, where some are in coverage and some are out of coverage. A key advantage of in-coverage D2D communications is tighter control of reuse of the band through network directed resource allocation, potentially leading to more efficient use of the spectrum and reduced interference. The main motivation for out-of-coverage D2D communications is to provide the opportunity for peer-to-peer communication in unserved areas (e.g., remote areas, indoor environments, and underground). The out-of-coverage scenario is of particular interest to the public safety community, which currently relies on the direct-mode of communications of its legacy narrowband technology. While the analysis of this paper is agnostic with respect to in-coverage versus out-of-coverage scenarios, the latter scenario lends itself to convenient bounds on interference, as noted above and discussed further below.

III. Performance Metrics

When evaluating the performance of the infrastructure network in the presence of D2D reuse of the uplink, a number of metrics can be considered. This section describes the performance metrics used in our analysis.

A. Noise Rise

A common metric of the uplink environment in cellular systems is the noise rise due to out-of-cell emissions. Noise rise is defined here as the ratio of the interference-plus-thermal-noise power to the thermal noise power:

$$NR \triangleq \frac{I_{D2D} + N}{N} > 1$$

where N is the average receiver noise power due to thermal energy.

In the out-of-coverage scenario, we have observed that the average interference power at the eNB from a D2D transmitter is upper-bounded by the average received cellular UE signal power. Let $\gamma_0 = S_0/N$ be the minimum required signal-to-noise ratio (SNR) on the cellular uplink for a cellular UE located at the cell edge. Then, the noise rise due to a single out-of-coverage D2D transmitter can be upper-bounded as follows:

$$NR = \frac{I_{D2D}}{N} + 1 < \frac{S_0}{N} + 1 = \gamma_0 + 1.$$

For example, if $\gamma_0 = -1.6$ dB—which according to our simulations achieves a 2 % block error rate (BLER) with the 3GPP Extended Vehicular A (EVA) channel model [8] and modulation-coding scheme (MCS) 0 using five resource blocks and two-antenna receive diversity[1]—then the noise rise is at most 2.3 dB.

B. Increase in Required SNR

An increase in the noise rise naturally translates to a decrease in the signal-to-interference-plus-noise ratio (SINR). From another point of view, it also translates into an increase in the required SNR to maintain some coverage contour or some data rate, as illustrated in Fig. 2. Typically, thermal noise is modeled as an additive white Gaussian process, and the BLER is some function of the SNR: $BLER = f(S/N)$. If the interference can be modeled as additive white Gaussian noise (which is not the case, in general), then we have

$$BLER = f\left(\frac{S}{I+N}\right) = f\left(\frac{S}{N}\cdot\frac{N}{I+N}\right) = f\left(\frac{\gamma}{NR}\right)$$

where $\gamma = S/N$ is the SNR in the absence of interference and NR is the noise rise due to interference from the D2D network. If γ_0 is the required SNR to achieve some target BLER, then to maintain the same BLER in the presence of D2D interference, the new required SNR must be $\gamma_1 = \gamma_0 \cdot NR$, and the *increase* in required SNR, γ_1/γ_0, is just the noise rise, NR. Since, in general, the interference does not fit a white Gaussian noise model, the increase in required SNR will be some unknown function of the noise rise, $g(NR)$, and $\gamma_1 = \gamma_0 \cdot g(NR)$. The objective of the performance evaluation below is to characterize the increase in required SNR, $g(NR) = \gamma_1/\gamma_0$, as a function of the noise rise.

Fig. 2 shows illustrative receiver BLER curves versus SNR when a given MCS is used, for the cases where a D2D interferer is present and where there is no D2D interference. As the figure shows, the addition of an interference signal pushes the BLER curve outward, so that the SNR γ_1 is required to achieve the target BLER that can be achieved with SNR γ_0 when no interference is present. Note that the increase in SNR, $g(NR)$, can change with the required BLER and also depends on the MCS in use. Part of the analysis is thus determining which subset of the parameter space we need to examine.

