Pairwise Error Probability Evaluation of Cooperative Mobile Femtocells

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Abstract— Cellular subscribers while travelling in public transportation vehicles, such as streetcars and buses, often experience poor signal reception and low bandwidth when using their cellular devises onboard. Small cell deployment of, for example, femtocells is considered as one of the most promising solutions for cellular operators to enhance coverage and meet the increasing need for capacity and OoS support expected by cellular subscribers. We consider a mobile Femto Base Station (mobFBS) installed in the public transportation vehicle, with an external antenna installed on the roof, to offer enhanced coverage and improved capacity onboard. We investigate the performance gains of a communication scheme in downlink LTE-A networks with mobFBSs. Users are assumed to be travelling using a public transportation vehicle, and the transmission between macroBS and users occurs through a mobFBS. The associated wireless links for this type of fast mobility are characterized by a doublyselective fading channel. This causes performance degradation in terms of increased error probability. By taking advantage of the more powerful central processing mobFBS, we make use of a precoded technique to overcome the performance degradation that results from the wireless fading channel. We investigate the performance gain in terms of pairwise error probability (PEP) via a derived closed-form expression. Our analytical and simulation results indicate that significant diversity gains are achievable and error rates are tremendously reduced.

Keywords—Mobile femtocell, SNR, PEP, cooperative link, direct link.

I. INTRODUCTION

The growing demand on capacity and coverage by users of cellular networks is challenging cellular operators. In order to meet these demands, various solutions are put forward to improve the coverage and to enhance the capacity of cellular networks. Solutions range from deployment of heterogeneous networks with Wireless Fidelity (Wi-Fi) networks for dual-mode¹ devices, to the installation of more cell sites and signal

boosters. Small cell deployments such as femtocells are considered as one of the most cost effective and beneficial of all proposed solutions for cellular operators and in turn for cellular subscribers [1] [2].

Femtocells are cellular coverage cells that are served by Femto Base Stations (FBSs). A FBS is a miniature low-power base station that offers cellular coverage in a limited area; typically less than 100 meters square and operates in the licensed cellular spectrum. User equipment (UE), such as smartphones, laptops, and tablets, are connected to the FBS through a cellular interface, such as Long Term Evolution (LTE). Cellular traffic is then routed to the operator's core network (CN) through the FBS's backhaul, normally through an Internet connection, e.g. Digital Subscriber Line (DSL) or cable network. Femtocells offer excellent coverage, enhanced capacity and facilitate offloading traffic from the macrocells. We remark that cellular operators have started to deploy outdoor small cells in densely populated rural and urban areas [3] [4]. A recent report [3] indicates that the total number of small cells is greater than the total number of macrocells currently deployed.

Due to the proliferation of smartphones and their datahungry applications into our daily life, cellular subscribers are using smartphones almost everywhere, including on public transportation vehicles. The cellular traffic from this group of moving users also affects the macrocells' performance. As well, cellular users in public transportation vehicles may experience weak Received Signal Strength (RSS) and low levels of Signal to Interference and Noise Ratio (SINR) due to path loss, shadowing, Doppler shift effect, vehicle speed and distance to macroBSs. Therefore, improved onboard cellular coverage and capacity are both becoming very challenging issues for cellular operators; opening the door for new deployment scenarios for femtocells. For example, deploying mobile femtocells in public transportation vehicles to offer enhanced coverage and capacity onboard and to decrease the distance between UEs and infrastructures is presented in [5]. UEs will communicate with mobile FBSs (mobFBSs) onboard instead of macroBSs. The mobFBSs will connect with the macroBSs through a cooperative wireless link.

¹ A device with Wi-Fi and cellular radio interfaces.

