Cellular System Performance Analysis Under Correlated Shadow Fading

Tingting Lu, *Student Member, IEEE,* Pei Liu, *Member, IEEE,* and Shivendra S. Panwar, *Fellow, IEEE*

***Abstract*—In a cellular network, connections between the Base Station (BS) and Mobile Stations (MSs) may be disrupted when the channel has low signal-to-interference-plus-noise ratio (SINR). Shadow fading is large-scale fading, which can significantly affect signal strength and reduce SINR over a wide area. Empirical measurements show that shadowing has significant spatial correlation in realistic scenarios. Correlated shadow fading could result in long-lasting outage for stationary and mobile users, which will lead to intermittent connections and consecutive packet losses. Such a link is especially harmful to real-time applications that are delay sensitive. Increasing diversity of the system is one way to increase SINR. Therefore, increasing the BS density can help to reduce the number of long-lasting outages, and provide better Quality of Service (QoS) support for delay sensitive applications. This paper focuses on a study of the downlink performance of a multi-cell communication system under correlated shadow fading. First, we compare the outage probability of two different BS layout models with similar correlated shadow fading. Simulation results indicate that the grid model has better performance than the more realistic random model. Secondly, the outage probability with independent shadow fading and correlated shadow fading for the random BS layout is computed. At the end, we present the distribution of outage durations and show that increasing the BS density can mitigate the effect of correlated shadow fading and improve the system performance by reducing outage durations.**

***Index Terms*—Correlated shadow fading, outage probability, outage duration.**

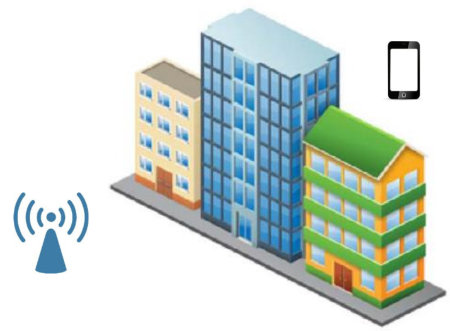

Fig. 1. An example of building blockage.

I. Introduction and Related Works

In a cellular communication system, the connection between a BS and a MS may be dropped when the MS enters a deep fading area. Fading phenomena can substantially affect the performance of a wireless communication system. In general, fading can be divided into two categories: large-scale fading and small-scale fading. A signal transmitted from source to destination will experience both large-scale and small-scale fading. Small-scale fading is caused by multipath propagation. Large-scale fading, which is also known as shadow fading, is caused by obstacles (trees, buildings, etc.) in the propagation path. In most cases, shadow fading is assumed to be temporally and spatially independent [1]. However, researchers have also shown that shadow fading is spatially correlated [2], [3]. For example, in Fig. 1, the MS is moving behind a row of tall buildings which block the signals from the BS. These tall buildings result in deep shadow fading, and the shadow fading of different positions behind these buildings are closely correlated. In [4] and [5], the effects of correlated shadowing in connectivity is demonstrated, which indicates that reliable connectivity will be much more difficult to maintain than indicated by independent shadow fading models. However, in [4] and [5], the authors investigated the effects of correlated channel fluctuations on ad-hoc and sensor networks, not cellular networks. The spatial correlation of shadow fading is important when studying the QoS of a mobile application since it will result in long-lasting outage durations, which will deteriorate the performance of the applications running on the network. Therefore, in this paper, we focus on the effects of correlated shadow fading in connectivity between a BS and an MS of a cellular system.

There have been a lot of studies on the outage probability of cellular communication systems [6–8]. The author of [9] analyzed the outage probability and the coverage area under independent shadow fading, which follows either Log-normal distribution, Weibull distribution or Gamma distribution. By contrast, there is much less work on the outage probability and outage duration, given the correlations in shadow fading. Consequently, performance of a multi-cell system with correlated shadow fading remains an open problem. In [10] and [11], we discussed the outage probability and the outage duration distribution of a single-cell communication system under exponentially correlated shadow fading and distance-angle correlated shadow fading. For a single-cell model, exponentially correlated shadow fading can be modeled as a Markov chain. Highly correlated shadow fading will result in long-lasting outage durations. In [11], a single-cell model under the distance-angle correlated shadow fading is investigated. Correlated shadow fading leads to correlated outage events and long-lasting outage durations. To overcome these disadvantages, we propose a cooperative communication

The authors are with the Department of Electrical and Computer Engineering, Tandon Engineering School of New York University, Brooklyn, NY, 11201

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scheme to mitigate shadow fading by deploying relays at the cell edge. In [10] and [11], results are limited to the single-cell model. In this paper, we are going to extend the study to review the impact of correlated shadow fading on a multi-cell model, and provide a solution to overcome long-lasting outage durations.

For the multi-cell system, a new general model for the user SINR was developed using stochastic geometry [12]. The cellular network was modeled by placing BSs at locations determined by a homogeneous Poisson Point Process (PPP). The author concluded that, under general fading, increasing the number of BS did not affect the coverage probability and/or the outage probability, as long as the MS was connecting to the nearest BS. Moreover, the paper did a comparison between the grid model and the PPP model, and concluded that the regular grid model provided an upper bound on the coverage probability, while the PPP model provided a lower bound. The authors also considered the effect of independent log-normal interference, and concluded that, higher log-normal interference increases coverage probability, which seems counter-intuitive. The author explained that increasing randomness gave the cell edge users, which have poor mean SINR, an increased chance of being in coverage. However, the authors did not consider a scenario with correlated log-normal shadow fading.

