Energy-Efficient and Interference-Aware Handover Decision for the LTE-Advanced Femtocell Network

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***Abstract* – Femtocells will play a key role for the wide adoption of the LTE-Advanced system, as they bring the access network closer to the end user in a cost-effective manner. This disruptive communication paradigm, however, dictates the use of advanced interference and mobility management algorithms to cope with the dense yet unplanned network layout. In this paper, we present an interference-aware handover decision algorithm for the LTE-Advanced femtocell network, which utilizes standard signal measurements to select the candidate cell that a) attains the minimum required channel gain for sustaining service continuity and b) minimizes the mean UE transmit power for a prescribed mean SINR target. The proposed algorithm attains backwards compatibility with the LTE-Advanced system, as it is deployed by using the private mechanism for non-standard use. Based on the evaluation methodology of the Small Cell forum, we validate the performance of the proposed algorithm and compare it against that of other state-of-the-art algorithms.**

***Index Terms*: LTE-Advanced; femtocells; handover decision; interference; energy efficiency;**

I. INTRODUCTION

Release 10 of the 3rd Generation Partnership Project (3GPP) for the Long Term Evolution (LTE) system, a.k.a. LTE-Advanced (LTE-A), describes a wide range of technical improvements for the LTE system, mainly including carrier aggregation, advanced multi-antenna techniques, enhanced support for heterogeneous deployments, and relaying [1] [2]. Support of femtocells is an integral part of the LTE-A system and will play a key role for its wide adoption in a broad scale. Femtocells are low-power and low-cost cellular access points that support fewer users compared to macrocells, embody the functionality of a regular base station, and operate in the mobile operator's licensed spectrum [3]. Femtocells can improve the energy saving potential for the network nodes and enhance the Quality of Service (QoS) perceived by the users. Existing reports foresee that the number of deployed femtocells will surpass that of macrocells by up to six times within the next few years [4]. To this end, the smooth integration of femtocells into the macro-cellular network layout is of critical importance in future LTE-A deployments.

Support of femtocells comprises several technical challenges that span over the areas of energy saving [5], interference management [6]-[7], and handover (HO) decision making [8]-[11]. Energy saving is essential in the presence of femtocells, owing to the vastly overlapping cell coverage and the dense network layout. Interference management is critical in the LTE-A femtocell network as well, to mitigate the negative impact of cross-tier interference on the Signal to Interference plus Noise Ratio (SINR) performance. More sophisticated HO decision making is also required in the presence of LTE-A femtocells to sustain a low HO probability without sacrificing the femtocell utilization opportunities.

Current literature includes various energy saving approaches for the LTE-A femtocell network that mainly focus on reducing the energy expenditure at the cells [5]. A wide range of femtocell-specific interference mitigation techniques have also been proposed, founded on the concepts of interference avoidance and cancellation [6]. Different from existing energy saving and interference mitigation approaches, in this paper we focus on reducing the energy-expenditure and the received interference at the User Equipment (UE). To achieve this, we propose interference-aware HO decision making, an approach which has not been thoroughly investigated in the literature.

Even though HO decision making is challenging in the LTE-A femtocell network, only a few reports are engaged with the matter [8]-[11]. Assuming a single-femtocell single-macrocell network layout, the algorithm in [8] uses a combined Received Signal Strength (RSS) metric to choose between the macrocell and the femtocell service. The algorithm in [9] accounts for the UE speed to avoid inbound mobility to femtocells for medium to high speed users. The authors in [10] perform mobility prediction to estimate the cell residence time of the user and reduce the number of unnecessary HO events in the system. The policy in [11] uses standard measurements to reduce the mean UE transmit power in the two-tier LTE femtocell network. Different from the proposals in [8]-[10], this paper presents a HO decision algorithm that accounts for the impact of interference at the cell sites to reduce the energy expenditure and interference at the UE side. In addition, different from our previous work in [11], in this paper we describe an algorithm that a) applies to the LTE-A system, b) avoids using a fixed HO Hysteresis Margin (HHM) to perform the decision phase, and c) attains a low HO probability by avoiding cells with poor channel conditions, i.e., channel gain.

The remainder of the paper is organized as follows. Section II describes the system model. Section III presents the proposed algorithm and discusses the required network signaling. The performance of the algorithm is demonstrated in Section IV, whereas Section V concludes the paper.