We aim to study the impact of the use of mobFBS in public transportation vehicles on network performance. First, we propose to apply an appropriate precoder to the mobFBS in the vehicle to overcome the degraded performance of the received signal in outdoor wireless links. The precoded transmission helps in extracting the underlying rich multipath-Doppler diversity inherited in this type of double-selective fading link. Second, we derive a closed form expression of pairwise error probability (PEP) for mobile femtocells in order to evaluate the PEP performance of UEs with/without mobile femtocell deployments. We further contribute by providing a closed-form expression as a benchmark to assess our analysis. We also 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 and highlight the necessity for such mobile femtocell deployments. Section III presents our system model. The PEP derivation and gain analysis are presented in Section IV. Numerical results are provided in Section V. Section VI concludes the paper and highlights future directions.

Notation: (.)^T denotes transpose operation, (.)^{*} denotes conjugate operation and (.)^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 $\mathbf{H} \cdot \mathbf{I}_N$ indicates an $N \times N$ -size identity matrix. 1 and 0 represents, respectively, all-ones and all-zeros matrix with proper dimensions. [.] and [.] denotes integer ceil and integer floor operations, respectively. * is the convolution operator.

II. BACKGROUND AND RELATED WORK

A. Concept of Mobile Femtocell and Related Work

Mobile femtocells (mobFBS) in public vehicular environments (e.g., buses, streetcars) are introduced to offer better coverage and capacity onboard [5]. A MobFBS may be connected to the operator's CN via satellite, Wi-Fi or through macrocells similar to a mobile relay. However, FBSs are different than relays, as UEs will identify the mobFBSs as regular BSs and only communicate with FBSs. In the relay scenario, the UEs are aware of the donor BS that the relay is communicating with [6]. Hence, FBSs work as regular BSs: they are responsible to assign frequency and scheduling resources for UEs, unlike the relays.

MobFBSs deal with different deployment aspects, such as: frequency allocation, handover (HO) for mobFBS between different macrocells, HO process of the attached group of UEs, and wireless backhaul link with macrocells. Therefore, a limited number of contributions in the literature proposed to deploy mobile femtocells. For example, in our previous work [7], we propose to deploy mobile femtocells in public transportation vehicles to offload data traffic via utilizing urban Wi-Fi coverage as backhaul for mobFBSs. The authors in [8]



Figure 1. Mobile femtocell overview

propose deploying femtocells in vehicular environments to show the impact of the outage probability and uplink throughput. The FBS is connected to the cellular operator's CN through the serving macroBS or satellite communication. Results show that mobile femtocells can reduce the outage probability with an acceptable level of SINR. The authors in [9] investigate 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 the cellular subscribers onboard, their results show that there is large saving in volume of the control signaling from using mobile femtocells. The authors of [10] offer an infrastructure and a scheduling algorithm to provide seamless multimedia service for cellular users in high-speed trains through deploying femtocells onboard. The onboard femtocells will communicate with macrocells known before the next cell to facilitate the seamless HO. Research in [11] offers a resource management scheme for a group of cellular users that are communicating with a mobile femtocell through a dynamic reservation policy based on the QoS class requested.

B. The Necessity for Mobile Femtocells

Besides experiencing low SNR, low capacity, and consuming more power to communicate with the distant macroBSs, cellular users moving across macrocells can significantly affect the macroBSs performance in terms of traffic and power. Mobile femtocells can potentially solve these issues and offer the following advantages:

- Enable UEs to receive stronger RSS and a better level of SINR due to the shorter distance to the mobFBS.
- Reduce power consumption in UEs and macroBSs, as the UEs will communicate with the close by mobFBS, also the macroBS will only communicate with the mobFBS instead of communicating with a group of moving UEs.
- Decrease the macrocell's traffic, as the mobFBS will communicate with the macroBS on behalf of many UEs, which leads to saving in control signaling traffic.

- Enable location-based services in transportation vehicles through the mobFBSs.
- Move complexity of advanced techniques, e.g., precoding, to the mobFBSs instead of applying on all UEs eliminating the need to upgrade or modify UEs.

III. SYSTEM MODEL

A. Network Model

We consider a single macrocell using orthogonal frequency division multiplexing (OFDM) in an urban area with downlink (DL) transmission (see Figure 1). The macrocell is served by a macroBS. A mobile femtocell is deployed in a bus to provide cellular coverage onboard. The mobile femtocell is served by a mobile FBS (mobFBS)². The onboard UEs communicate directly with mobFBS. A UE might be any device with a cellular interface. All transmitters in macroBS, mobFBS and UEs are equipped with a single antenna.

