The Impact of Inter-Site Distance and Time-to-Trigger on Handover Performance in LTE-A HetNets

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***Abstract*—Future cellular networks as envisaged by mobile operators, are expected to consist of macro cells overlaid with small nodes in dense architectures. These multi-tier deployments pose challenges to Mobility Management procedures like Handover, since traditional algorithms fail to keep up with heterogeneity, thus causing degradations in Handover performance. Finding ways to reduce unnecessary Handovers, mainly for fast moving users, and boost offloading of the lower speed ones to small cells, are subjects undergoing intense study. Most studies propose solutions based on the appropriate selection of the key parameters involved in the Handover procedure, such as the Hysteresis Margin and Time-to-Trigger. However, they do not take into account the impact that inter-site distance has on the Handover performance. In this framework, we study the dependency of the Handover procedure on the inter-site distance between a small cell and the overlaid macro cell in a two-tier deployment. Moreover, a Handover performance analysis in terms of Handover, Radio Link Failure, Handover Failure and Ping-Pong probabilities is carried out and evaluated through extensive simulations. Finally, the impact of TTT on the Handover performance is presented, while it is concluded that the appropriate TTT value should be selected according to inter-site distance, user profile (i.e speed) and overall mobility in the network automatically and in line with the concept of Self-Organized Networks (SON).**

***Index Terms*—LTE-A, Mobility Management, Handover, Time-to-Trigger (TTT), Inter-Site Distance**

I. Introduction

The need for mobile operators to support the demands of their subscribers due to capacity limitations of macro-only deployments, is considered the driving force for the introduction of small cells [1]. Hence, the transformation of cellular networks to dense multi-tier ones will be the next step in LTE - A networks, the so-called Heterogeneous Networks (HetNets) [2]. The new architecture that will consist of macro cells, used for spatial coverage, and low power nodes (i.e. small cells) with the ability of offering high bitrates, is expected to improve the coverage, augment capacity and offer more flexibility to operators [3].

In this framework, study of handover (HO) has attracted large attention from both academia and industry [4]. It has been proven that using in HetNets the same set of HO parameters (i.e Hysteresis Margin (H), Time-to-Trigger (TTT)) as in homogeneous networks degrades HO performance. Specifically, reduced coverage areas of small cells may result in frequent HOs, Ping-Pongs (PPs), Handover Failures (HOFs) and Radio Link Failures (RLFs), mainly for fast User Equipments (UEs) [5]. Therefore, the aforementioned transformation undergone in the networks' architecture imposes a reconsideration of the HO procedure to keep up with the increasing complexity. Given that, as stated above, the degradation of the HO metrics is tightly coupled with the UE profile (e.g. the UE speed), the proposed solutions must be UE specific and in alignment with the Self-Organized Networks (SON) concept.

The main objective of the studies in this area [6]-[14] is the reduction of the frequent (and unnecessary) HOs and the HOF probability, principally experienced by fast UEs. Specifically, they propose appropriate H and TTT selection algorithms based on the UE profile (e.g speed, type of service etc.) and networks' conditions.

For instance, the work in [6] proposes an adaptive hysteresis algorithm that accounts for factors like UE speed, type of service and the load difference between the target and the serving cells, in order to reduce HOFs in a two-tier network. Similarly, an efficient handoff algorithm is presented in [7]. The idea is to combine both signals from the macro and the small cell, to compensate the uneven transmission power between nodes in different tiers, thereby creating an adaptive hysteresis margin and encouraging HOs to small cells.

A first attempt to shed some light on the relationship between HO performance and the appropriate TTT selection can be found in [8]. In it, the TTT is selected according to the UE speed and the target/source cells type to guarantee a minimum RLF probability, mainly caused by high TTT values.

Further studies on mobility performance in co-channel HetNet deployments are presented in [9] and [10]. Barbera et al. [9] investigate how TTT impacts on mobility performance. Furthermore a suitable adjustment of TTT according to UE speed and cell type is proposed in order to find a balance between RLF, HOF and PP probabilities. An extension of this work, which can be found in [10], focuses more on mobility. Through the proposal of enhanced mobility estimation schemes or UE autonomous HO decisions, their work maximizes the offloading of low speed UEs while, in parallel, prevents fast UEs from executing a HO to small cells.

