Outage Probability Analysis of Mobile Small cells over LTE-A Networks

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***Abstract*—Cellular operators have concluded that small cell deployments are a very cost-effective and quick solution to meet the ever growing demands on capacity and coverage in cellular networks for indoor and outdoor environments. While traveling in public transit vehicles, cellular subscribers usually experience poor signal reception and low bandwidth. We hence consider deploying small cells onboard (i.e., mobile small cells) such vehicles. This should enhance subscribers' quality of experience (QoE). We consider a Small Base Station (SBS) mounted in a public transit bus (i.e., mobile SBS) to serve onboard users. The mobile SBS aggregates users' traffic to and from the macroBSs. To further extract the underlying rich multipath-Doppler diversities resulting from the fast mobility and the associated selective fading channel, a pre-coded transmission is deployed in the mobile SBS. We examine the achievable gain from enabling aggregation through mobile SBS in terms of the outage probability. We derive a tight-bound closed-form expression for the outage probability in the downlink (DL). Our results indicate that significant gain in outage probability and coverage are achievable.**

***Index Terms*—mobile small cell; outage probability; coverage extension.**

I. Introduction

Due the proliferation of mobile devices (e.g., smartphones, tablets and laptops), they have been used in a massive way everywhere, indoor, outdoor, and on the go. According to Cisco Global Visual Networking Index (VNI) [1], global mobile data traffic has experienced more than a ten-fold growth. In fact, the current number of mobile devices already exceeds our world's population, and the number of Internet connected devices through mobile networks is exponentially growing [1]. Unfortunately, mobile users are experiencing poor received signal quality in many situations which currently are infeasible to fix via macro base stations (macroBSs) deployment only. Mobile operators are extensively searching for solutions to increase capacity and improve coverage to satisfy mobile users. As improvements in radio link are approaching theoretical limits, most mobile operators have established that the next performance leap will stem from changing the network topology. Using a mixture of macrocells overlaid with small cells, referred to as a Heterogeneous Network (HetNet), is considered as a core part of the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) and LTE-Advanced [2] [3].

A Small cell is a cellular coverage area that is served by low-power small base station (SBS). A SBS is a fully featured miniature base station for indoor deployment and backhauled to the operator's core network (CN) via an Internet connection (such as cable, DSL, etc.) [2] [3]. Small cell types include femtocells, picocells and metrocells. Recently, several operators are starting to deploy small cells outdoors in urban and hot-spot areas. Due to their benefits, small cell deployments have generated significant interest in the mobile industry and research groups and the total number of already deployed SBSs has exceeded the total number of macroBSs [2].

The number of mobile users using smartphones, tablets and laptops through mobile networks onboard (e.g., public transit vehicles) is growing exponentially. Therefore, many users experience poor signal reception and low bandwidth due to path loss, shadowing, Doppler shift effect, vehicle velocity and distance to macroBSs. Improving onboard mobile coverage and capacity to satisfy mobile users is becoming very challenging to operators. Also, mobile traffic from groups of moving users affects the macroBSs' performance. Current research efforts have considered deploying small cells in public transit vehicles including buses and streetcars [4] [5]. Mobile small cells are introduced to boost coverage and capacity for vehicular users by deploying SBSs onboard [6]. User equipment (UE) communicates with mobile SBSs (mobSBSs) instead of distant macroBSs. The mobSBS communicates with the macroBSs through a wireless backhaul link.

In this paper, we study the impact of the use of mobSBS in public transportation vehicles on UE performance. First, we propose to apply an appropriate precoder to the onboard mobSBS to overcome the degraded performance of the received signal in wireless backhaul links. Precoded transmission helps in extracting the underlying rich multi path-Doppler diversity inherited in this type of double-selective fading link. Second, we derive a tight closed-form expression of outage probability (OP) for mobile small cells in order to evaluate the outage

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performance of UEs with/without mobile small cell deployments and as a contribution to define a benchmark to assess our analysis and future studies. Finally, we provide numerical results to evaluate the performance gain of such a deployment.

The remainder of this paper is structured as follows. In Section II, we review the related work. Section III presents our network and signaling models. The outage derivation and gain analysis are presented in Section IV. Numerical results are provided in Section V. Section VI concludes the paper.