C. Decrease in Cell Coverage/Throughput/Capacity

While noise rise and required SNR are fundamental metrics at the physical layer, of ultimate concern to a cellular operator and cellular users is the impact of D2D interference on higher layer metrics such as throughput, cell capacity, and cell coverage. From a design point of view, it may be desirable to map these higher layer metrics to margins on lower layer

[1] For comprehensive simulation results without D2D interference, see [7].

metrics. For example, one might like to know how much noise rise can be tolerated by the cellular system subject to some maximum degradation in cell coverage, link throughput, and/or cell capacity. Answering such questions requires additional assumptions, such as a propagation model to predict cell coverage. Section V presents an example application of the results below to the question of cell coverage degradation.

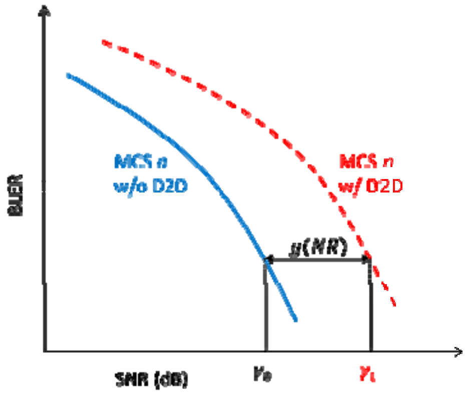


Fig. 2: Impact of D2D interference on required SNR

IV. Performance Evaluation

In this section, we focus on evaluating LTE performance degradation at different noise rise values when the noise rise comes from in-band D2D transmissions. In addition to the noise rise, other factors to be considered in the evaluation are modulation and coding scheme (MCS) selection and the fading channel model. We assume D2D communications share the LTE FDD uplink spectrum resulting in LTE uplink performance degradation from D2D interference.

A. Approach and Assumptions

We simulate multiple scenarios for the source and victim links where a scenario is defined by MCS selection as well as the 3GPP fading channels assigned to both LTE and D2D links. The MCS is one of the following: MCS0 (QPSK), MCS15 (16QAM), and MCS25 (64QAM). The 3GPP fading channel models for LTE users may be one of the following, which are defined in [8] and [9]: Extended Pedestrian A with 5 Hz Doppler (EPA5), Extended Typical Urban with 70 Hz Doppler (ETU70), and Extended Vehicular A with 70 Hz Doppler (EVA70). We assume D2D users have low mobility, and therefore we model the interferer channel from the D2D transmitter to the eNB using the EPA5 channel. Furthermore, we assume the D2D physical layer is very similar to that of the LTE uplink, therefore the interferer signal is simulated as another LTE uplink signal, unsynchronized with the desired signal. Practical systems use a variety of channel estimation schemes; we eliminate the variation associated with the choice of an estimator by assuming perfect channel estimation in the simulation. One can model the effect of imperfect channel estimation in practical systems by applying an extra (1–2) dB loss. All links utilize 1×2 receive antenna diversity and the 3GPP Rel. 8 HARQ process [10]. Also, the D2D link and the infrastructure link share the same time-frequency resources in our simulations. In practice, they may only partially overlap. Therefore, the results below provide lower bounds on performance, and average performance can be obtained by assigning a probability of resource collision.

For each scenario, we obtain a family of BLER-vs-SNR curves for a range of noise rise values by Monte Carlo simulation. Fig. 3 illustrates an example of these BLER curves for the scenario in which the cellular uplink uses MCS0 over the EVA70 channel. From this family of curves, we obtain the increase in required SNR, $g(NR)$, to maintain a given BLER for each noise rise value. To quantify the uncertainty of the $g(NR)$ values, we derived 95 % confidence intervals by treating the BLER estimates as Gaussian random variables with the mean and variance of a binomial random variable having parameters n and p, where n is the number of LTE blocks simulated and p is the ratio of blocks in error to n. Typically, the SNR pertaining to a target BLER is obtained by interpolating between neighboring points. The linear interpolation of the SNR is a function of the aforementioned Gaussian random variables. We obtain the confidence interval of the interpolated SNR by a Monte Carlo method [11].