A comparative analysis of a random topology and a grid topology for a small cell network deployment was given in [13]. In this paper, the spatial outage probability and the spatial average throughput, versus the number of access points for two different network deployments are illustrated under independent shadow fading. Approximating the outage probability and the capacity for $\kappa - \mu$ shadow fading was discussed in [14]. $\kappa - \mu$ shadow fading includes the one-sided Gaussian, the Rayleigh, the Nakagami-m and the Rician. As we mentioned before, empirical shadow fading measurements did not exhibit such features. Therefore, these complex shadow fading probability distribution models are not the main focus when investigating system performance under correlated shadow fading.

In most cases, shadow fading is modeled as an independent log-normal distribution [15] with a standard deviation derived from empirical measurements. An independent log-normal shadowing model is used widely when shadow fading cannot be ignored. In the log-normal shadowing model, the path loss ψ is assumed random, with a log-normal distribution given by

$$p(\psi) = \frac{\xi}{\sqrt{2\pi}\sigma_{\psi_{dB}}\psi} exp[-\frac{(10\log_{10}\psi - \mu_{\psi_{dB}})^2}{2\sigma^2_{\psi_{dB}}}], \psi > 0, \tag{1}$$

where $\xi = 10/\ln 10$, $\mu_{\psi_{dB}}$ is the mean of $\psi_{dB} = 10\log_{10}\psi$ and $\sigma_{\psi_{dB}}$ is the standard deviation of ψ_{dB}. The distribution of the dB value of ψ is Gaussian with mean $\mu_{\psi_{dB}}$, standard deviation $\sigma_{\psi_{dB}}$ and is given by:

$$p(\psi_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{dB}}} exp[-\frac{(\psi_{dB} - \mu_{\psi_{dB}})^2}{2\sigma^2_{\psi_{dB}}}]. \tag{2}$$

The above model fails to capture the spatial correlations in shadow fading. The independent model is adequate for stationary network where MUs are in random locations. However, to describe the spatial/temporal channel gain of MUs, a correlated shadow model is essential. Moreover, empirical measurements show that shadowing has significant correlations in realistic scenarios that can affect system performance [16]. Considering the distribution of obstructions and the speed of the MS, a realistic channel propagation model should incorporate correlated shadow fading. Szyszkowicz et al. [17] presented a review and analysis of the feasibility of different correlated shadowing models. For a multi-cell model with multiple BSs at different places, both autocorrelation and cross-correlation need to be taken care of. To simplify the simulation, the exponential correlation model is chosen in this paper. To investigate the system performance under correlated shadow fading, this paper focuses on outage probability and outage duration analysis under correlated shadow fading in a multi-cell communication system. Based on the analysis, we provide a solution to reduce the frequency and duration of dropped connections.

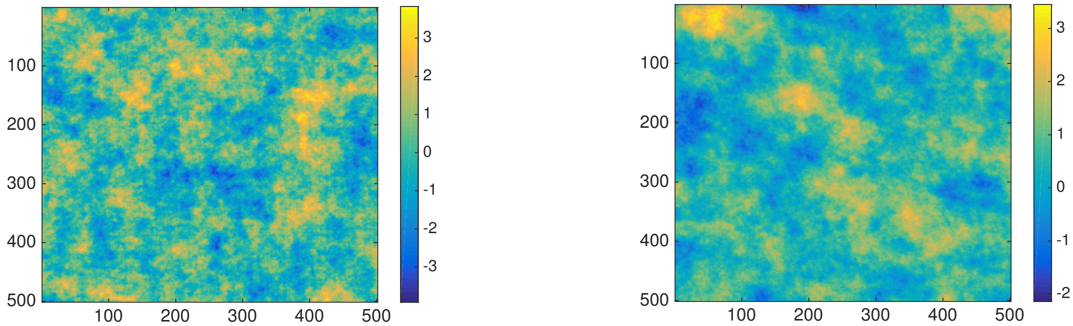
The key contributions of this paper are summarized as follows:

- Analyze the relationship between correlated shadow fading and correlated outage events under correlated outage fields.
- Investigate the outage probability of both the Grid model and the Random model under correlated shadow fading.
- Illustrate how increasing the BS density helps mitigate the correlated shadow fading for the Random model in terms of reducing the outage probability (or increasing the coverage probability) and the percentage of long-lasting outage durations.
- Analyze the relation between the tunable parameter (decorrelation distance) of the correlated shadow fading model and the outage probability.
- Compare the performance of the system with regard to different MS-BS connection strategies: MS connecting to the nearest BS versus MS connecting to the BS providing the highest SINR.

The paper is organized as follows: Section II presents the correlated shadow fading model used in this paper and the resultant correlated outage field. Section III illustrates the system model with two different BS deployments and investigates the outage probability given the two deployments. Section IV gives a theoretical analysis of the outage probability given correlated shadow fading. Section V presents the simulation setup and analyzes the simulation results from different BS densities. Section VI summarizes the paper and proposes future work directions.