The link between the macroBS and the mobFBS is called a wireless cooperative link (macroBS-to-mobFBS). It is a wireless radio interface for connecting the mobFBS with the macroBSs through a transmitter mounted on the roof of the vehicle. The wireless link between the mobFBS and the UE is called a wireless access link (mobFBS-to-UE). The mobFBS communicates with the onboard UEs and macroBS on two different frequency bands in order to mitigate the selfinterference frequency in the mobFBS. The mobFBSs is deployed by the cellular operator and is set to open access mode. The macroBS should be aware of the mobFBS and its associated UEs. The mobFBS has its own physical cell ID, so it appears to the UE as a different cell than the macroBS. However, the UE receives scheduling information and feedback directly from the mobFBS and sends its control channel information to the mobFBS. The mobFBS transmits information on its own control channels to the serving macroBS.

Once a UE enters the coverage of a mobFBS, it senses the mobFBS. A HO procedure is initiated based on a predefined parameter such as, SNR, RSSI, operator's preferences, enforced handover, etc.

For simplicity, from this point on, the aforementioned links will be written as $M \rightarrow F$ and $F \rightarrow U$, respectively.

B. Propagation Model

The propagation models for all wireless links are presented in the following.

1) $mobFBS-to-UE(F \rightarrow U)$

As the onboard UEs receive signals from the mobFBS, we consider the propagation model used between UEs and mobFBS as indoor Line of Sight (LOS) fading channel with Rician K-factor = 4 dB [12]. Hence, the path loss can be derived from modified Keenan Motley model [13] as follows

$$P_L = 32.5 + 20 \, \log_{10}(d) + 20 \, \log_{10}(f_f). \tag{1}$$

where P_L is the path loss between mobFBS and onboard UEs in dB, d is the distance between mobFBS and onboard UEs in meters, and f_f is the frequency used between the mobFBS and UEs in MHz.

2) macroBS-to-mobFBS $(M \rightarrow F)$

As the mobFBS receives signals from the macroBS, we consider the propagation model as outdoor None LOS (NLOS) Rayleigh fading channel with fast fading. The path loss associated with the distance d from the macroBS to the mobFBS is modeled as follows

$$\Omega(d) = 10^{(128.1 - 36.7 \log_{10} d)/10}.$$
(2)

Now let d_{MU} , d_{MF} and d_{FU} denote the distances of macroBSto-UE (M \rightarrow U), (M \rightarrow F), and (F \rightarrow U) links, respectively. Normalizing the path loss in M \rightarrow U to be unity, the relative geometrical gains are defined respectively as

$$G_{MF} = (d_{MU}/d_{MF})^{\circ}$$
 and $G_{FU} = (d_{MU}/d_{FU})^{\circ}$

3) macroBS-to-UE $(M \rightarrow U)$

The UEs communicate with the macroBSs in the typical cellular network deployment. Therefore, we consider the propagation model as outdoor NLOS Rayleigh fading channel with fast fading. The path loss used is given by expression (2).

C. Transmission and Signalling Model

After converting the time-sampled OFDM signal into frequency domain by applying the discrete Fourier transform (DFT), the discrete finite sequence of complex coefficient is given by

$$s(\ell) = \frac{1}{\sqrt{N}} \sum_{k=0}^{(N-1)} x(k) e^{-jw_k}, \qquad n = 0, \dots, N-1$$
(3)

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 discretetime baseband equivalent channel for the doubly-selective channel for an urban scenario, and is given by

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

$$\tag{4}$$

where $w_q = 2\pi \ell (q - Q/2)/N$, and $h_q(n;l)$ 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. Now, from expressions (3) and (4), we can obtain the following expression

$$h_{B}(\ell;l)s(\ell) = \frac{1}{\sqrt{N}} \sum_{q=0}^{Q} \sum_{k=0}^{(N-1)} h_{q}(n;l)x(k)e^{-jw},$$
(5)

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

² The mobFBS is a regular FBS installed in the vehicle.