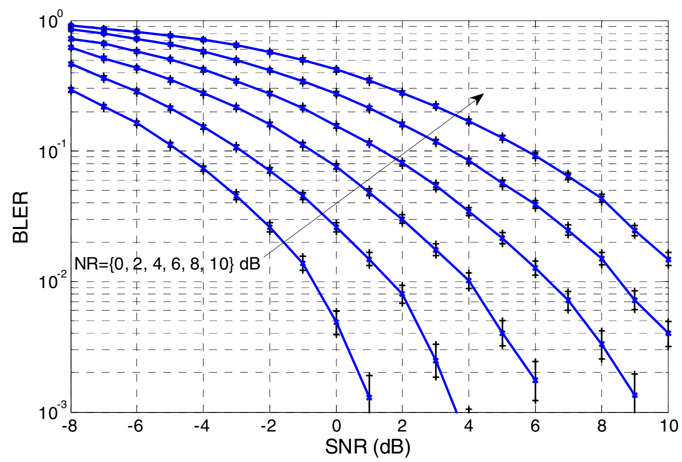


Fig. 3: BLER vs. average SNR with MCS0 and the EVA70 channel for a range of noise rise values resulting from a single D2D interferer, shown with 95 % confidence intervals

B. Single Interferer Results

The first set of results pertains to the case when the interference is due to a single D2D transmitter. Fig. 4 thru Fig. 6 plot the normalized increase in required SNR at 2 % and 10 % BLER versus the noise rise for MCS0, MCS15, and MCS25, respectively. The increase in required SNR is normalized by the noise rise (i.e., $g(NR)/NR$) in order to make differences between the curves easier to see. Recall that $g(NR)/NR = 1$ when the interference behaves like additive white Gaussian noise. The normalized metric is a measure of how sensitive the LTE uplink is to D2D interference.

For each target BLER, three curves are shown, one each for the EPA5, ETU70, and EVA70 channel models of the victim cellular uplink channel. In general, the $g(NR)/NR$ values shown in these figures are higher at 2 % target BLER than at 10 % target BLER, indicating that the cellular uplink is more sensitive to the interference at a lower target BLER. At the lower target BLER, there is a clearer differentiation among the multipath fading channels. The ETU70 victim channel tends to be most sensitive to the interference for MCS0 and MCS15, compared with EPA5 and EVA70 channels. However, there is no significant difference among the fading channels for MCS25, possibly due to operation in a higher SNR regime.

The increase in required SNR is higher for MCS0 compared with MCS15 and MCS25, which have a higher required SNR to begin with. The implication is that cell-edge users, who typically employ a lower MCS, are more sensitive to D2D interference. The increase in required SNR at MCS0 effectively translates to a reduction in uplink coverage. These results can be used in conjunction with a propagation model to quantify this coverage reduction (see Section V).

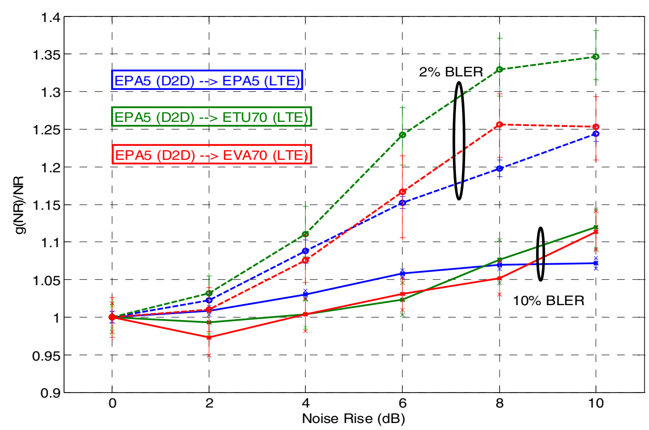


Fig. 4: $g(NR)/NR$ with MCS0 due to a single interferer, with 95 % confidence intervals

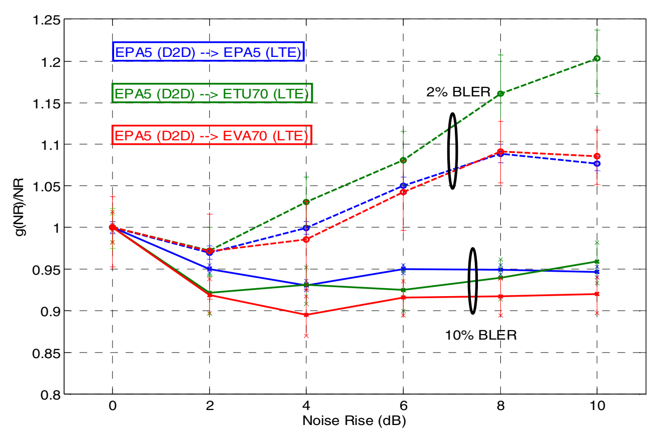


Fig. 5: $g(NR)/NR$ with MCS15 due to a single interferer, with 95 % confidence intervals