II. SYSTEM MODEL

We consider a LTE-A network consisted of a macrocell and a femtocell tier. Macrocells are referred to as evolved Node B (eNB), while femtocells as Home eNB (HeNB). Both tiers operate in the band set denoted by $\boldsymbol{N} \coloneqq \{1, \dots, N\}$. Let $\boldsymbol{C_n}$ denote the set of cells operating in band n, including both eNBs and HeNBs, and $\boldsymbol{U_n}$ the set of users served from a cell in $\boldsymbol{C_n}$. We focus our analysis on the HO decision phase for a tagged LTE-A user $u \in \boldsymbol{U_n}$, which is served from cell $s \in \boldsymbol{C_n}$ and is in proximity of the (candidate and accessible) cell set $\boldsymbol{L} \subseteq \bigcup_{n \in \boldsymbol{N}} \boldsymbol{C_n}$. To sustain service continuity, the tagged user is assumed to have a minimum requirement in terms of Reference Signal Received Power (RSRP) [12], denoted by $RSRP_{th}$, while to support its ongoing services it is assumed to have a prescribed mean SINR target, denoted by γ_t.

Table I summarizes the notation used for the system model parameters and measurements. Note that all these parameters are assumed to be derived in the context of the HO decision phase, i.e., averaged in the operating bandwidth of the target cell over the time interval Time To Trigger (TTT) [11] [12].

System Model Parameters	**Notation**
Mean Transmit Power of node x (LTE-A cell or user)	$P(x)$
Mean Noise Power in node x (LTE-A cell or user)	$\sigma(x)^2$
Mean Channel Gain from node x to node y (LTE-A cells or users)	$h(x,y)$
Maximum Allowed Transmit Power of node x (LTE-A cell or user)	$P_{max}(x)$
Handover Hysteresis Margin (HHM) for cell c	$HHM(c)$
LTE-A Signal Quality Measurements [12]	**Notation**
Reference Signal Received Power (RSRP) in cell c	$RSRP(c)$
Received Interference Power (RIP) in cell c	$I(c)$
Downlink Reference Signal Transmit Power (DL RS Tx) of cell c	$P_{RS}(c)$

Table I: System model parameters and LTE-A measurements

For the tagged time interval TTT, the mean uplink (UL) SINR of user u is given by Eq. (1).

$$\gamma(s) = \frac{P(u) \cdot h(u,s)}{\sum_{u' \in \boldsymbol{U_n} - \{u\}} P(u') \cdot h(u',s) + \sigma(s)^2} \qquad (1)$$

where the numerator corresponds to the signal strength from user u in cell s, while the denominator to the interference caused by in-band operating users plus the noise power in cell s. Given the prescribed mean SINR target γ_t, we can show that the mean UE transmit power of user u in the candidate cell $c \in \boldsymbol{L}$, denoted by $P(u,c)$, can be derived as follows:

$$P(u,c) = \frac{\gamma_t \cdot \left(\sum_{u' \in \boldsymbol{U_n} - \{u\}} P(u') \cdot h(u',c) + \sigma(c)^2 \right)}{h(u,c)} \qquad (2)$$

Note that the positive impact of handing over to cell c in terms of lower interference is included in Eq. (2), as we omit the interference caused by the user connection with cell s, i.e., $P(u) \cdot h(u,s)$. Assuming that the transmit power is a primary contributor to the UE power consumption, Eq. (2) can be used to estimate the mean power consumption of user u as well.

III. THE PROPOSED HANDOVER ALGORITHM

The proposed HO decision algorithm utilizes standard LTE-A measurements to mitigate the negative impact of user mobility and lower the mean UE transmit power for the prescribed mean SINR target. The former is achieved by excluding cells with channel gain lower than that required to sustain service continuity, while the latter by estimating the mean UE transmit power for the remainder cells and handing over to the one with the minimum requirements.

The remainder of this section is organized as follows. Section III.A describes a novel criterion for excluding cells with channel gain lower than the one required for sustaining service continuity, while Section III.B describes a criterion for handing over to the cell with the minimum required mean UE transmit power. Both these criteria are integrated in the proposed algorithm in Section III.C, which also discusses the network signaling for deploying the algorithm.