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 s(n)s are the input to a linear precoder Θ with size of $N_s \times N_t$. The $N_s = PZ$, and the $N_t = (P+Q)(Z+L)$. We define $\mathbf{H}_{MF,q}^{(0)}$ and $\mathbf{H}_{FU,q}^{(0)}$ as the lower triangular Toeplitz channel matrices with entries given by equation (4). L_{MF} and L_{FU} are the channel multipath lengths for $M \rightarrow F$ and $F \rightarrow U$ links, respectively. Whereas Q_{MF} and Q_{FU} represent the number of resolvable Doppler components for the aforementioned links.

The received signal at the mobFBS can be written as a matrix form as follows

$$\mathbf{y}_{MF}\left(n\right) = \sqrt{G_{MF}E_{s}} \sum_{q=0}^{Q} \mathbf{D}(w_{q}) \mathbf{H}_{MF,q}^{(0)}\left(n\right) \mathbf{u}\left(n\right) + \mathbf{n}_{MF}\left(n\right), \tag{6}$$

where $\mathbf{u}(\ell) = \mathbf{\Theta} \mathbf{s}(\ell)$ is the transmitted data blocks, E_s is the modulated symbol energy, $Q = \max(Q_{MF}, Q_{FU})$, $\mathbf{D}(w) := \operatorname{diag}[1, \dots, \exp(jw(N_t - 1))]$ and $\mathbf{n}_{MF}(n)$ is the $M \rightarrow F$ 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 $\mathbf{H}_{MF,q}^{(0)}(n)\mathbf{u}(n)$ to $\mathbf{U}(n)\mathbf{h}_{MF,q}(n)$. We can then rewrite the expression in (6) as

$$\mathbf{y}_{MF}\left(n\right) = \sqrt{G_{MF}E_{s}} \sum_{q=0}^{Q} \mathbf{D}(w_{q}) \mathbf{U}(n) \mathbf{h}_{MF,q}(n) + \mathbf{n}_{MF}(n).$$
(7)

After defining the augmented matrices

 $\mathbf{h}_{MF}(n) = [\mathbf{h}_{MF,0}^{\mathrm{T}}(n) \cdots \mathbf{h}_{MF,Q}^{\mathrm{T}}(n)]^{\mathrm{T}}$ and

 $\mathbf{\Phi}(n) = [\mathbf{D}(w_0)\mathbf{U}(n) \cdots \mathbf{D}(w_0)\mathbf{U}(n)], \text{ we get}$

$$\mathbf{y}_{MF}(n) = \sqrt{G_{MF}E_s}\mathbf{\Phi}(n)\mathbf{h}_{MF}(n) + \mathbf{n}_{MF}(n).$$
(8)

During the cooperative (relaying) stage, the mobFBS's received signals is fed to ML detector and is given by

$$\arg \min_{\overline{s}} \left\{ \left\| \mathbf{y}_{MF}\left(n\right) - \sqrt{G_{MF}E_{s}} \sum_{q=0}^{Q} \mathbf{D}(w_{q}) \mathbf{H}_{MF,q}^{(0)}\left(n\right) \mathbf{\Theta} \overline{s} \right\|^{2} \right\}.$$
(9)

with \overline{s} by means of all possible signal block combinations. We apply an "ideal Decode and Forward (DF)" relaying [14] at the mobFBS. The mobFBS 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

$$\mathbf{y}_{FU}(\ell) = \sqrt{G_{FU}E_s}h_{FU}\dot{\mathbf{s}}(\ell) + \mathbf{n}_{FU}(\ell) , \qquad (10)$$

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

IV. PEP DERIVATION AND GAIN ANALYSIS

In this section, we study the performance of cellular UEs with mobile femtocell deployment. Also, we derive a closed form expression for the pairwise error probability (PEP), which is the error probability that for a transmitted signal (\mathbf{S}) its corresponding but distorted version ($\hat{\mathbf{S}}$) will be received.