II. Correlated Shadow Fading

As stated in the introduction, empirical measurements of shadowing show that there exist different patterns of correlation. Independent log-normal shadow fading model, while is very useful for static MS performance analysis, cannot reflect the correlation of shadow fading between different locations. In this section, we will give a brief introduction to shadow fading models, including the model used in this paper. In most cases, shadow fading is considered as independent log-normal. But from empirical measurements we can conclude



(a) Correlated shadowing field with $20m$ decorrelation distance

(b) Correlated shadowing field with $100m$ decorrelation distance

Fig. 2. Exponentially correlated shadowing field (the color of the area refers to the normalized standard deviation which is $S_i/\sigma_s(i)$)

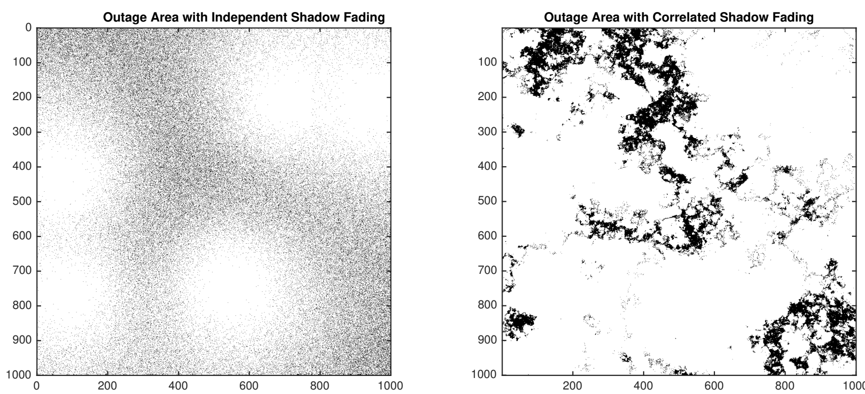


Fig. 3. Correlated outage fields (Dark areas are outage areas while white areas are non-outage areas)

that there exist different correlations between shadow fading factors. There is no single mathematical model which captures all categories of correlation[17]. In this paper, we use the most commonly used exponentially correlated shadow fading model [18]. In [18], the author states that correlation in shadowing is indispensable for the analysis of interference of large networks. An exponentially correlated shadowing field S with shadow fading factor s_i for each position p_i has a correlation matrix as below:

$$\mathbf{K}_{N\times N} = [\sigma_s(p_i)\sigma_s(p_j)\rho(i,j)], \tag{3}$$

where N is the length of the shadowing field. Suppose A and B are two neighboring points, the shadow fading (in dB) is $N(0,\sigma^2)$ where σ is the standard deviation. The spatial correlation between s_A and s_B will be given by

$$\rho_{A,B} = \frac{E[s_A s_B]}{\sigma^2} = e^{-\frac{d_{A,B}}{d_0}}, \tag{4}$$

where d_0 is decorrelation distance and $d_{A,B}$ denotes the distance between A and B.

Following the shadowing field generation algorithm, we generate shadowing fields with different decorrelation distances. Two sample correlated shadowing fields are shown in Fig. 2. In Fig. 2(a), a correlated shadowing field with $20m$ decorrelation distance is shown while Fig. 2(b) gives a correlated shadowing field with $100m$ decorrelation distance. Compare the two figures, we confirm that a larger decorrelation distance results in a wider correlated shadowing area. In Fig. 2, a deeper color means deeper fading. Deep blue colors are aggregating together to show the pattern of correlation. When the MS gets into the blue region (deep fading region), it will stay in that region for a certain period of time. Due to this correlation, a MS in deep fading area may experience long-lasting outage duration.

Given a correlated shadowing field, the outage events at different locations are correlated. Without considering small-scale fading, the channel gain at different locations has a spatial correlation. An outage event occurs when SINR becomes less than γ, where γ is a given SINR threshold. Based on the aforementioned correlated shadow fading model and the Random model in section III, a correlated outage field can be generated as in Fig. 3. On the left, an outage field with independent log-normal shadow fading is shown, while the correlated outage field with correlated shadow fading is given on the right. The black color indicates outage areas. Outage areas due to the independent shadow fading are independent and discontinuous dots. In contrast, those under the correlated shadow fading contain several connected areas . Therefore, we conclude that correlated shadow fading results in correlated

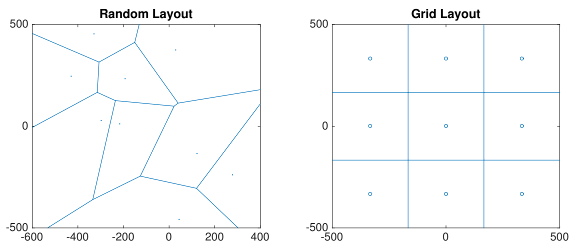


Fig. 4. Random model and Grid model with $\lambda = 9$.

outage areas.

III. System Model

In this section, we consider two system models with two different BS deployments: the Grid model and the Random model.