A. *Criterion for sustained service continuity*

Sustaining service continuity is of critical importance in the presence of femtocells, if we consider the short-range nature of communications, the denser network layout and the fast varying radio environment. Taking into account the definition of the RSRP and the DL RS Tx measurements in [12], it can be readily shown that they are related as follows:

$$RSRP(c) = P_{RS}(c) \cdot h(c,u) \qquad (3)$$

In macrocell deployments, higher RSRP typically results in improved channel gain, i.e., comparable RS transmit powers are radiated among the cells. In the presence of femtocells, however, the RSRP is biased in favor of the cells with the higher RS transmit powers (Eq. (3)). As a result, handing over to the strongest cell does not necessarily improve the channel gain or the SINR performance. Based on this observation, we propose a criterion that can be used to avoid cells with poor channel conditions, i.e., compromised service continuity.

Taking into account the minimum required RSRP for sustaining service continuity, i.e., $RSRP_{th}$, and the maximum allowed transmit power for user u and cell c, i.e., $P_{max}(u)$ and $P_{max}(c)$, respectively, we can estimate the channel gain threshold, denoted by $h_{min}(c)$, above which the service continuity between cell c and user u is sustained:

$$h_{min}(c) = \frac{RSRP_{min}}{\min(P_{max}(u), P_{max}(c))} \qquad (4)$$

Note that the $P_{max}(u)$ and $P_{max}(c)$ constraints can be owed to either an interference limitation for the cell or the user, or to the power class of the cell or the UE. It follows that sustaining service continuity is equivalent to satisfying the condition: $h(c,u) > h_{min}(c)$. By using Eq. (3) and (4), it can be shown that the set of candidate cells that sustain service continuity, denoted by $\boldsymbol{M}$, can be identified by the following criterion:

$$\boldsymbol{M} \coloneqq \{c | RSRP(c) > RSRP_{th} + P_{RS}(c) - \min(P_{max}(u), P_{max}(c)), c \in \mathbf{L}\} \qquad (5)$$

where the parameters in Eq. (5) are assumed to be taken in decibels (dB).

B. *Criterion for reduced UE transmit power*

This section describes a LTE-A compliant methodology for estimating the mean UE transmit power of the user on a per candidate cell basis, given a prescribed mean SINR target. The incorporation of the SINR target enhances the supported QoS, while the utilization of standard LTE-A measurements provides an accurate estimation for the mean UE transmit power requirements. By taking into account the definition of the RIP measurement in [12], it follows that:

$$I(s) = \sum_{u' \in \boldsymbol{U_n} - \{u\}} P(u') \cdot h(u',s) + \sigma(s)^2 \qquad (6)$$

Assuming a symmetric channel gain, i.e., $h(s,u) = h(u,s)$, and by using Eq. (2), (3), and (6), it follows that the mean UE transmit power for the current serving cell s can be estimated by Eq. (7).

$$P(u) = \frac{\gamma_t \cdot P_{RS}(s) \cdot I(s)}{RSRP(s)} \quad (7)$$

Under the same viewpoint, the mean UE transmit power for a candidate cell c ∈ $\boldsymbol{M}$ can be estimated as follows:

$$P(u,c) = \begin{cases} \dfrac{\gamma_t \cdot P_{RS}(s) \cdot \left(I(s) - \frac{\gamma_t \cdot P_{RS}(s) \cdot I(s)}{RSRP(s)} \cdot \frac{RSRP(c)}{P_{RS}(c)} \right)}{RSRP(c)}, & if\ c,s \in \boldsymbol{C_n} \\ \dfrac{\gamma_t \cdot P_{RS}(c) \cdot I(c)}{RSRP(c)}, & otherwise \end{cases} \quad (8)$$

where the condition $c, s \in \boldsymbol{C_n}$ is introduced to remove the interference caused by the ongoing user link with cell s, i.e., $P(u) \cdot h(u,c)$, if cells c and s operate in the same band. We can argue that a HO to the candidate cell c ∈ $\boldsymbol{M}$ is expected to lower the mean UE transmit power if the condition $P(u) > P(u,c)$ is met. By using Eq. (8) and taking the values in dB, it can be shown that this condition can be rearranged in a relative RSRP comparison with adaptive HHM as follows:

$$RSRP(c) > RSRP(s) + HHM(c) \quad (9)$$

where the $HHM(c)$ parameter is adapted according to Eq.(10).