The PEP at the UE is given by [14]

$$P\left(\mathbf{S} \to \hat{\mathbf{S}}\right) \leq \left(1 - P_{MF}\left(\mathbf{S} \to \hat{\mathbf{S}}\right)\right) P_{Coop}\left(\mathbf{S} \to \hat{\mathbf{S}}\right) + P_{MF}\left(\mathbf{S} \to \hat{\mathbf{S}}\right), (11)$$

where $\hat{\mathbf{S}}$ represents the decoded data matrix instead of the original transmitted data, $P(\mathbf{S} \rightarrow \hat{\mathbf{S}})$ is the end-to-end PEP,

 $P_{MF}(\mathbf{S} \rightarrow \hat{\mathbf{S}})$ is the PEP of the M \rightarrow F link, $P_{Coop}(\mathbf{S} \rightarrow \hat{\mathbf{S}})$ is the PEP of from the cooperative link, i.e., M \rightarrow F and F \rightarrow U in the case that the mobFBS 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 [14] as follows

$$P(\mathbf{S} \to \hat{\mathbf{S}}) \le P_{Coop}(\mathbf{S} \to \hat{\mathbf{S}}) + P_{MF}(\mathbf{S} \to \hat{\mathbf{S}}).$$
(12)

Reference [15] gives the conditional PEP for each individual term in (12) as follows

$$P(\mathbf{S} \to \hat{\mathbf{S}} | \mathbf{h}) = Q\left(\sqrt{\frac{1}{2N_0} d^2\left(\mathbf{S}, \hat{\mathbf{S}} | \mathbf{h}\right)}\right).$$
(13)

Using the approximated bound proposed in [16], the expression in (13) can be approximated by the following expression

$$P(\mathbf{S} \to \hat{\mathbf{S}} | \mathbf{h}) \approx \sum_{m=1}^{3} \varepsilon_{m} \exp\left(-\frac{\rho_{m}}{4N_{0}} d^{2} \left(\mathbf{S} \to \hat{\mathbf{S}} | \mathbf{h}\right)\right),$$
(14)

where
$$\varepsilon_1 = \varepsilon_2 = 2\varepsilon_3 = 1/12$$
, $\rho_1 = 12(\sqrt{3}-1)/\pi$,
 $\rho_2 = 4(3-\sqrt{3})/\pi$ and $\rho_3 = 2\sqrt{3}/\pi$.

The Euclidean distance conditioned on the fading channel coefficients is $d^2 \left(\mathbf{S} \rightarrow \hat{\mathbf{S}} \middle| \mathbf{h} \right) = \mathbf{h}^{\mathrm{H}} \left(\mathbf{S} - \hat{\mathbf{S}} \right)^{\mathrm{H}} \left(\mathbf{S} - \hat{\mathbf{S}} \right) \mathbf{h}$. Starting with $P_{Coop} \left(\mathbf{S} \rightarrow \hat{\mathbf{S}} \middle| \mathbf{h} \right)$, expression (14) can be rewritten as

$$P_{Coop}\left(\mathbf{S} \to \hat{\mathbf{S}} \middle| h_{FU}\right) \leq \sum_{m=1}^{3} \varepsilon_{m} \exp\left(-\rho_{m} \frac{G_{FU} h_{FU}^{\mathsf{H}} \chi h_{FU}}{4} \gamma\right), \qquad (15)$$

where $\chi = \dot{\mathbf{s}}^{\text{H}} \dot{\mathbf{s}} - \hat{\mathbf{s}}^{\text{H}} \hat{\mathbf{s}}$ and $\gamma = E_s / N_0$ is the transmitted symbol signal-to-noise ratio (SNR). Now, we need to average (15) over h_{FU} . Note that the channel autocorrelation matrix is given by $\mathbf{R}_{h,FU} \coloneqq L \times \mathbb{E}[h_{MU} h_{MU}^{\text{H}}]$, and the channel rank is $r_a \coloneqq \operatorname{rank}(R_{h,FU}) = 1$. From expression (12), averaging the result expression with respect to $|h_{FU}|$ which is Rayleigh distributed, we obtain the following

$$P_{Coop}\left(\mathbf{S} \to \hat{\mathbf{S}}\right) \leq \sum_{m=1}^{3} \varepsilon_{m} \left(1 + \rho_{m} \frac{1}{4} \gamma\right)^{-1} \,. \tag{16}$$