- Grid model: λ BSs are placed on a regular grid deterministically.
- Random model: λ BSs are placed randomly in a fixed area.

On the right side of Fig. 4, an example of the grid model is presented, where cells are square-shaped and of the same size. For the Random model shown on the left, cells form a Voronoi tessellation. Distances between nearest base stations have a large variation from cell to cell.

IV. Outage Probability Analysis

Let $\varphi = \{1, 2, \dots, N\}$ denote the set of all BSs, then the received signal from BS i to the destination user D is given by:

$$y_{i\to D} = G_{i\to D} x_i + n_D, \tag{5}$$

where x_i is the signal transmitted by the source BS and $y_{i\to D}$ is the signal received by the destination user. $n_D \sim \mathcal{CN}(0, N_0)$ is additive white Gaussian noise. $G_{i\to D}$ is the channel gain from source BS to MS including path loss and shadow fading. The end-to-end received SINR is given below:

$$\text{SINR} \triangleq \frac{P_i * G^2_{i\to D}}{N_0 + \sum_{j\in\varphi/i} P_j * G^2_{j\to D}}, \tag{6}$$

where P_i is the transmitted power of BS i. The MS successfully receives the signal if no outage event occurs, i.e., $\log_2(1+\text{SINR}) \geq R$, where R is the required data rate. From the definition of SINR, no outage event occurs as long as $\text{SINR} > \gamma$, where $\gamma = 2^R - 1$.

For a particular MS, outage event occurs when its received SINR is less than a threshold to decode the received signal. In our scenario, the probability that the receiver cannot decode signals received from its serving BS is defined as:

$$P(out_i) = P[\text{SINR}_{i\to D} < \gamma]. \tag{7}$$

We investigate two connection strategies:

- Nearest BS: MS chooses to connect to the nearest BS.
- Strongest BS: MS chooses to connect to the BS providing highest SINR.

In the Nearest BS mode, we assume that the MS is served by the nearest BS, then the outage probability will be

$$P_{out} = P_{out_i}, \tag{8}$$

where i is the index of the nearest BS.

In the Strongest BS mode, under the assumption that an MS is always connecting to the BS which provides the highest SINR, the outage event occurs if no BS can provide high enough SINR to the receiver. Based on this assumption we have:

$$P_{out} = \max_{i=1,\cdots,N} P[\text{SINR}_{i\to D} < \gamma]. \tag{9}$$

The probability density function (pdf) of shadow fading S given L propagation paths under correlated shadow fading is

$$\begin{aligned} f_{\mathbf{S}}(\mathbf{s}) =& \frac{\lambda^L}{\sqrt{2\pi}|\mathbf{K}_{L\times L}|^{1/2}\prod_{i=1}^{L} s_i} \\ &\cdot \exp(-\frac{1}{2}(10\log_{10}\mathbf{s} - \boldsymbol{\mu})^T \mathbf{K}^{-1}_{L\times L}(10\log_{10}\mathbf{s} - \boldsymbol{\mu})), \end{aligned} \tag{10}$$

where $\lambda = 10/\ln 10$ and $\boldsymbol{\mu}$ is the average shadow fading which is normally 0. $\mathbf{K}_{L\times L}$ is the correlation matrix which is defined in (3). Let $\theta_i = \frac{10\log_{10} s_i - \mu_i}{\sqrt{2}\sigma_i}$, and doing a change of variables gives us the pdf of $\boldsymbol{\Theta}$ as follows:

$$f_{\boldsymbol{\Theta}}(\boldsymbol{\theta}) = \frac{1}{\pi^{L/2}|\boldsymbol{\Sigma}|^{1/2}} \exp(-\boldsymbol{\Theta}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\Theta}), \tag{11}$$

where $\boldsymbol{\Sigma}$ is the correlation coefficient matrix which is

$$\begin{bmatrix} 1 & h_{1,2} & \cdots & h_{1,L} \\ \vdots & \ddots & \ddots & \vdots \\ h_{L,1} & h_{L,2} & \cdots & 1 \end{bmatrix}. \tag{12}$$

Since $\text{SINR}_{i\to D} = PL_{i\to D} + S_i - N_0 - \sum_{j\in\varphi/i}(PL_{j\to D} + S_j)$ in dB, $\text{SINR}_{i\to D} < \gamma$ means

$$S_i - \sum_{j\in\varphi/i} S_j < \gamma - PL_{i\to D} + \sum_{j\in\varphi/i} PL_{j\to D} + N_0, \tag{13}$$

where φ denotes the set of all BSs. Then the outage probability can be written as:

$$P_{out} = \underbrace{\int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty}}_{i=1,\cdots,N} g(PL_i S_i - \gamma \sum_{j\in\varphi/i} PL_j S_j) f(\mathbf{s}) d\mathbf{s}, \tag{14}$$

where $\mathbf{s}$ is the correlated shadow fading experienced by all BSs; $g(PL_i S_i - \gamma \sum_{j\in\varphi/i} PL_j S_j)$ is a step function defined in (15).