Although the relationship between HO metrics is outlined in most of the aforementioned proposals, like in [11], the absence of solutions based on mathematical analysis is evident. Motivated by the above, the work in [12] uses a geometrical approach to derive closed-form expressions for HOF and PP probability as a function of UE speed, TTT and range expansion bias. The conclusion is that there is an optimal TTT value for a given UE and cell.

The geometric approach followed in [12] as well as the assumption regarding the circular area of the small cell [5], were used in [13] for expressing the HOF probability in a HetNet deployment as a function of the L3 sampling period. Finally, a work that investigates the dependency of the outbound HOF probability on parameters like UE speed, TTT and shadowed channel fading can be found in [14]. Closed-form expressions of the HOF probability as a function of the aforementioned parameters are derived by using stochastic geometry.

Despite the plethora of proposals on HO performance that stress out the significance of parameters such as type of cell, UE speed etc., the distance between source and target cell (i.e inter-site distance) has been overlooked.

The aim of this work is firstly to prove the dependency of the HO performance on the inter-site distance in a two-tier network. Secondly, to derive closed-form expressions for the different HO performance metrics as a function of inter-site distance and speed of UEs. Finally we aim to demonstrate how an appropriate TTT selection should be made, taking into account the inter-site distance and the UE's speed in order to offload traffic to small cells without degrading HO performance and ensuring that the RLF probability will not exceed 2% per HO as suggested in [8] and [15].

The rest of the paper is organized as follows: Section II gives insight on the problem under study while the HO performance analysis is carried out in Section III. Numerical results are presented in Section IV and Section V contains concluding remarks.

II. Problem Formulation

HO performance is studied in a two tier deployment consisting of a small cell located at a distance D (inter-site distance) from the center of the overlaid macro cell. UEs connected to the macro cell, cross the area of the small cell, moving on a straight line triggering a HO. This procedure is based on the A3 event, according to which a HO initiates when the received signal strength (RSS) from the target cell becomes an offset better than the source cell for a period equal to TTT [16]. The offset is known as Hysteresis Margin. The above definition can be expressed as follows

$$RSS_t \geq RSS_s + H \tag{1}$$

where RSS_t and RSS_s are the Received Signal Strength received from the target and the source cells, respectively, expressed in dBm, while H stands for the Hysteresis Margin, expressed in dB. Note that the region where (1) holds, defines the coverage area of the small cell. As suggested in [5], [12] and [14], the region can be approximated as a circumference centered at the small cell site, depicted in Fig. 1 as the light shaded circle. Given this scenario, the HO performance is expressed in terms of HOFs, RLFs and PPs probabilities [5].

RLF is the loss of connection with the serving node as a result of degraded Signal to Interference Noise Ratio (SINR). Specifically, when SINR falls below a threshold, denoted as Q_{out}, and remains below Q_{in} for 1s, an RLF event is declared and the cell re-selection procedure is triggered [16], [17]. The values recommended by 3GPP for Q_{in} and Q_{out} are -6 dB and -8 dB respectively.

HOF is the interruption of the HO process due to degradation of the signal quality received from the serving node and is declared in three cases. Firstly, when the RLF timer, namely T310, is still running at the end of the HO preparation time (T_p). Secondly, a HOF occurs if at the expiration of T310, TTT timer is active. Finally, if after HO execution time (T_{ex}), target SINR is below Q_{out}, a HOF event is declared [5].

A successful HO results in a PP if the time a UE is connected to the target cell, namely Time of Stay (ToS), is less than Minimum-Time-of-Stay (MTS) before it handoffs back to the source cell. The MTS suggested by 3GPP is 1s [5].