Notation: $(.)^{\mathrm{T}}$ denotes transpose operation, $(.)^{*}$ denotes conjugate operation and $(.)^{\mathrm{H}}$ denotes Hermitian operation. $\mathbb{E}[.]$, $|.|$ and $\otimes$ denotes expectation, absolute value and Kronecker product, respectively. Bold letters denote the matrices and vectors. $[\mathbf{H}]_{k,m}$ represents the (k,m)th entry of $\mathbf{H}$. $\mathbf{I}_N$ indicates an $N \times N$-size identity matrix. 1 and 0 represents, respectively, all-ones and all-zeros matrix with proper dimensions. $\lceil . \rceil$ and $\lfloor . \rfloor$ denotes integer ceil and integer floor operations, respectively. $*$ is the convolution operator.

II. Related Work

Small cells have been widely considered for indoor and outdoor environments. Several research efforts have been made to analyze and evaluate the performance of typical small cell deployments. For example, the authors in [7] evaluate the performance advantage of using fixed femtocells as relays by communicating with the macroBSs to improve and extend coverage for mobile users. A limited number of researchers though have studied innovative mobile small cell deployment as an option. In the mobile small cells, the mobSBS may be connected to the operator's CN via satellite, Wi-Fi or through macroBSs similar to a mobile relay. However, SBSs are different than relays, as UEs will identify the mobSBSs as regular BSs and only communicate with SBSs. In the relay scenario, the UEs are aware of the donor BS that the relay is communicating with [6]. Hence, SBSs work as regular BSs and assign frequency and scheduling resources for UEs, unlike relays.

Mobile small cell deployments deal with several deployment aspects, such as: frequency allocation, handover for mobSBS between different macroBSs, handover of the group of attached UEs, and wireless backhaul link to macroBSs. The authors in [6] study the potential advantages of using moving cells to boost performance for UEs in transit vehicles. The work in [4] investigates the effects of using mobile femtocells in vehicles, specifically on the amount of signaling overhead between mobile femtocells and macrocells. As the mobile femtocell will communicate with the macrocells on behalf of onboard mobile users, their results show that there is a large saving in volume of the control signaling from using mobile femtocells. Research in [5] proposes deploying femtocells in vehicles to improve the uplink throughput for mobile users. The mobSBS is connected to the operator's CN through the macroBSs or satellite, the communication is based on the available scenario. Results show that mobile femtocells can

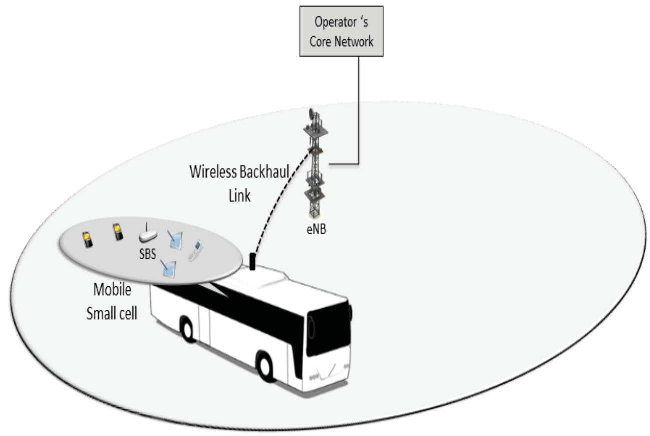

Fig. 1. Instance of Considered Network

enhance service quality and maintain an acceptable level of signal to interference plus noise ratio (SINR).

However, research efforts targeting the performance gains of mobile small cells remain limited, and further studies are needed. In our previous work [8], we investigate the pairwise error probability (PEP) of mobile small cells and its impact on UEs by providing a closed-form expression. To this end, we propose to investigate the outage probability for mobile small cells to quantify the potential gain in terms of outages and errors. Outage probability is considered an important performance metric to assess UEs quality of service (QoS) and due to its huge impact on the network performance and power consumption.

III. System description

In this section, we provide our network, propagation, and signaling models.

A. Network and Propagation Models

We consider downlink (DL) transmission of an orthogonal frequency division multiplexing (OFDM) heterogeneous network that consists of a macrocell served by a single evolved Node B (eNB) with an overlaid mobile small cell served by a mobSBS as depicted in Fig.1. The mobSBS is installed on a bus with an outdoor antenna mounted on the bus's roof top to communicate with the distant eNB via a decode and forward (DF) relay assisted transmission. The transmission here is half duplex; in the first step, the SBS decodes part or the entire received signal. Whereas in the second step, the SBS re-encodes the decoded message and forwards it to the UE. The onboard UEs communicate directly with the mobSBS instead of communicating with the distant eNB.