V. Simulation Results

In this section, we present the simulation setup and results. Firstly, we execute simulations to compare the outage probability of the two different network topologies: the Grid model and the Random model. Secondly, the SINR distribution and the outage probability of the Random model given different BS densities are investigated. Two scenarios are considered: MS connecting to the nearest BS and MS connecting to the BS providing highest SINR. At the end, the outage duration distribution is simulated and discussed given different BS

$$g(PL_iS_i - \gamma \sum_{j\in\varphi/i} PL_jS_j) = \begin{cases} 1, & \text{when } PL_iS_i - \gamma \sum_{j\in\varphi/i} PL_jS_j < \frac{\gamma N_0}{P} \\ 0, & \text{when } PL_iS_i - \gamma \sum_{j\in\varphi/i} PL_jS_j > \frac{\gamma N_0}{P} \end{cases}. \tag{15}$$

TABLE I
SIMULATION CONFIGURATION PARAMETERS

Target Area	$1000m \times 1000m$
Number of BS in Target Area	$3, 10, 50, 100, 200, 300, 500$
Path Loss Exponent	4
BS Transmission Power	$P : 40dbm$
Minimum SINR Requirement	$-5dB$
Decorrelation Distance	$20m, 200m$

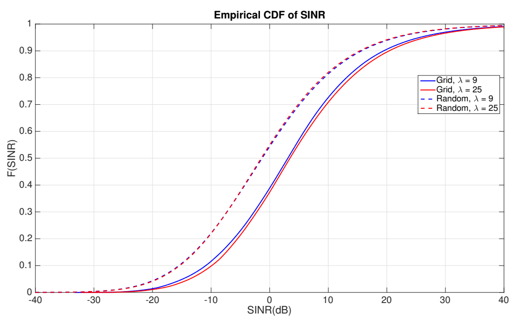


Fig. 5. CDF of SINR given Grid model and Random model (decorrelation distance: $20m$)

densities. The simulation parameters are presented in Table I.

We employ Monte-Carlo simulation to calculate the probability distribution of the SINR. To start the simulation, a large number of correlated shadowing fields are generated. BSs and the MS are placed over the correlated shadow fading field with the MS in the middle of the shadowing field. Fig. 5 shows the cumulative distribution function (CDF) of SINR when the MS is connecting to the nearest BS. The decorrelation distance of the correlated shadow fading is $20m$. The figure suggests that the Grid model outperforms the Random model, which is consistent with findings in [12]. Fig. 6 shows the outage probability with SINR threshold being $-5dB$. The outage probability of the Grid model (blue) is lower than that of the Random model (yellow). Without considering frequency reuse, the outage probability of the Random model is as high as 38%. In the next section, we will focus on the Random model, which is more realistic than the Grid model.

For the Random model, the SINR distribution and the outage probability of different BS densities are investigated for both the Nearest BS mode and the Strongest BS mode. Simulations are implemented under independent shadow fading and correlated shadow fading. CDF curves of SINR are generated and the outage probability given the SINR threshold being $-5dB$ are presented for increasing BS densities. Fig. 7 shows the SINR of the MS when connecting to the nearest BS. From Fig. 7(a) and Fig. 7(b), it is obvious that the CDF curves are overlapping each other, which means increasing BS density does not change the CDF of SINR. From this we

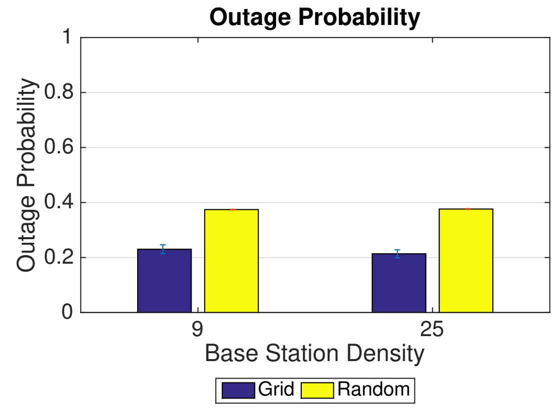
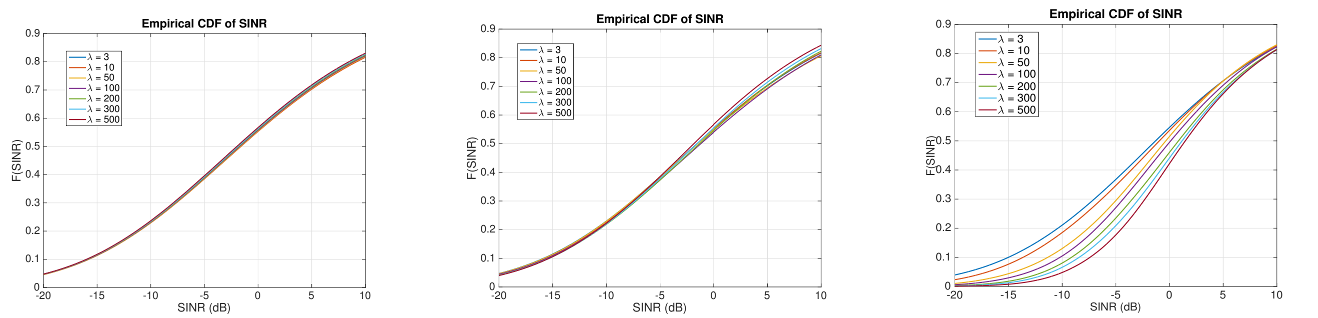