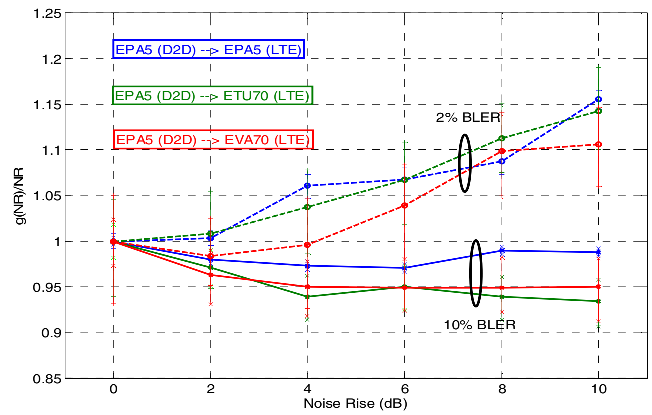


Fig. 6: $g(NR)/NR$ with MCS25 due to a single interferer, with 95 % confidence intervals

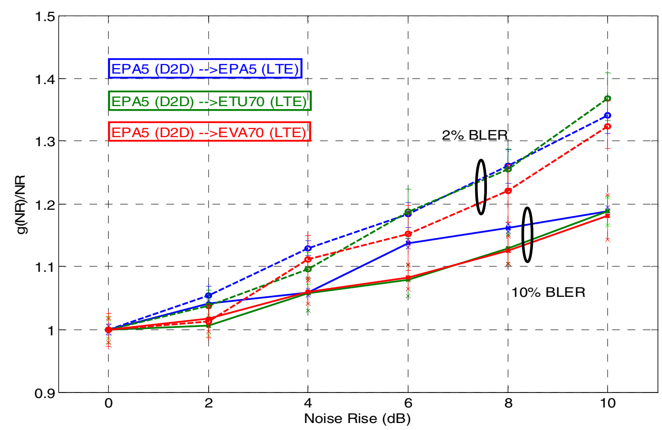


Fig. 7: $g(NR)/NR$ with MCS0 due to two interferers, with 95 % confidence intervals

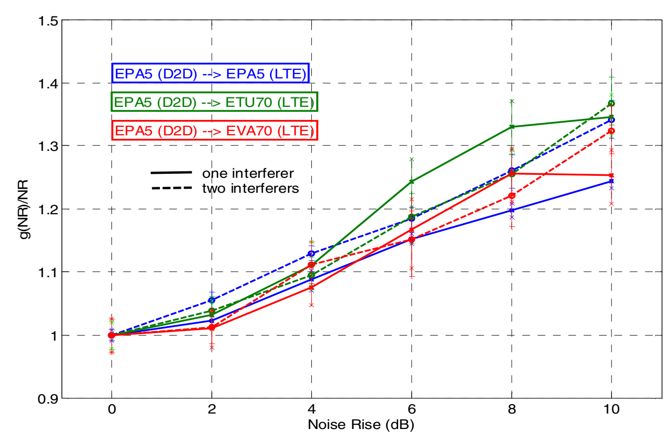
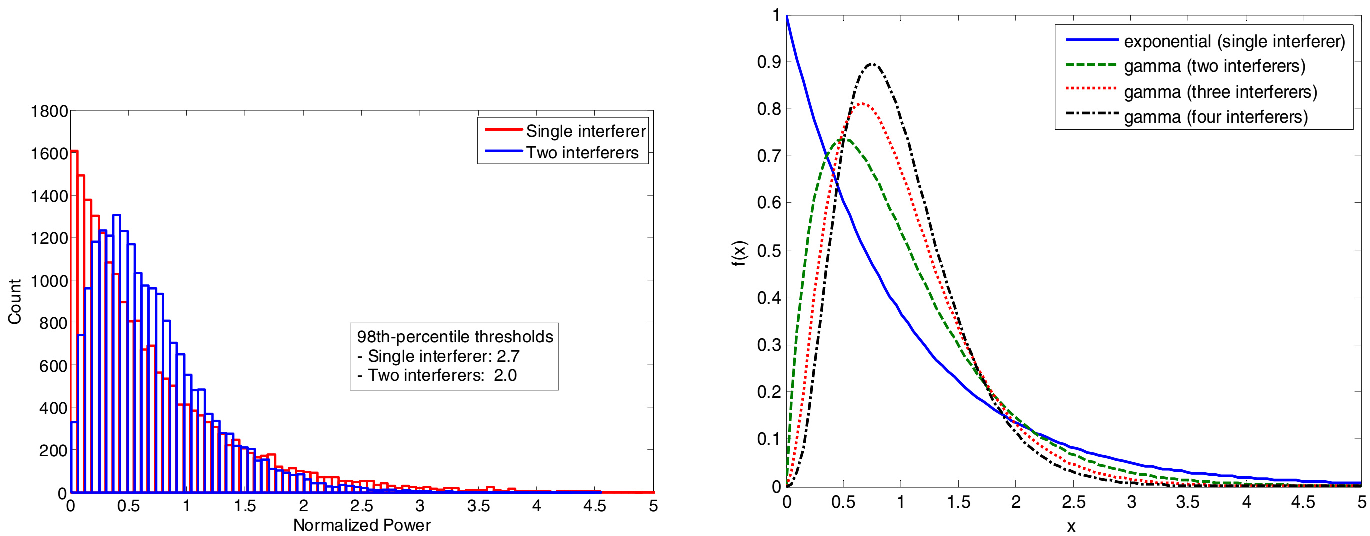