Let us consider a generic UE located at the boundary of the small cell, defined in (1), at distance d_t from the target cell, and d_s from the source cell (both of them expressed in km). The relationship between d_s and d_t is then described by

$$d_s = \sqrt{D^2 + 2Dd_t \cos(\Theta_{inner}) + d_t^2} \tag{2}$$

where Θ_{inner} is defined as the angle formed by the straight line joining the UE location and the small cell site, and the line joining the small cell and the macro cell sites (see Fig. 1). Focusing on (1), it can be reformulated as

$$d_t^{\alpha_t} \leq d_s^{\alpha_s} \cdot 10^{\gamma - \frac{H}{10}} \tag{3}$$

where α_t and α_s are the exponents of the corresponding path loss models and

$$\gamma = \frac{(P_{T_t} - P_{T_s}) + (A_{s_1} - A_{t_1})}{10}$$

where A_{s_1}, and A_{t_1} are distance independent components of the path loss models [18] [19], while P_{T_t} and P_{T_s} stand for the transmitted power from target and source cell respectively.

If we define the small cell radius (R_Θ) as the maximum d_t (for a given Θ_{inner}) for which (3) holds, the radius may be numerically calculated from the following expression

$$R_\Theta = 10^{\frac{\gamma - 0.1H}{\alpha_t}} \cdot (D^2 + 2R_\Theta D \cos(\Theta_{inner}) + R_\Theta^2)^{\frac{\alpha_s}{2\alpha_t}} \tag{4}$$

At the edge of the region defined by (1), (3) or (4), TTT initiates and should expire within it in order for a HO to be executed successfully. However, if at expiration of TTT, the UE is located inside the small cell but the SINR received from the source cell is below Q_{out}, there is a HOF. This region, where $SINR_s \leq Q_{out}$, is depicted in Fig. 1 as a white coloured circle (the inner circle, also known as HOF circle) and has a radius hereof denoted as r_Θ. Similarly to (4), r_Θ is given by

$$r_\Theta = 10^{\frac{\gamma+0.1Q_{out}}{\alpha_t}} \cdot (D^2 + 2r_\Theta D\cos(\Theta_{inner}) + r_\Theta^2)^{\frac{\alpha_s}{2\alpha_t}} \quad (5)$$

Once a UE is associated to the small cell, the outbound HO procedure starts (i.e. the TTT countdown) when (1) holds. Note, however, that in this case the macro cell plays the role of target cell and the small cell is the source cell. Following the same reasoning, the radius of the outbound HO, namely S_Θ, (the dark shaded circle in Fig. 1) may be calculated numerically from the following

$$S_\Theta = 10^{\frac{-\gamma+0.1H'}{\alpha_s}} \cdot (D^2 + 2S_\Theta D\cos(\Theta_{inner}) + S_\Theta^2)^{\frac{\alpha_t}{2\alpha_s}} \quad (6)$$

where H' is the hysteresis margin used to handoff from the small cell to the macro cell. It is worth noting that all these radii, i.e. R_Θ, r_Θ and S_Θ, do depend on the inter-site distance D and Θ_{inner}. As UEs are assumed to be distributed randomly around the scenario, the mean radius R can be expressed as

$$R = \mathbb{E}[R_\Theta] = \frac{1}{\pi}\int_0^\pi R_\Theta d\Theta_{inner} \quad (7)$$

Likewise, the mean of r_Θ and S_Θ are given by $r = \mathbb{E}[r_\Theta]$ and $S = \mathbb{E}[S_\Theta]$, respectively. In Section III, the analytical expressions for inbound HO (P_{HO}), RLF (P_{RLF}), HOF (P_{HOF}) and PP (P_{PP}) probabilities are derived as a function of R, r and S to further analyze the impact of UE's speed and D on the appropriate selection of TTT values. Although there are other factors that could impact the performance of the described probabilities, e.g. the L3 filter or the measurement errors [13], the presented model will assume perfect measurement and no L3 delay to focus on the effect of the TTT and inter-site distance

III. Analytical Model

Let us focus on the same generic UE, located at distance R from the center of the small cell. This UE, moving at speed v, crosses the small cell coverage area with an entry angle θ_e (see Fig. 1). Due to symmetry, the whole analysis will be done hereafter for $0 \leq \theta_e \leq \frac{\pi}{2}$. In this situation, this UE may perform a HO, suffer from a HOF, an RLF, or/and a PP. Before proceeding with the analysis of the aforementioned probabilities, it is necessary to define a set of important angles.