Fig. 6. Outage probability given Grid model and Random model with $\gamma = -5dB$ (decorrelation distance: $20m$)

can conclude, under the circumstance that the shadow fading is independent or the decorrelation distance of the correlated shadow fading is small, increasing the BS density will not improve the system performance in terms of reducing the outage probability. Fig. 7(c) illustrates that CDF of SINR improves (curve moves toward the bottom-right corner) as we increase the BS density. Therefore, increasing the BS density will result in better system performance when the decorrelation distance is large, by reducing the outage probability. Fig. 9 shows the outage probability of different correlated shadow fading models and different BS densities when SINR threshold is set to $-5dB$. These blue and green bars suggest that increasing the BS density will not decrease the outage probability when shadow fading is independent or correlated with $20m$ decorrelation distance. Meanwhile, these yellow bars suggest that when the decorrelation distance is $200m$, increasing the BS density will reduce the outage probability. For example, when the BS density is 3, the outage probability is around 38%. Increasing the BS density to 500, the outage probability decreases to 18%. The above simulation results suggest that when the decorrelation distance is relatively large, and the MS is connecting to the nearest BS, increasing the BS density will reduce the outage probability and improve the system performance.

Next, we move forward to investigate the system performance when the MS chooses to connect to the BS which provides the highest SINR. The same simulations as done for the nearest BS scenario are executed to explore this scenario. Fig. 8 presents the receiving SINR of the MS when connecting to the strongest BS. In Fig. 8(a), 8(b) and 8(c), the CDF curves of SINR almost overlap each other when increasing BS densities, which means increasing BS density will not change the CDF of SINR significantly. Fig. 10 shows the outage probability bars. In Fig. 10, for each shadow fading

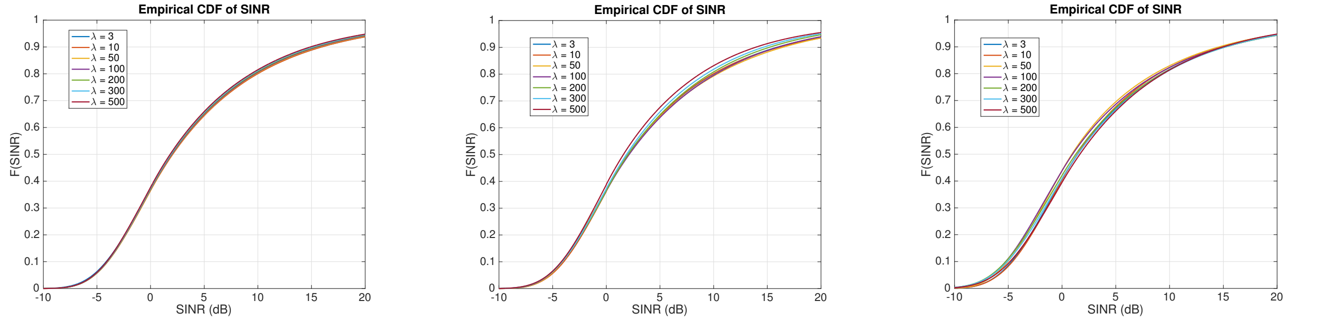


(a) Independent shadow fading

(b) Correlated shadow fading with $20m$ decorrelation distance

(c) Correlated shadow fading with $200m$ decorrelation distance

Fig. 7. CDF of MS's receiving SINR when connecting to the Nearest BS (three different shadow fading modes and different BS densities).



(a) Independent shadow fading

(b) Correlated shadow fading with $20m$ decorrelation distance

(c) Correlated shadow fading with $200m$ decorrelation distance

Fig. 8. CDF of MS's receiving SINR when connecting to the Strongest BS (three different shadow fading modes and different BS densities).

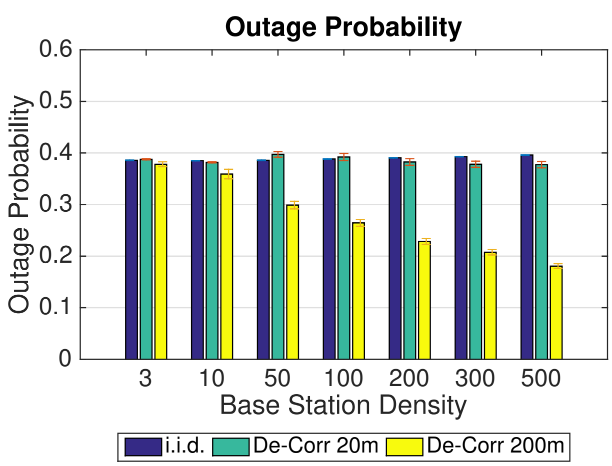


Fig. 9. Outage probability given $-5dB$ SINR threshold (Nearest BS mode)