The link between the macroBS and the mobSBS is called a wireless backhaul link (macroBS-to-mobSBS). It is a wireless radio interface for connecting the mobSBS with the macroBS through a transmitter mounted on the roof top of the vehicle (i.e., relay feature). The wireless link between the mobSBS and the UE is called a wireless access link (mobSBS-to-UE). Where in the typical deployment, the wireless link between the macroBS and the UE is also called wireless access link (macroBS-to-UE). The mobSBS communicates with the onboard UEs and macroBS on two different dedicated frequency bands in order to mitigate the self-interference frequency in the mobSBS. The mobSBS will be deployed by the operator. The macroBS should be aware of the mobSBS and its associated UEs. The mobSBS has its own physical cell ID, so it appears to UEs as a different cell than the macroBS, unlike relays, where the relay acts as transparent and does not perform as a regular base station as SBSs do. However, the UE receives scheduling information and feedback directly from the mobSBS and sends its control channel information to the mobSBS. The mobSBS transmits information on its own control channels to the serving macroBS.

1) macroBS-to-mobSBS ($\mathrm{M} \rightarrow \mathrm{S}$*) Link:* As the outdoor antenna of the mobSBS receives signals from the macroBS, we consider the propagation model to be outdoor None Line Of Sight (NLOS) Rayleigh fading channel with fast fading and can be derived from the COST-Hata-Model (Outdoor propagation model) [9] as

$$\begin{aligned} PL_{ms}\left(dB\right) &= 46.3 + 33.9\log_{10}\left(f_m\right) - 13.82\log_{10}\left(h_m\right) \\ &\quad - a\left(h_s\right) + \left[44.9 - 6.55\log_{10} h_m\right]\log_{10} d_{ms} + G \end{aligned} \tag{1}$$

where PL_{MS} is the median path loss between mobSBS and macroBS in dB, f_m is the frequency used between the mobSBS and macroBS in MHz, h_m is the macroBS antenna height, h_s is the mobSBS antenna height, d_{ms} is the distance between mobSBS and the macroBS in meters, $G = 3dB$ for urban areas, and $a\left(h_s\right) = \left(1.1\log_{10}\left(f_m\right) - 0.7\right)h_s - \left(1.56\log_{10}\left(f_m\right) - 0.8\right)$.

2) mobSBS-to-UE ($\mathrm{S} \rightarrow \mathrm{U}$*) Link:* UEs onboard receive signal from the mobSBS, so the path loss model of the mobSBS is considered as Line Of Sight (LOS) fading channel and can be derived from a modified Keenan Motley model [10] as

$$PL_{SU}\left(dB\right) = 32.5 + 20\log_{10}\left(d_{su}\right) + 20\log_{10}\left(f_s\right) \tag{2}$$

where PL_{SU} is the median path loss between mobSBS and onboard UEs in dB, d_{su} is the distance between mobSBS and the onboard UE in meters, and f_s is the frequency used between the mobSBS and UEs in MHz.

3) macroBS-to-UE ($\mathrm{M} \rightarrow \mathrm{U}$*) Link:* Similar to the ($\mathrm{M} \rightarrow \mathrm{S}$) model with takes into account additional parameters as UEs onboard (inside vehicle), the propagation model in this case can be represented as

$$\begin{aligned} PL_{MU}(dB) &= 46.3 + 33.9\log_{10}\left(f_m\right) - a\left(h_u\right) \\ &\quad + \left[44.9 - 6.55\log_{10} h_m\right]\log_{10} d_{mu} \\ &\quad + G\left(L_{sh} + L_{pen}\right) \end{aligned} \tag{3}$$

where h_u is the UE antenna height, d_{mu} is the distance between mobSBS and the UE in meters, L_{sh} is the shadowing standard deviation and L_{pen} is the penetration loss and $a\left(h_u\right) = \left(1.1\log_{10}\left(f_m\right) - 0.7\right)h_u - \left(1.56\log_{10}\left(f_m\right) - 0.8\right)$.

Herein forth, and for simplicity, the aforementioned links are represented as $M \rightarrow S$, $S \rightarrow U$ and $M \rightarrow U$, respectively.