In the same way, we need to average equation (14) over \mathbf{h}_{MF} by using the eigenvalues decomposition. Hence, we obtain the following expression

$$P_{MF}\left(\mathbf{S} \to \hat{\mathbf{S}}\right) \leq \prod_{k=0}^{r_{MF}-1} \sum_{m=1}^{3} \varepsilon_{m} \left(1 + \rho_{m} G_{MF} \frac{\alpha_{k}}{4} \gamma\right)^{-1} , \qquad (17)$$

where the eigenvector of $\overline{\mathbf{h}}_{MF}$ is $\overline{\mathbf{D}}_{MF} \coloneqq \text{diag}[\alpha_0, \alpha_1, \dots, \alpha_{r_{MF}-1}]$ and r_{MF} is the channel rank of \mathbf{h}_{MF} . Substituting $P_{Coop}(\mathbf{S} \rightarrow \hat{\mathbf{S}})$ and $P_{MF}(\mathbf{S} \rightarrow \hat{\mathbf{S}})$ in (12), we have the end-to-end PEP expression as follows

$$P\left(\mathbf{S} \to \hat{\mathbf{S}}\right) \leq \prod_{k=0}^{r_{MF}-1} \sum_{m=1}^{3} \varepsilon_{m} \left(1 + \rho_{m} G_{MF} \frac{\alpha_{k}}{4} \gamma\right)^{-1} + \sum_{m=1}^{3} \varepsilon_{m} \left(1 + \rho_{m} \frac{1}{4} \gamma\right)^{-1}.$$
(18)

However, at relatively high SNR values, we observe from (18) that an asymptotic gain of $D_{gain} = \min(r_{MF}, 1) = 1$ is achievable.

For the sake of fair comparison, we provide the PEP expression for non-precoded signal through the direct link from the macroBS to the UE as follows

$$P_d\left(\mathbf{S} \to \hat{\mathbf{S}}\right) \leq \sum_{m=1}^{3} \varepsilon_m \left(1 + \rho_m G_{BU} \frac{\beta_k}{4} \gamma\right)^{-1} , \qquad (19)$$

where β_k is the time-selective channel associated random variable in the macroBS-to-UE link (M \rightarrow U), and modeled by a short-term fading coefficient. The receiving terminals have low elevation antennas and are located within a highly scattered area; accordingly the channel is characterized as single Rayleigh - double Doppler. We adopt the double-ring channel model of which assumes that the scattering reflectors lay uniformly over a ring around the UE [17]. The channel autocorrelation function is given by the following expression

$$R(\tau) = \sigma^2 J_0 \left(\frac{2\pi}{\lambda} v_1 \tau\right) J_0 \left(\frac{2\pi}{\lambda} v_2 \tau\right), \tag{20}$$

where $J_0(.)$ is the zero order Bessel function, and the maximum velocities for the two communicating terminals are v_1 and v_2 . Since we have a stationary macroBS antenna (i.e., $v_1 = 0$). Assuming single Rayleigh distribution with a single Doppler, the power spectrum and time correlation mathematical functions reduce back to have the autocorrelation function and the power spectrum of the complex envelope given by $R(\tau) = \sigma^2 J_0 (2\pi v_2 \tau/\lambda)$.