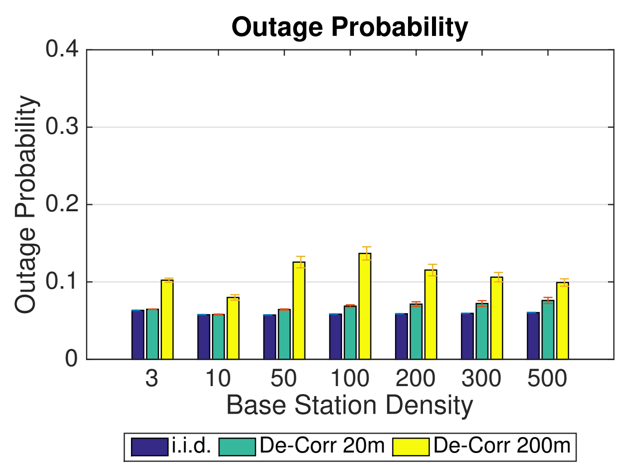
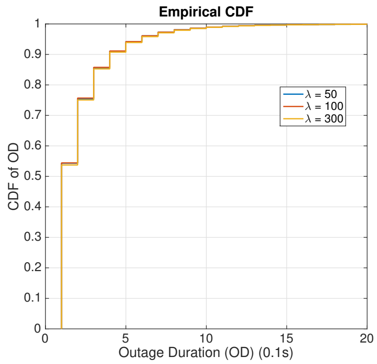


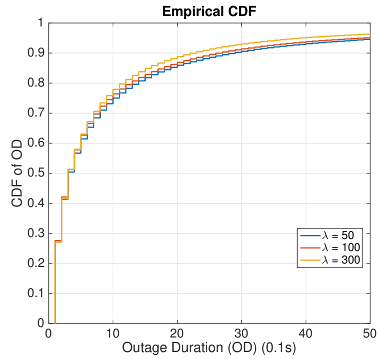
Fig. 10. Outage probability given $-5dB$ SINR threshold (Strongest BS mode)

model, the difference between the highest outage probability and the lowest outage probability is less than 5%. This means increasing the BS density will not reduce the outage probability when the MS is connecting to the Strongest BS, which are consistent with our conclusion. Comparing three different shadow fading models, we can conclude that when the MS is connecting to the strongest BS, long decorrelation distance will harm the system performance by increasing the outage probability (yellow bars are higher than green or blue bars).

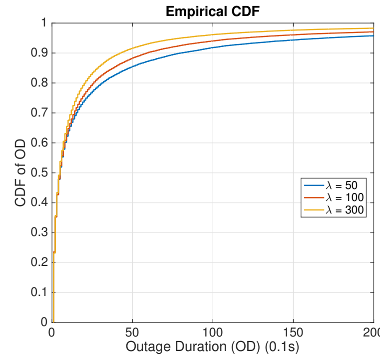
Comparing Fig. 9 with Fig. 10, we find that with the same BS density, outage probabilities are lower for every shadow fading model if the MS is connecting to the strongest BS. For example, with the independent shadow fading and the BS



(a) Independent shadow fading

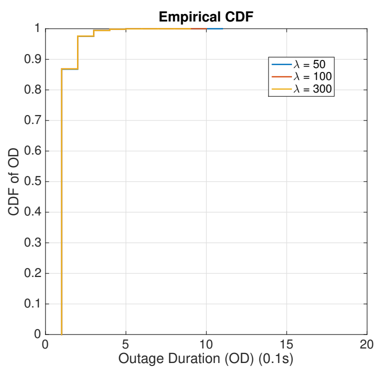


(b) Correlated shadow fading with $20m$ decorrelation distance

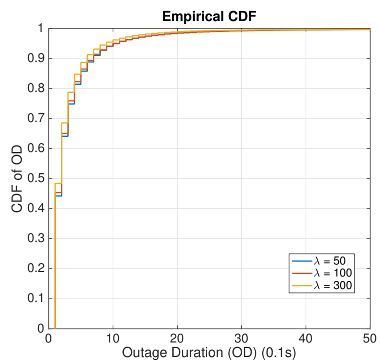


(c) Correlated shadow fading with $200m$ decorrelation distance

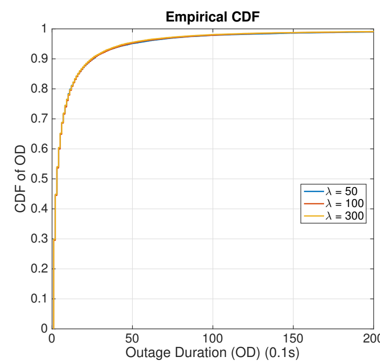
Fig. 11. CDF of Outage Durations when MS is connecting to the Nearest BS with correlated shadowing



(a) Independent shadow fading



(b) Correlated shadow fading with $20m$ decorrelation distance



(c) Correlated shadow fading with $200m$ decorrelation distance

Fig. 12. CDF of Outage Durations when MS is connecting to the Strongest BS with correlated shadowing

density being 50, the outage probability of the Nearest BS mode is 38%, while this probability for the Strongest BS mode is 6%. For correlated shadow fading with the decorrelation distance being $200m$ and the BS density being 50, we find that the outage probability of the Nearest BS mode is around 30%. This is higher than that of the Strongest BS mode, which is 14%. Therefore, we confirm that connecting to the BS which provides highest SINR will improve the system performance significantly for the same network setup.