B. Signalling Model

The discrete Fourier transform (DFT) is applied to convert the time-sampled OFDM signal into frequency domain. Then, the discrete finite sequence of complex coefficient is given by

$$s\left(\ell\right) = \frac{1}{\sqrt{N}}\sum_{k=0}^{(N-1)} x\left(k\right)e^{-jw_k}, n = 0, \ldots, N-1 \tag{4}$$

where N is the total number of the orthogonal subcarriers, $x(k)$ is the k^{th} modulated data symbols, and $w_k = 2\pi\ell k/N$. The basis expansion model (BEM) is then used to denote discrete-time baseband equivalent channel for the doubly-selective channel under consideration, and is given by

$$h_B\left(\ell; l\right) = \sum_{q=0}^{Q} h_q\left(n; l\right)e^{jw_q}, l \in [0, L] \tag{5}$$

where $w_q = 2\pi\ell\left(q - Q/2\right)/N$ and $h_q\left(n; l\right)$ is the zero-mean complex Gaussian. ℓ denotes the index of the data symbols. The block index is given by $n = \lfloor \ell/N_t \rfloor$, the number of the resolvable multipath components is given by $L = \lceil \tau_d/T_s \rceil$, and the number of Doppler phase shifts is given by $Q = \lceil N_t T_s f_d \rceil$, where T_s is the symbol duration. From (4) and (5) we can obtain the following expression

$$h_B\left(\ell; l\right)s\left(\ell\right) = \frac{1}{\sqrt{N}}\sum_{q=0}^{Q}\sum_{k=0}^{(N-1)} h_q\left(n; l\right)x\left(k\right)e^{-jw} \tag{6}$$

where $w = 2\pi\ell\left(k + q - Q/2\right)/N$.

The input data blocks generated from the multi-level quadrature amplitude modulation (M-QAM) constellation, with length of N_t are divided to shorter sub-blocks with length N_s. We denote each sub-block by $s(n)$. The values $s(n)$ are the input to a linear precoder Θ with size of $N_s \times N_t$, ($N_s = PZ$, and $N_t = (P+Q)(Z+L)$). We define $\mathbf{H}_{ms,q}^{(0)}$ and $\mathbf{H}_{su,q}^{(0)}$ as the lower triangular Toeplitz channel matrices with entries given by equation (5), L_{ms} and L_{su} are the channel multipath lengths for $\mathrm{M} \rightarrow \mathrm{S}$ and $\mathrm{S} \rightarrow \mathrm{U}$ links, respectively. Whereas Q_{ms} and Q_{su} represent the number of resolvable Doppler components for the aforementioned links.

The received signal at the mobSBS can be written in matrix form per

$$\begin{aligned} &\mathbf{y}_{ms}\left(n\right) = \\ &\qquad \sqrt{G_{ms}E_s}\sum_{q=0}^{Q}\mathbf{D}(w_q)\mathbf{H}_{ms,q}^{(0)}\left(n\right)\mathbf{u}\left(n\right) + \mathbf{n}_{ms}\left(n\right) \end{aligned} \tag{7}$$

where $\mathbf{u}(\ell) = \Theta\mathbf{s}(\ell)$ is the transmitted data blocks, E_s is the modulated symbol energy, $Q = \max\left(Q_{ms}, Q_{su}\right)$, $\mathbf{D}(w) := \mathrm{diag}[1, \ldots, \exp(jw(N_t - 1))]$ and $\mathbf{n}_{ms}\left(n\right)$ is $\mathrm{M} \rightarrow \mathrm{S}$ additive white Gaussian noise (AWGN) vector with entries of zero mean and $N_0/2$ variance. After using the commutatively of products of Toeplitz matrices with vector, we can exchange $\mathbf{H}_{ms,q}^{(0)}(n)\mathbf{u}(n)$ to $\mathbf{U}(n)\mathbf{h}_{su,q}(n)$. We can then rewrite the expression in (7) as

$$\mathbf{y}_{ms}(n) = \sqrt{G_{ms}E_s}\sum_{q=0}^{Q}\mathbf{D}(w_q)\mathbf{U}(n)\,\mathbf{h}_{ms,q}(n) + \mathbf{n}_{ms}(n) \quad (8)$$

After defining the augmented matrices $\mathbf{h}_{ms}(n) = [\ \mathbf{h}_{ms,0}^{\mathrm{T}}(n) \ \cdots \ \mathbf{h}_{ms,Q}^{\mathrm{T}}(n)\ ]^{\mathrm{T}}$ and $\Phi(n) = [\ \mathbf{D}(w_0)\mathbf{U}(n) \ \cdots \ \mathbf{D}(w_Q)\mathbf{U}(n)]$, we get

$$\mathbf{y}_{ms}(n) = \sqrt{G_{ms}E_s}\Phi(n)\,\mathbf{h}_{ms}(n) + \mathbf{n}_{ms}(n) \quad (9)$$