V. NUMERICAL RESULTS

In this section, we present numerical results to demonstrate the error rate performance. LTE-A addresses those challenges by targeting peak data rates up to 1 Gb/s with up to 100 MHz supported spectrum bandwidth and by making use of highorder multiple antennas transmission [18]. Unless otherwise stated, we consider quadrature phase-shift keying (QPSK) modulation and assume $f_c = 2.5 \text{ GHz}$, $T_s = 500 \,\mu s$, $v_r = 120 \,\text{km/h}$, $\alpha = 3.67$, $\theta = \pi$, $G_{MF} / G_{FU} = -30 \,\text{dB}$ and $\tau_d = 1.328 \,\mu s$ [19]. We assume that perfect channel state information is available at the receiving UEs. We use the precoder Θ with parameters P = 2 and Z = 2. This results in $[L_{Coop}, Q_{Coop}] = [1,1]$ for $M \rightarrow F$ and a frequency-time flat channel is used for $F \rightarrow U$ link, i.e. $[L_{MF}, Q_{MF}] = [0,0]$.

In Figure 2, we compare the PEP of the end-to-end link with the performance of the network with mobile femtocell and without mobile femtocell. We also compare the derived PEP expression (18) and (19) illustrated using dashed lines, to the exact expression (13) using solid lines. Exact PEP can be found by taking the expectation of the unconditional PEP numerically through the random generation of h with proper statistics³. We observe that the derived PEP provides a tight upper bound on the exact one with about $\simeq 0.5 \text{ dB}$ difference. A power consumption saving is clearly observed when the cooperative relaying link using the femtocell is used, for example at PEP= 10^{-2} a transmitting power consumption saving of 10 dB, compared to the direct link, i.e., $M \rightarrow U$. The UEs with no mobile femtocells have to communicate with the macroBS with a higher transmit power. While in the mobile femtocell case, the UEs communicate with the mobFBS with lower transmit power to achieve the same error performance.

In Figure 3, we plot the slope of the performance curves for the $M \rightarrow U$ and the $M \rightarrow F$ links, i.e., $P_d(\mathbf{S} \rightarrow \hat{\mathbf{S}})$ and $P_{Coop}(\mathbf{S} \rightarrow \hat{\mathbf{S}})$, respectively. The slope of the curves $-\log P(\mathbf{S} \rightarrow \hat{\mathbf{S}})/\log (\gamma)$ precisely shows the achieved asymptotical diversity gains and the rate of the change of the system performance with respect to change of the SNR. It should be noted from Figure 3 that a diversity gain of 4 is achieved by deploying our transmission scheme in the $M \rightarrow F$ with respect to diversity gain of 1 in the traditional direct transmission in the $M \rightarrow U$ link.

VI. CONCLUSION AND FUTURE WORK

In this paper, mobile femtocell deployment in public transportation vehicles is proposed to enhance and improve the coverage and capacity of cellular networks. We study the impact of mobile femtocells in cellular networks, as well as quantify performance enhancements in terms of error probability and diversity gains. We provide a closed form expression for the PEP. Analytical and numerical simulation results demonstrated significant contributions in performance gains, where a notable diversity gain is achieved at the outdoor

³ We remark though that unlike our derived exact formula, such exact values are not readily available for designers.



Figure 2. Comparison of the derived PEP and the exact PEP, and between the direct and cooperative link.

fading wireless link, as well as a tremendous reduction in the error rates. Furthermore, a reduction in the required transmitting powers compared to the traditional transmission schemes is observed subjected to a specific error rate.

The proposed scheme offers several future research opportunities that need further attention from the upper layers prospective, including scheduling, coding, mobility management, etc. Other directions include considerations for the deployment of multiple antennas at the macroBS and the mobFBS, and quantifying the performance gains in terms of power consumption, received signal and capacity for UEs.