First, let $(TTT + T_p)$ be the time needed for an inbound HO to be completed, from now on denoted as T. The distance covered by the UE during time T is then equal to vT. Accordingly, if we define θ_i as the maximum entry angle for which the inbound HO can be completed (i.e. the distance covered within the small cell coverage area is, at least, vT, as shown in Fig. 1), it may be expressed as

$$\theta_i = arccos\left(\frac{vT}{2R}\right) \quad (8)$$

with $0 \leq v \leq \frac{2R}{T}$. If $v > \frac{2R}{T}$, the UE will not handoff to the small cell regardless of the entry angle.

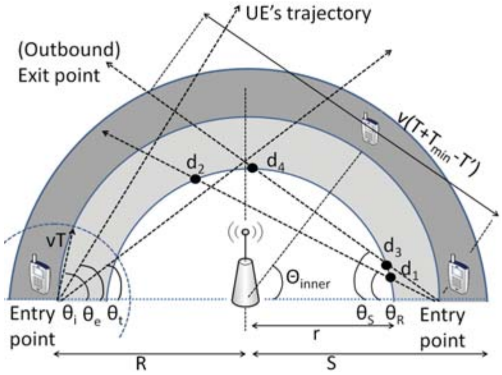

Fig. 1. Small cell area and considered angles

The second angle to consider, θ_t, is defined as the maximum angle for which T expires within the HOF circle (Fig. 1). By using the Cosine Law, θ_t may be expressed as

$$\theta_t = arccos\left(\frac{(vT)^2 + R^2 - r^2}{2vTR}\right) \quad (9)$$

where $\frac{R-r}{T} \leq v \leq \frac{R+r}{T}$. Note that, if $v < \frac{R-r}{T}$, the UE will not suffer from a HOF, even if the entry angle $\theta_e = 0$. Likewise, if $v > \frac{R+r}{T}$, there will not be a HOF either.

As explained in Section II, the RLF occurs after the UE has moved over the HOF region for more than a particular time, usually 1s. If we define this maximum time as T_R, the UE will suffer from a RLF if the distance covered within the HOF circle is above vT_R while a HO is not yet successfully completed. Thus, the maximum angle for which the distance covered by a UE within the HOF region is larger than vT_R, is given by

$$\theta_R = arcsin\left(\sqrt{\frac{r^2}{R^2} - \left(\frac{vT_R}{2R}\right)^2}\right) \quad (10)$$

where $\frac{R-r}{T} \leq v \leq \frac{2r}{T_R}$. Otherwise θ_R is not defined and a UE will not suffer from RLF. It is worth noting that, for a given entry angle $\theta_e = \theta_R$, the UE intersects the HOF circle at two points. Thus, if we denote the distance covered by the UE from the entry point to the first intersection as d_1 and to the second intersection as d_2, they may be expressed as

$$d_1 = \sqrt{R^2 - r^2 + \left(\frac{vT_R}{2}\right)^2} - \frac{vT_R}{2} \quad (11)$$

$$d_2 = d_1 + vT_R \quad (12)$$

These two points will be used later on to characterize the HO, the RLF and the PP probabilities. As initially stated in Section II, a UE causes a PP if, after completing an inbound HO (which entire process lasts T), the ToS is below the MTS, hereafter referred to as T_{min}. Note that the outbound HO process is triggered when the UE trajectory intersects the circumference with radius S, and it is finally completed after the outbound $(TTT + T_p)$ expires, namely T'. Therefore, a

UE will cause a PP if, after completing a successful HO, it covers a total distance within the small cell (from the entry point to the exit point) shorter than $v(T+T_{min}-T')$. Hence, the maximum entry angle for which a UE will not cause a PP (θ_s) is given by

$$\theta_s = arccos\left(\frac{R^2-S^2+v^2(T+T_{min}-T')^2}{2Rv(T+T_{min}-T')}\right) \quad (13)$$

where,

$$\frac{\sqrt{S^2-R^2}}{T+T_{min}-T'} \leq v \leq \frac{R+S}{T+T_{min}-T'} \quad (14)$$