We also investigated the system performance from the perspective of outage duration. We use the Random Waypoint mobility model [19] to model the user mobility. The parameters of the Random Waypoint model are given in Table II. The MS speed is assumed to be uniformly distributed between $1m/s$ (pedestrian speed) and $20m/s$ (highway car speed). The MS pause interval is assumed to be uniformly distributed between $0s$ to $60s$. The simulation time slot is set to be $0.1s$, which means we check the MS's SINR every $0.1s$ to determine if it is in the outage area or not. For each simulation scenario, a correlated shadowing field is generated with the MS at the center of the shadowing field and a $50s$ trajectory of the MS is investigated. The shadow fading factor of each BS are determined by the relative distance between the BS and the MS. Monte-Carlo simulations are run to generate the probability distribution of the outage durations. Simulation results are shown in Fig. 11 and Fig. 12. Comparing Fig. 11(a) with Fig. 11(b) and Fig. 11(c), and Fig. 12(a) with Fig. 12(b) and Fig. 12(c), we conclude that when the channel is under independent shadow fading, the outage duration is usually less than $2s$. However, when the channel is under correlated shadow fading with $20m$ decorrelation distance, the outage duration can be longer than $5s$; and when the decorrelation distance is $200m$, the outage duration can be longer than $20s$. Therefore, we draw the conclusion that correlated shadow fading leads to long-lasting outage durations. This in turn can negatively effect higher layer protocols like TCP and real-time applications like voice and video-conferencing. It will also cause noticeable delays even in more delay-tolerant applications like web browsing. Comparing Fig. 11(a) with Fig. 12(a), Fig. 11(b) with Fig. 12(b), Fig. 11(c) with Fig. 12(c), we find that connecting to the strongest BS will reduce the outage duration. For example, in Fig. 11(a), the percentage of outage durations of the Nearest BS mode with a length less than $0.5s$ is 94%, while in Fig. 12(a), that of the Strongest BS mode is 100%. Fig. 11(b) and Fig. 12(b) confirm this conclusion with the percentage of outage durations of the Nearest BS mode with a length less than $5s$ being 95% while that of the Strongest BS mode being 100%. In addition, the

TABLE II
RANDOM WAYPOINT MOBILITY MODEL PARAMETERS

Speed Interval	$1m/s - 20m/s$
Pause Interval	$0s - 60s$
Sample Time	$0.1s$

percentage of outage durations less than $5s$ in Fig. 11(c) is 85% with BS density being 50. However, this percentage in Fig. 12(c) increases to 95%. Furthermore, Fig. 11(c) indicates that increasing the BS density will reduce the percentage of long-lasting outage durations if the MS is connecting to the nearest BS. For example, in Fig. 11(c), when the BS density increases from 50 to 300, the percentage of outage durations longer than $5s$ is reduced from 15% to 8%. In contrast, for independent shadow fading and correlated shadow fading with the MS connecting to the strongest BS, increasing the BS density will not change the distribution of outage durations, which is confirmed by Fig. 11(a), Fig. 12(a) and Fig. 12(c). All CDF curves of outage durations are the same for different BS densities. Comparing Fig. 11(b) and Fig. 11(c), Fig. 12(b) and Fig. 12(c), we conclude that correlated shadow fading with long decorrelation distance brings about long-lasting outage durations. For example, in Fig. 11(c) with $\lambda = 50$, the percentage of outage durations shorter than $5s$ is 85%. However, that percentage is 95% in Fig. 11(b). Long decorrelation distance results in long-lasting outage durations and long-lasting outage durations will decrease the network layer throughput and consequently harm the performance of network applications. Cooperative communications [11] is considered as an efficient way to overcome the long-lasting outage durations other than increasing the BS density. Simulation codes are available at [20] and [21].

VI. CONCLUSIONS

Shadow fading is large-scale fading, which can cause significant received power loss for a wide area. In general, shadow fading is considered to be independent log-normal distributed to simplify the analysis; however, this can be misleading. In reality, shadow fading at two close by locations are correlated to each other. Correlated shadow fading will result in correlated outage events and long-lasting outage durations. To investigate the performance of a multi-cell system given correlated shadow fading, simulations are implemented to analyze the outage probability and the outage duration distribution. First of all, the probability of two different BS layouts: Grid model and Random model are investigated. We find that the Grid model predicts better performance than the Random model. Secondly, we present simulated outage probabilities given different BS densities and two different connecting strategies: Nearest BS mode and Strongest BS mode. We conclude from simulation results that connecting to the strongest BS will reduce the outage probability compared with the nearest BS. Increasing the BS density will not reduce the outage probability when the MS is connecting to the strongest BS. However, when the MS is connecting to the nearest BS and the decorrelation distance of correlated shadow fading is large enough, increasing the BS density will reduce the outage probability. Finally, we analyze the system performance in terms of outage duration. Simulation results show that correlated shadow fading will result in long-lasting outage durations. Long decorrelation distance leads to long-lasting outage durations. Simulation results also show that increasing the BS density will reduce the percentage of long-lasting outage durations if the MS chooses to connect to the nearest BS. Therefore, we suggest a dense BS layout might be a proper strategy for next generation mmWave communication networks characterized by correlated shadow fading.

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