$$HHM(c) = \begin{cases} 10 \log \dfrac{P_{RS}(c) \cdot \left(I(c) - \frac{\gamma_t \cdot P_{RS}(s) \cdot I(s)}{RSRP(s)} \cdot \frac{RSRP(c)}{P_{RS}(c)} \right)}{P_{RS}(s) I(s)} & c,s \in \boldsymbol{C_n} \\ 10 \log \dfrac{P_{RS}(c) \cdot I(c)}{P_{RS}(s) \cdot I(s)} & otherwise \end{cases} \quad (10)$$

Combined with the criterion for sustained service continuity in Eq. (5), Eq. (9)-(10) can be used to select the candidate cell with the minimum required mean UE transmit power as follows:

$$\arg\max_{c \in \boldsymbol{M}} RSRP(c) := \{c \mid RSRP(c) > RSRP(s) + HHM(c)\} \quad (11)$$

where the RSRP measurements are assumed to be taken in dB.

Note that Eq. (11) provides a backwards compatible method with the standard HO decision procedure in cellular networks, i.e., the strongest cell criterion. The key difference is that the HO decision criterion in Eq. (11) a) adapts the HHM based on standard LTE-A context, i.e., signal measurements, and b) is performed on the candidate cells that sustain service continuity.

C. *Proposed HO decision algorithm*

The proposed HO decision algorithm integrates the criteria for sustained service continuity and reduced UE transmit power, to enhance the HO decision efficiency in the LTE-A femtocell network. Note that the required HO decision context consists of the following information for the candidate cells: a) operating frequency, b) current LTE-A measurement status (Table I), and c) maximum allowed transmit power constraint.

The proposed HO decision algorithm is illustrated in Fig. 1. Upon HO decision triggering (step 1), the proposed algorithm acquires the HO context from the candidate cells in $\boldsymbol{L}$ (step 2). The network signaling for performing this step is discussed in Section III.D. Based on the acquired HO decision context, the algorithm performs the criterion for sustained service continuity in step 3, and evaluates whether there exists at least one cell that satisfies the criterion. If not, the cell search procedure is triggered and the algorithm is completed (step 5). In the opposite case, the HHM per candidate cell in $\boldsymbol{M}$ is calculated (step 6), and the HO decision criterion for reduced UE transmit power is deployed (step 7). If the current serving cell is the one that satisfies the criterion in step 7, the algorithm is terminated and no further action is taken. However, if another candidate cell satisfies the condition, a HO is executed and the algorithm is completed (step 8).

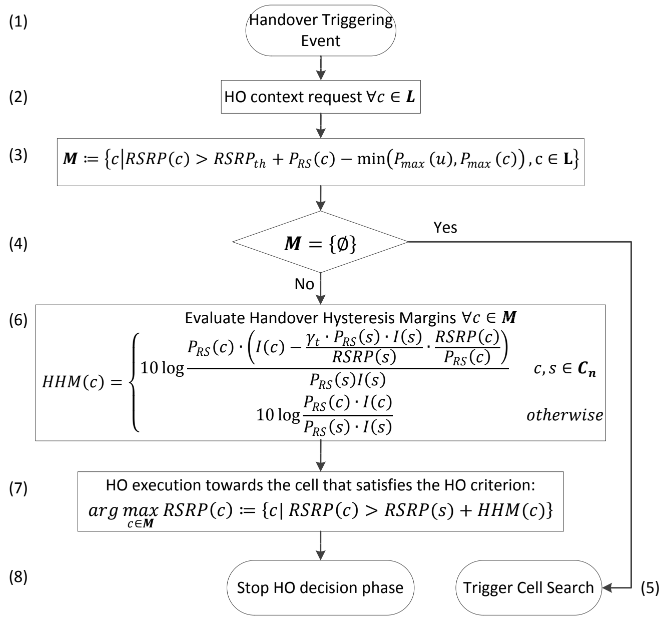

Figure 1: Proposed HO decision algorithm for the LTE-A femtocell network

D. *Network signaling for HO context acquisition*

Let us now focus on how the HO context acquisition in Fig. 1 can be performed (step 2). The LTE-A standard describes a wide set of signals for the S1 and X2 interfaces which, however, are not provisioned to transfer the entire HO decision context required for deploying the proposed algorithm. Nevertheless, the HO context acquisition signals can be performed by using the *private message mechanism* for non-standard use described in [13] for the X2 interface, and in [14] for the S1 interface. Provided that both the HO context under use and the procedure for exchanging it among the cells, i.e., the private mechanism, are already part of the LTE-A standard, it follows that the proposed algorithm is backwards compatible with the LTE-A system and can be performed by using a simple software update at the eNBs and HeNBs.