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REFERENCES

- J. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. Reed, "Femtocells: Past, present, and future," *IEEE J. select. Areas Commun.*, vol. 30, no. 3, pp. 497 –508, Apr. 2012.
- [2] D. Calin, H. Claussen, and H. Uzunalioglu, "On femto deployment architectures and macrocell offloading benefits in joint macro-femto deployments," *IEEE Commun. Mag.*, vol. 48, no. 1, pp. 26 –32, Jan. 2010.
- [3] "Small cell market status." white paper, *Informa and Small Cell Forum*, no. 1, Feb. 2013.
- [4] M. Qutqut and H. Hassanien, "Mobility management in wireless broadband femtocells." tech. report 2012-590, Queen's University, July 2012.
- [5] F. Haider, C. Wang, H. Haas, D. Yuan, H. Wang, X. Gao, X. You, and E. Hepsaydir, "Spectral efficiency analysis of mobile femtocell based cellular systems," in *IEEE 13th Intl. Conf. Commun. Technol.*, ICCT, Sept. 2011, pp. 347–351.
- [6] Y. Sui, A. Papadogiannis, and T. Svensson, "The potential of moving relays - a performance analysis," in *IEEE 75th Veh. Technol. Conf.*, VTC-Spring, May 2012, pp. 1–5.



Figure 3. Diversity order gains for mobile femtocell Vs. typical direct transmission deployment.

- [7] M. Qutqut, F. Al-Turjman, and H. Hassanein, "MFW: mobile femtocells utilizing WiFi, a data offloading framework for cellular networks using mobile femtocells," in *IEEE Intl. Conf. Commun.*, ICC, Budapest, Hungary, June 2013.
- [8] M. Chowdhury, M. Bui, and Y. Jang, "Neighbor cell list optimization for femtocell-to-femtocell handover in dense femtocellular networks," in *3rd Intl. Conf. Ubiquitous and Future Networks*, ICUFN, June 2011, pp. 241–245.
- [9] F. Haider, M. Dianati, and R. Tafazolli, "A simulation based study of mobile femtocell assisted LTE networks," in *IEEE 7th Intl. Wireless Commun. Mobile Compu. Conf.*, IWCMC, Istanbul, Turkey, July 2011, pp. 2198–2203.
- [10] O. Karimi, J. Liu, and C. Wang, "Seamless wireless connectivity for multimedia services in high speed trains," *IEEE J. Select. Areas Commun.*, vol. 30, no. 4, pp. 729–739, May 2012.
- [11] M. Chowdhury, S. H. Chae, and Y. Jang, "Group handover management in mobile femtocellular network feployment," in *4th Intl. Conf. Ubiquitous and Future Networks*, ICUFN, pp. 162–165, July 2012.
- [12] T. Fernández-Caramés, M. González-López, and L. Castedo, "Mobile WiMAX for vehicular applications: Performance evaluation and comparison against IEEE 802.11p/a," *Elsevier Comput. Networks*, Vol. 55, no. 16, pp. 3784-3795, Nov. 2011.
- [13] F. Hasan, H. Siddique, and S. Chakraborty, "Femtocell versus WiFi a survey and comparison of architecture and performance," in *IEEE 1st Intl. Conf. Wireless Commun. Veh. Technol. Inform. Theory Aerospace Electron. Syst. Technol.*, Wireless-VITAE, Coleraine, UK, May 2009, pp. 916 –920.
- [14] Y. Ma, N. Yi, and R. Tafazolli, "Bit and power loading for OFDM-based three-node relaying communications," *IEEE Trans. Signal Process.*, vol. 56, no. 7, pp. 3236–3247, July 2008.
- [15] V. Tarokh, N. Seshadri, and A. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *IEEE Trans. Inform. Theory*, vol. 44, no. 2, pp. 744–765, Mar. 1998.
- [16] M. Wu, X. Lin, and P. Kam, "New exponential lower bounds on the gaussian Q-function via jensen's inequality," in *IEEE 73rd Veh. Technol. Conf.*, VTC-Spring, Yokohama, Japan, May 2011, pp. 1–5.
- [17] J. Proakis and M. Salehi, *Digital Communications*. USA: McGraw-Hill, 2009.
- [18] C. Zhang, S. Ariyavisitakul, and M. Tao, "LTE-advanced and 4G wireless communications [Guest Editorial]," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 102–103, Feb. 2012.
- [19] I. Sen and D. Matolak, "V2V channels and performance of multiuser spread spectrum modulation," *IEEE Veh. Technol. Mag.*, vol. 2, no. 4, pp. 19-25, Dec. 2007.