During the relaying stage, the mobSBS's received signals is fed to ML detector and is given by

$$\arg\min_{\bar{\mathbf{s}}}\left\{\left\|\mathbf{y}_{ms}(n) - \sqrt{G_{ms}E_s}\sum_{q=0}^{Q}\mathbf{D}(w_q)\mathbf{H}_{ms,q}^{(0)}(n)\,\Theta\bar{\mathbf{s}}\right\|^2\right\} \quad (10)$$

with $\bar{\mathbf{s}}$ by means of all possible signal block combinations. We apply an "ideal DF" relaying at the mobSBS. The mobSBS then forwards a fresh decoded version of the received precoded signal, i.e., $\dot{\mathbf{u}}(n)$ Hence, the received signal during the relaying stage at the UE is given by

$$\mathbf{y}_{su}(\ell) = \sqrt{G_{su}E_s}h_{su}\dot{\mathbf{s}}(\ell) + \mathbf{n}_{su}(\ell) \quad (11)$$

where $\mathbf{n}_{su}(\ell)$ is the associated $\mathrm{S} \to \mathrm{U}$ AWGN vector with entries of zero mean and $N_0/2$ variances. Then, ML detection will be performed at the UE.

IV. OUTAGE PROBABILITY AND GAIN ANALYSIS

In this section, we study the performance of the outage probability of UEs with mobile small cell deployment by deriving a closed form expression.

The pair-wise error probability (PEP) [11] at the UE is given by

$$\begin{aligned} &P_r\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}_{ms}, h_{su}\right) \le P_{ms}\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}_{ms}, h_{su}\right) \\ &+ \left(1 - P_{ms}\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}_{ms}\right)\right) P_{Coop}\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}_{ms}, h_{su}\right) \end{aligned} \quad (12)$$

which is the error probability that for a transmitted signal ($\mathbf{s}$) its corresponding but distorted version ($\hat{\mathbf{s}}$) will be received. Where $\hat{\mathbf{s}}$ represents the decoded data matrix instead of the original transmitted data, $P\left(\mathbf{s} \to \hat{\mathbf{s}}\right)$ is the end-to-end PEP, $P_{ms}\left(\mathbf{s} \to \hat{\mathbf{s}}\right)$ is the PEP of the $\mathrm{M} \to \mathrm{S}$ link, $P_{Coop}\left(\mathbf{s} \to \hat{\mathbf{s}}\right)$ is the PEP of the relaying link, i.e., $\mathrm{M} \to \mathrm{S}$ and $\mathrm{S} \to \mathrm{U}$. In the case that the mobSBS detects the signal correctly but the signal that results from the cooperative link is detected incorrectly. Then, the PEP in (12) can be upper bounded as follows [11]

$$\begin{aligned} &P_r\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}_{ms}, h_{su}\right) \le \\ &P_{ms}\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}_{ms}\right) + P_{su}\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| h_{su}\right) \end{aligned} \quad (13)$$

The conditional PEP for each individual term in (13) is given by [12]

$$P(\mathbf{S} \to \hat{\mathbf{S}}\big| \mathbf{h}) = Q\left(\sqrt{\frac{1}{2N_0}d^2\left(\mathbf{S}, \hat{\mathbf{S}}\middle| \mathbf{h}\right)}\right) \quad (14)$$

Using the approximated bound proposed in [13], the expression in (13) can be approximated using the following expression

$$P\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}\right) \approx \sum_{m=1}^{3}\varepsilon_m \exp\left(-\frac{\rho_m}{4N_0}d^2\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}\right)\right) \quad (15)$$

where $\varepsilon_1 = \varepsilon_2 = 2\varepsilon_3 = 1/12$, $\rho_1 = 12\left(\sqrt{3} - 1\right)/\pi$, $\rho_2 = 4\left(3 - \sqrt{3}\right)/\pi$ and $\rho_3 = 2\sqrt{3}/\pi$. The Euclidean distance conditioned on the fading channel coefficients is $d^2\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \mathbf{h}\right) = \mathbf{h}^{\mathrm{H}}\left(\mathbf{S} - \hat{\mathbf{S}}\right)^H\left(\mathbf{S} - \hat{\mathbf{S}}\right)\mathbf{h}$. Using the Eigen value decomposition [14], we get $\gamma_{ms} = G_{ms}\mathbf{h}_{ms}^{\mathrm{H}}\chi\mathbf{h}_{ms} = G_{ms}\sum_{j=0}^{ms-1}\lambda_j|\beta_j^{ms}|^2$ and $\gamma_{su} = G_{su}\mathbf{h}_{su}^{\mathrm{H}}\chi\mathbf{h}_{su} = G_{su}\sum_{k=0}^{r_{su}-1}\alpha_k|\beta_k^{su}|^2$. From (13), we have