Fig. 8: Comparison of $g(NR)/NR$ between one and two interferers using MCS0 at 2 % BLER, with 95 % confidence intervals

C. Multiple Interferer Results

While the preceding section considered the case of a single D2D transmitter using the same resource blocks as an LTE uplink transmission, when the number of D2D transmitters increases, there is a greater probability that multiple D2D transmitters will collide with the LTE transmission. The relative powers of the D2D transmissions at the eNB will likely differ, depending on their locations, transmission powers, and fading channels. If the power of one of these interfering transmissions dominates the others, the scenario can be approximated by the single interferer case examined above. However, if the interfering signals are comparable in power, their effect on the LTE uplink should also be considered. Following are results for the case of two equal-power, uncorrelated interferers. We argue that the likelihood of larger numbers of equal-power interferers using the same resource blocks as a cellular uplink transmission diminishes rapidly, especially for cells that are not heavily loaded on the uplink.



(a) (b)

Fig. 9: (a) Histogram of normalized interference power with EPA5 channel model; (b) Probability density functions of cumulative interference power resulting from independent flat Rayleigh fading channels

In order to compare with single interferer results using the same noise rise, each interferer in the two-interferer case transmits with half the power of the single interferer. Fig. 7 plots the normalized increase in required SNR in the presence of two interferers when MCS0 is used. A similar distinction between the two target BLERs is observed as before, where 2 % BLER operation is impacted more than 10 % BLER. Comparing with Fig. 4, the cellular uplink is slightly more sensitive to two half-power interferers than to one full-power interferer at 10 % BLER. At the lower target BLER, for which the comparison is shown in Fig. 8, the increased sensitivity to two interferers is conclusive only for the EPA5 channel.

To gain insight into the effect of multiple interferers, Fig. 9(a) plots histograms of the interference power from a single full-power interferer and two half-power interferers through the EPA5 channel. The single-interferer power is more likely to have low values but also has a heavier tail. However, there is a mid-range of values which the two-interferer power is more likely to take than the single-interferer power.

The same effect is observed on a simpler, frequency-flat (single tap) Rayleigh fading channel. Here, the power from a single interferer has an exponential distribution, and the cumulative power from k equal-power interferers with the same total average power as the single interferer has a gamma distribution with shape parameter k and scale parameter $1/k$. The probability density functions of the received power from one to four interferers are shown in Fig. 9(b). As the number of interferers grows, the density becomes narrower and peaks around the total normalized mean power, and the variation in interference power decreases. Because the probability of outliers also decreases, we expect the impact of a large number of interferers on the cellular uplink to be less than that of a few interferers.

V. Application of Results

The preceding results can be used in higher layer and other systems-level analyses of D2D in the context of LTE. To illustrate the application of these results, we consider in this section the effect of D2D interference on the coverage of an LTE cell.