IV. NUMERICAL RESULTS

This section evaluates the performance of the proposed algorithm based on an extended version of the system-level methodology described by the Small Cell forum in [15]. A hexagonal LTE-A network is considered with a main cluster composed of 7 eNBs, where each eNB consists of 3 sectors. The wrap-around technique is used to extend the network, by copying the main cluster symmetrically on each of the 6 sides. A set of blocks of apartments, referred to as femtoblocks, are uniformly dropped within the main cluster area with respect to the femtoblock deployment density parameter, denoted by d_{FB}, which indicates the percentage of the main cluster area covered with femtoblocks. Femtoblocks are modeled in line with the dual stripe model for dense urban environments in [15] and the path loss models are adapted accordingly. The deployment of HeNBs within each femtoblock is based on the HeNB deployment density parameter, denoted by r_{fc}, which indicates the percentage of femtoblock apartments with a HeNB installed. Note that a higher d_{FB} corresponds to denser femtoblock layout within the main cluster, whereas a higher r_{fc} to denser HeNB deployment within the femtoblocks. HeNBs and users are uniformly dropped inside the apartments, where each HeNB initially serves one user and can serve up to four users. Each eNB sector initially serves ten users, which are uniformly dropped within it. The users are members of up to one Closed Subscriber Group (CSG), where three CSG IDs are used. The rest simulation parameters are given in Table II.

System operating parameters				
Parameter			**eNB (macrocells)**	**HeNB (femtocells)**
Carrier frequency			2000 MHz	Uniformly picked from the set {1980, 2000, 2020} MHz
Channel bandwidth			20 MHz	20 MHz
RS transmit power (DL RS Tx)			Normally distributed with a mean value of 23 dBm and standard deviation 3dB	Uniformly distributed within the [0,20] dBm interval
Link-to-system mapping			Effective SINR mapping (ESM) [15]	
UE parameters				
Mean UL SINR target	$\gamma_t = 3$ dB			
Traffic model	Full buffer [15]			
Mobility model	User speed v_t	$v_t = N(\bar{v}, s_u)$ m/s		
		Mean user speed	$\bar{v} = 3$ km/h	
		User speed standard deviation	$s_u = 1$ km/h	
	User direction φ_t	$\varphi_t = N\left(\varphi_{t-1}, 2\pi - \varphi_{t-1}\tan\left(\frac{\sqrt{v_t}}{2}\right)\Delta t\right)$		
	where Δt is the time period between two updates of the model, and $N(a, b)$ the Gaussian distribution of mean a and standard deviation b			
Other simulation parameters				
Overall simulation time				200 sec
Simulation time unit				$\Delta t = 1$ sec

Table II: System-level simulation model and parameters

The performance of the proposed algorithm is compared against the strongest cell algorithm, referred to as the SC algorithm, and the algorithm in [9], referred to as the Zhang algorithm. All the results are derived for increasing d_{FB} and r_{fc}, to investigate the impact of uniform and non-uniform femtocell deployment on the algorithms' performance.

Table III depicts the number of femtocell users to the number of total users in the main cluster, which is a good measure of the femtocell utilization. At first, we observe that compared to the predominant SC algorithm, the deployment of femtocell-specific HO decision substantially improves the femtocell utilization, i.e., the proposed and Zhang algorithm. Nevertheless, the proposed algorithm substantially increases the femtocell utilization compared to the SC and the Zhang algorithms, where a fourfold increase is observed under low d_{FB} and r_{fc} densities.