$$P\left(\mathbf{S} \to \hat{\mathbf{S}}\middle| \dot{\gamma}_{ms}, \dot{\gamma}_{su}\right) \le \sum_{k=1}^{3}\varepsilon_k e^{-\rho_m\frac{\dot{\gamma}_{ms}+\dot{\gamma}_{su}}{4}} \quad (16)$$

where $\dot{\gamma}_{ms} = \gamma\gamma_{ms}$ and $\dot{\gamma}_{su} = \gamma\gamma_{su}$ are the SNR resulting from the $\mathrm{M} \to \mathrm{S}$ and $\mathrm{S} \to \mathrm{U}$, respectively. Define $\dot{\gamma} = \dot{\gamma}_{ms} + \dot{\gamma}_{su}$ as the total end-to-end SNR. The pdf of $\dot{\gamma}$ is given by

$$f(\dot{\gamma}) = f(\dot{\gamma}_{ms}) * f(\dot{\gamma}_{su}) \quad (17)$$

$\dot{\gamma}_{ms}$ and $\dot{\gamma}_{su}$ are a summation of weighted independent exponential distributed random variables and following the hypoexponential distribution also known as the generalized Erlang distribution. The pdf of $\dot{\gamma}_{su}$ [15] can then be calculated and results in the form

$$f_{\gamma_{ms}}(x) = \sum_{j_3=0}^{r_{ms}-1}\left(\prod_{\substack{k \ne j_3 \\ k=0}}^{r_{ms}-1}\frac{\lambda_k}{(\lambda_k - \lambda_{j_3})}\lambda_{j_3}e^{-\lambda_{j_3}x}\right) \quad (18)$$

Similarly we have

$$f_{\gamma_{su}}(x) = \sum_{j_3=0}^{r_{su}-1}\left(\prod_{\substack{k \ne j_3 \\ k=0}}^{r_{su}-1}\frac{\alpha_k}{(\alpha_k - \alpha_{j_3})}\alpha_{j_3}e^{-\lambda_{j_3}x}\right) \quad (19)$$

¿From (17), (18) and (19) we have (20) shown at the top of the next page.

Wireless transmission is constrained by a regulated transmission power, which limits the size of the coverage area to receive a given signal strength. We show that relaying the transmission using a mobSBS's transmitter mounted on the bus' roof top can improve the quality of the received signal. The outage probability P_{out} is the measurement of probability that an error exceeds a specified value $\dot{\gamma}_{th}$.

Mathematically speaking $P_{out} = \int_0^{\dot{\gamma}_{th}} f_{\dot{\gamma}}(\dot{\gamma})\,d\dot{\gamma}$ [16] which is the cumulative distribution function (CDF) of $\dot{\gamma}$, namely $F_{\dot{\gamma}}(\dot{\gamma}_{th})$. By defining our un-normalized aggregate channel model which takes into account both path-loss and small-scale fading, the relative geometrical gain are re-defined as $G_{mu} =$

$$f_{\dot{\gamma}}(x) = \sum_{j_1=0}^{r_{ms}-1} \sum_{j_2=0}^{r_{su}-1} \left(\prod_{\substack{k \neq j_1 \\ k=0}}^{r_{ms}-1} \frac{\lambda_k}{(\lambda_k - \lambda_{j_1})} \lambda_{j_1} \right) \left(\prod_{\substack{k \neq j_2 \\ k=0}}^{r_{su}-1} \frac{\alpha_k}{(\alpha_k - \alpha_{j_2})} \alpha_{j_2} \right) e^{-(\lambda_{j_1} + \alpha_{j_2}) x} \tag{20}$$

$$P_{out} = \sum_{j_1=0}^{r_{ms}-1} \sum_{j_2=0}^{r_{su}-1} \left(\prod_{\substack{k \neq j_1 \\ k=0}}^{r_{ms}-1} \frac{\lambda_k}{(\lambda_k - \lambda_{j_1})} \lambda_{j_1} \right) \left(\prod_{\substack{k \neq j_2 \\ k=0}}^{r_{su}-1} \frac{\alpha_k}{(\alpha_k - \alpha_{j_2})} \alpha_{j_2} \right) e^{-(\lambda_{j_1} + \alpha_{j_2}) \dot{\gamma}_{th}} \tag{21}$$