Let $\gamma(d)$ represent the SNR of the cellular LTE link at distance d in the absence of D2D interference, and let γ_0 be the required SNR at the cell edge to satisfy some requirement (e.g., outage probability and/or data rate). Then the cell radius without D2D interference, R_c, is that which satisfies $\gamma(R_c) = \gamma_0$.

Now, consider the case when D2D interference is present. Following the discussion in Section III.B, the required SNR to satisfy the same outage or data rate requirement at the cell edge is now $\gamma_0 \cdot g(NR)$. The increase in required SNR translates to a reduction in cell radius to R_c'; that is, $\gamma(R_c') = \gamma_0 \cdot g(NR)$, and since $g(NR) > 1$ and average SNR typically decreases with distance, we have $R_c' < R_c$. Using the numerical results for $g(NR)$ above and assuming some path loss model, we can quantify the reduction in cell size due to D2D interference.

From the preceding equations, we have

$$g(NR) = \frac{\gamma(R_c')}{\gamma(R_c)}$$

or, in decibels,

$$g_{dB}(NR) = L(R_c) - L(R_c')$$

where $L(d)$ is the path loss at distance d. Assuming a log-distance path loss model with path loss exponent, n, gives

$$g_{dB}(NR) = 10n\log_{10}\left(\frac{R_c}{R_c'}\right).$$

Noting that cell coverage area is proportional to the square of the radius, solving for the remaining fraction of coverage area (i.e., the ratio of reduced cell area to original cell area) gives

$$\frac{A_c'}{A_c} = \left(\frac{R_c'}{R_c}\right)^2 = 10^{-g_{dB}(NR)/5n}.$$

As an example, Fig. 10 plots the remaining fraction of coverage area of the ETU70 victim cellular uplink, using the numerical results for 2 % BLER in Fig. 4 and assuming the urban area path loss exponent of 3.76 from [12]. For each level of noise rise, two results are shown, one representing the case when the noise rise is from a single D2D transmitter and the other when the noise rise is additive white Gaussian. This comparison illustrates the difference between applying the simulation results above versus simply making a Gaussian assumption on the interference. For the range of noise rise values shown, the Gaussian assumption overestimates the coverage area by up to 17 %. Also, the difference in A_c'/A_c between the AWGN and D2D models increases monotonically as the noise rise increases, but the rate of increase diminishes.

Other applications of the results presented in this paper include network-layer simulations. For computational feasibility, network simulations of cellular systems typically utilize an abstracted model of physical layer performance rather than performing bit-level simulations. The model may take the form of a look-up table translating average SNR to BLER, for example, or may consist of a set of SNR thresholds for transmission success/failure. These models can be augmented to account for D2D interference by incorporating the simulation results presented earlier.

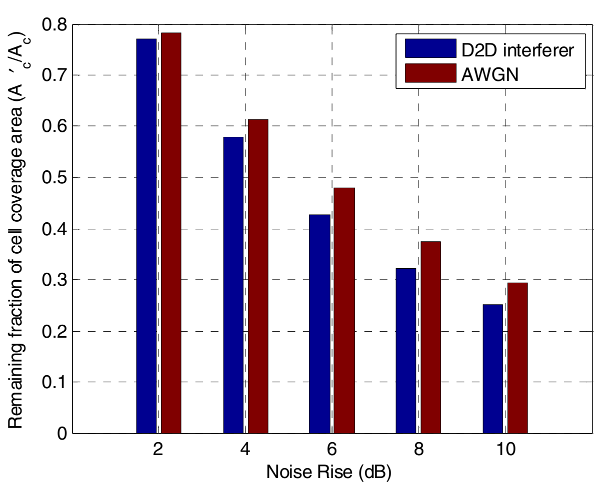


Fig. 10: Remaining fraction of urban cell coverage area as a function of noise rise

VI. Conclusions

In this paper, we used Monte Carlo simulations to evaluate the impact of interference from a D2D network on a cellular network when they share the cellular uplink channel. We measured this impact by computing the increase in the SNR required to achieve a target BLER in the presence of the D2D-induced noise rise on the link. We found that a lower BLER threshold results in bigger increases in the SNR requirement; also more conservative MCSs are more sensitive to the effects of an increased noise rise, given that they have lower required SNR to achieve a given BLER. We also examined the effect of multiple interferers, though the likelihood of a large number of D2D interferers producing similar uplink power levels at a victim eNB is low. Finally, we applied these results to quantify cell coverage reduction due to D2D interference.

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