d_{FB}	Number of femtocell users / total number of users					
	$r_{fc} = 0.1$			$r_{fc} = 0.5$		
	SC	Zhang	Prop	SC	Zhang	Prop
0,01	2,5/211	3/211	8/211	7,5/218	7,5/218	10/218
0,05	7,5/215	7/215	29/215	14/242	14/242	29/242
0,1	17,5/224	16,5/224	52,5/224	19,5/271	17/271	53,5/271
0,25	27/239	29/239	75,5/239	39,5/359	55,5/359	74/359
0,5	45,5/269	56,5/269	105/269	77,5/500	99/500	129,5/500
0,75	52/303	69,5/303	128,5/303	115,5/641	142,5/641	193,5/641
1	60,5/337	82,5/337	159/337	153,5/782	186/782	257,5/782

Table III: Number of femtocell users / total number of users

Fig. 2 illustrates the performance of the algorithms in terms of mean received interference at the UEs. For $r_{fc} = 0.1$ the SC and Zhang algorithms show a similar performance, whereas the proposed algorithm lowers the mean received interference by up to 10 and 8dB, respectively. Significantly lower interference is shown for the proposed algorithm under $r_{fc} = 0.5$ as well, with the higher gain attained under low to medium femtoblock deployment densities, i.e., $0.05 < d_{FB} < 0.3$. Noticeably, the performance of the proposed algorithm under dense HeNB deployments per femtoblock ($r_{fc} = 0.5$) is better, even compared to that of the competing algorithms in sparser HeNB densities per femtoblock ($r_{fc} = 0.1$). This result follows from the interference-awareness of the proposed algorithm, which accounts for the actual channel gain between the UEs and the candidate cells. The importance of this result is clearer if we consider that existing interference mitigation techniques primarily reduce the interference at the cell rather than the UE sites.

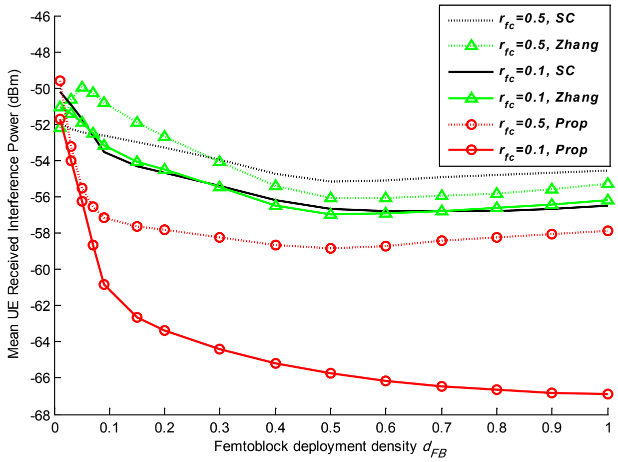

Figure 2: Mean received interference power at the UE vs. d_{FB}

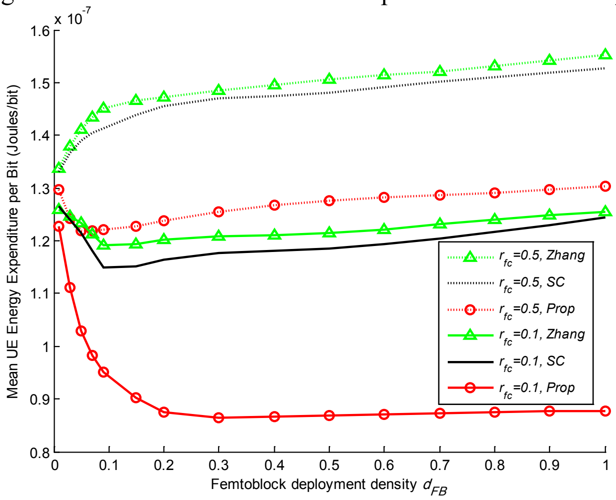

Figure 3: Mean energy consumption per bit at the UE vs. d_{FB}

Fig. 3 illustrates the performance of the algorithms in terms of mean UE energy consumption per bit, owing to transmit power. For dense HeNB deployments per femtoblock ($r_{fc} = 0.5$), as the d_{FB} increases, a constantly increasing UE energy expenditure per bit is required for the SC and Zhang algorithms to sustain the mean SINR target γ_t. On the other hand, comparably lower UE energy consumption is observed for the proposed algorithm as the d_{FB} increases, which reaches up to 19% compared to that of the competing algorithms. Comparably lower UE energy expenditure per bit is also observed for the proposed algorithm in sparser HeNB deployments per femtoblock ($r_{fc} = 0.1$), reaching up to 28% compared to both the SC and the Zhang algorithms. Note that this improvement follows from both the lower UE power emissions as well as the increased femtocell utilization, i.e., increased resource availability per served user.