$d_{mu}^{-\alpha}$, $G_{ms} = d_{ms}^{-\alpha}$ and $G_{su} = d_{su}^{-\alpha}$ These can be related to one another through the cosine theorem $G_{ms}^{-2/\alpha} + G_{su}^{-2/\alpha} - 2G_{ms}^{-1/\alpha} G_{su}^{-1/\alpha} \cos\theta = G_{mu}^{-2/\alpha}$, and assuming a normalized gain for a distance [17]. Hence $\gamma_{mu} = G_{mu} \mathbf{h}_{mu}^{\mathrm{H}} \chi \mathbf{h}_{mu} = G_{mu} \sum_{p=0}^{\mathrm{r}_{mu}-1} \lambda_p |\beta_p^{mu}|^2$. The outage probability is given by (21) at the top of the next page.

As defined earlier, the entries in α's and κ's are the eigenvalues that models the $\left(\mathbf{s} - \hat{\mathbf{s}}\right)^H \left(\mathbf{s} - \hat{\mathbf{s}}\right)$ vectors. ¿From the definitions, we find that $\left(\mathbf{s} - \hat{\mathbf{s}}\right)\dot{\mathbf{s}}$ holds the values of G_{ms} and G_{su} i.e., the relative geometrical gains for the $\mathrm{M} \rightarrow \mathrm{S}$ and $\mathrm{S} \rightarrow \mathrm{U}$ links, respectively, which is a function of the underlying link distances d_{ms} and d_{su}. Hence, the underlying link distances can be shown as an effective parameter on the resulting outage probability of our proposed scheme. In fading channels, the received signal has no constant power gain, and can be described by the probability model described above. Hence, the SNR also becomes a random variable and thus the maximum capacity of the channel becomes a random variable. Outage probability shows according to the variable SNR at the received end, what is the probability that a transmission rate or a specified threshold cannot be supported.

V. NUMERICAL RESULTS

In this section, we demonstrate using MATLAB the performance gains of the proposed scheme using numerical results from our mathematical model, as well as simulation results. As defined in the standard, LTE-A targets peak data rates up to 1 Gb/s with up to 100 MHz supported spectrum bandwidth and QPSK modulation is used [18]. We consider $f_c = 2.5$GHz, $\mathrm{T_s} = 500\mu s$, $v = 60$km/h, $\alpha = 3.67$, $\theta = \pi$ and $\tau_d = 1.328$ μs [19]. We assume perfect channel state information is available at the mobile small cell and the UEs. We use the precoder Θ with parameters $P = 2$ and $Z = 2$, this results in $[L_{ms}, Q_{ms}] = [1, 1]$ for $\mathrm{M} \rightarrow \mathrm{S}$ link. While for the $\mathrm{S} \rightarrow \mathrm{U}$ link we have a frequency-time flat fading channel that results in $[L_{su}, Q_{su}] = [0, 0]$.

In Fig. 2, we verify our analytical derivations by comparing the derived outage expressions for (21) with the exact outage expression. The exact outage can be found by taking the integration numerically for received signals SNR pdf's [12], through random generation of all the underlying links i.e., $\mathbf{h}_{mu}$, $\mathbf{h}_{ms}$ and $\mathbf{h}_{su}$, and using proper statistics via numerical techniques. A benchmark performance indicating the direct $\mathrm{M} \rightarrow \mathrm{U}$ transmission traditional scenario is simulated versus the performance of the proposed transmission scheme (mobile small cells). In the first transmission phase of the mobile small cell scheme, the macroBS transmits its pre-coded signal to the mobSBS's transmitter. In the second transmission phase, the mobSBS is engaged in forwarding the received signal to the onboard UEs only if it was decoded correctly, otherwise the mobSBS is silent. The mobSBS decodes and then forwards a newly decoded copy of the pre-coded signal to the UEs. In practice, the mobSBS can decide that an incorrect decision has been made through cyclic redundancy check (CRC) deployment. As shown, significant improvements are observed through our precoded transmission using the mobSBS, which takes advantages of diversity gains in the $\mathrm{M} \rightarrow \mathrm{S}$ link which improves the outage performance at lower SNRs compared to the direct $\mathrm{M} \rightarrow \mathrm{U}$ transmission traditional scenario.

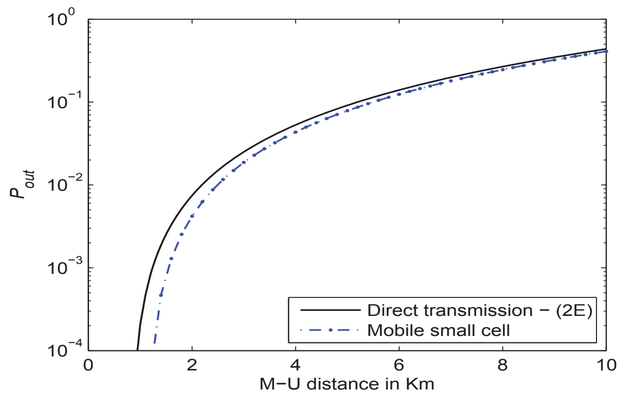

Fig. 2. Comparison of the distance advantage

For example at a target outage rate of 10^{-2}, our proposed system is $4dB$ superior to the reference curve indicating the direct transmission traditional scenario. It is clear that at high SNRs region, i.e. SNR $> 8dB$ a power gain advantage of $4dB$ is observed using our proposed transmission scheme. Further, our closed form derived unconditional outage expression presents a tight bound to the exact conditional outage. This contributes on providing a handy benchmark performance expression unconditioned on the model random variables and helps in avoiding high performance evaluation processing costs and eliminates the need to undergo early performance field

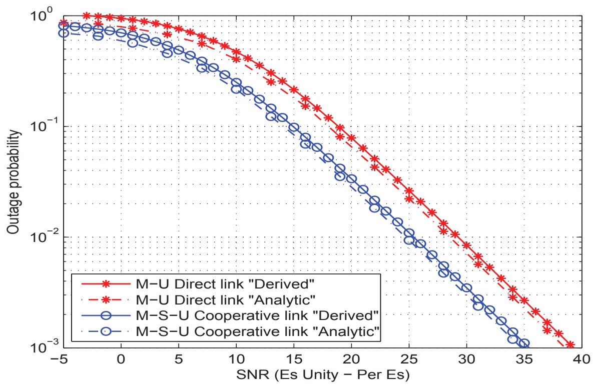

Fig. 3. Comparison of derived outage probability and exact outage probability

studies and evaluation for such an approach.

Fig. 3 shows the coverage extension gains when using mobile small cells cooperating transmission compared to the direct transmission using the outage probabilities in (21), for $\gamma = 10\text{dB}$ and $\acute{\gamma}_{\text{th}} = 5\text{dB}$ [20]. Since our scheme uses two transmission phases, we doubled the power for the reference curve for a fair comparison. For outage probability of 10_{-4}, coverage extension advantage $\simeq 0.3\text{km}$ is observed for using a mobile small cell compared to reference curve indicating direct transmission traditional scenario. In our study we assume that the precoder parameters $P = 2$ and $Z = 2$. Hence the input data blocks $\mathbf{s}(n)$ is of length $N_s \times 1$ (i.e., PZ) and the output of the precoder $\mathbf{u}(n)$ is of length $N_t \times 1$ (i.e., $(P + Q)(Z + L)$). We then have the precoder output rate equal to $N_s/N_t = PZ/((P + Q)(Z + L))$.

VI. Conclusion

Small cell deployments are among the most promising and cost-effective methods to meet the ever growing capacity and coverage demands in cellular networks for indoor and outdoor environments. Now another promising small cell deployment scenario is coming to the forefront that would satisfy the mobile devise user who is on the go: a small cell deployment on public transit vehicles, buses, street cars and trains. We study an enabling decode and forward relaying where small cells are mounted in public transit vehicles. We take advantage of a precoded transmission applied in the mobSBS to extract the underlying rich multipath-Doppler diversity for the doubly-selective macroBS to the mobSBS wireless backhaul link (macroBS-to-mobSBS).

To understand the full potential of mobile small cell deployments, we investigate performance gains on UEs. As outage probability is an important performance indicator to measure quality of service (QoS), we analytically derived an unconditional tight closed-form outage expression to compare the outage probabilities of users with and without mobile small cells. Our derived closed-form outage expression was shown to be tight as proved by our simulations. Our results show that if properly exploited, the outage performance can be improved for channels with higher time and spectral variations, where the wireless backhaul link is improved for SBSs. Finally, we demonstrate that using mobile small cells not only potentiates reduced levels of power consumption, but also provides extended coverage and improved signal reception.

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