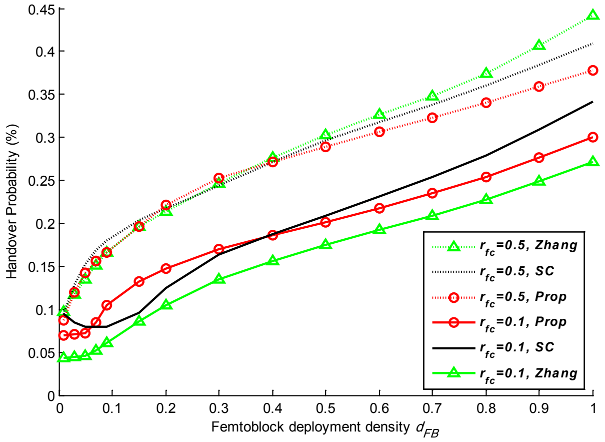

Figure 4: Handover probability vs. d_{FB}

Fig. 4 depicts the HO probability performance for all algorithms. As expected, a higher HO probability is observed for all algorithms as the d_{FB} increases. The same implies for denser HeNB deployments per femtoblock ($r_{fc} = 0.5$), where a comparably lower mean inter-site distance characterizes the HeNB deployment layout. For $r_{fc} = 0.1$ the Zhang algorithm sustains the lowest HO probability, whereas the proposed algorithm attains an improved performance compared to the SC algorithm under very low and medium to high d_{FB}, i.e., for $d_{FB} < 0.1$ and $d_{FB} \geq 0.4$, respectively. On the other hand, for $r_{fc} = 0.5$, all algorithms show similar performance under low to medium deployment densities ($d_{FB} < 0.4$). However, in medium to high femtoblock deployment densities the proposed algorithm attains the lowest HO probability ($d_{FB} \geq 0.4$). It follows that even though the proposed algorithm does not account for the actual UE speed, it attains comparable performance with the speed-based Zhang algorithm due to the incorporation of the criterion for sustained service continuity.

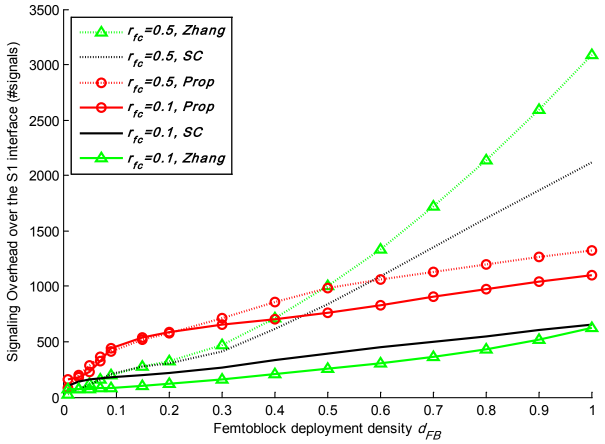

Figure 5: Number of signals over the S1 interface vs. d_{FB}

Fig. 5 depicts the S1 signaling overhead for all algorithms, which equals the number of signals exchanged in the core network over the S1 interface, during the phases of the HO decision and execution. Fig. 5 shows that the S1 signaling load strongly depends on the HeNB deployment density. In more detail, for $r_{fc} = 0.1$, the performance of all algorithms grows almost linearly with respect to the d_{FB} parameter. However, the proposed algorithm necessitates higher S1 signaling overhead due to the employment of the HO context acquisition step (Fig. 1). For $r_{fc} = 0.5$, a rapidly growing S1 signaling overhead is observed for the SC and the Zhang algorithms, whereas under medium to high d_{FB} the proposed algorithm requires the lowest S1 signaling overhead, owing to the increased use of the X2 interface.

V. CONCLUSION

In this paper, we have proposed a HO decision algorithm for the LTE-A femtocell network, which jointly considers the impact of user mobility, interference, and energy efficiency. The proposed algorithm utilizes standard signaling quality measurements to sustain service continuity and reduce the mean UE transmit power. System-level simulations showed that compared to existing algorithms, the proposed algorithm significantly reduces the interference and energy expenditure at the UEs, at the cost of a moderately increased core network signaling.

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