It may be easily calculated that a UE trajectory with an entry angle $\theta_e = \theta_s$ will not intersect the HOF circle if

$$v < \frac{\sqrt{R^2-r^2}+\sqrt{S^2-r^2}}{T+T_{min}-T'} \quad (15)$$

Then, if this UE trajectory does intersect the HOF circle, the distances covered from the entry point to the HOF circle intersections, denoted as d_3 and d_4, can be expressed as

$$d_3 = \delta - \sqrt{r^2-R^2+d^2} \quad (16)$$

$$d_4 = \delta + \sqrt{r^2-R^2+d^2} \quad (17)$$

where

$$\delta = \frac{R^2-S^2+v^2(T+T_{min}-T')^2}{2v(T+T_{min}-T')} \quad (18)$$

Based on the aforementioned definitions, expressions for P_{HO}, P_{HOF}, P_{RLF} and P_{PP} will be derived in the sequel.

A. Inbound Handover Probability

According to the definitions previously stated, a UE can only perform a successful HO if the entry angle is smaller than θ_i. Otherwise, the UE's TTT timer expires after leaving the small cell coverage area and the HO process is not completed. However, and despite having $\theta_e < \theta_i$, the HO could not be completed successfully due to either a HOF (i.e. $\theta_t \geq \theta_e$) or an RLF (i.e. $\theta_R \geq \theta_e$ and $\frac{R-r}{T} \leq v$). If we define Θ^v_{HO} as the set of entry angles that, for a given v, result in a successful HO, the P_{HO} is then given by

$$P_{HO} = \frac{2}{\pi}\int_{\theta_e \in \Theta^v_{HO}} \theta_e d\theta_e \quad (19)$$

With regard to Θ^v_{HO}, it will be $\Theta^v_{HO} = [0, \theta_i]$ when the HO is completed before reaching the HOF circle (i.e. $v < \frac{R-r}{T}$), $\Theta^v_{HO} = [\theta_t, \theta_i]$ when T expires inside the HOF circle (i.e $\frac{R-r}{T} \leq v \leq \frac{R+r}{T}$) and θ_R does not exist, $\Theta^v_{HO} = [\theta_t, \theta_i]$ while $\theta_R < \theta_t$ (if θ_R exists), $\Theta^v_{HO} = [\theta_R, \theta_i]$ if $vT \geq d_2$ and θ_R exists, and finally $\Theta^v_{HO} = [0, \theta_i]$ when θ_R does not exist and $\frac{R+r}{T} < v \leq \frac{2R}{T}$. Thus,

$$P_{HO} = \begin{cases} \frac{2}{\pi}\theta_i & \text{if } 0 \leq v < \frac{R-r}{T} \\ \frac{2}{\pi}(\theta_i - \theta_t) & \text{if } \frac{R-r}{T} \leq v \leq \frac{R+r}{T} \text{ and } \nexists\theta_R \\ \frac{2}{\pi}(\theta_i - \theta_t) & \text{if } \frac{R-r}{T} \leq v < \frac{d_2}{T} \text{ and } \exists\theta_R \\ \frac{2}{\pi}(\theta_i - \theta_R) & \text{if } \frac{d_2}{T} \leq v \leq \frac{2R}{T} \text{ and } \exists\theta_R \\ \frac{2}{\pi}\theta_i & \text{if } \frac{R+r}{T} < v \leq \frac{2R}{T} \text{ and } \nexists\theta_R \\ 0 & \text{otherwise} \end{cases} \quad (20)$$

B. Handover Failure Probability

A HOF occurs if T expires within the HOF circle. Analogously to P_{HO}, the set of entry angles for which a UE suffers from a HOF, namely Θ^v_{HOF}, is defined as $\Theta^v_{HOF} = [0, \theta_t]$ for $\frac{R-r}{T} \leq v \leq \frac{R+r}{T}$ and $\Theta^v_{HOF} = \emptyset$ otherwise. Therefore,

$$P_{HOF} = \begin{cases} \frac{2}{\pi}\theta_t & \text{if } \frac{R-r}{T} \leq v \leq \frac{R+r}{T} \\ 0 & \text{otherwise} \end{cases} \quad (21)$$

C. Radio Link Failure Probability

The probability of RLF (P_{RLF}) is different from 0 only when θ_R exists. Thus, assuming that θ_R exists, the RLF presents two possible situations (see Fig. 1): first, if $R-r \leq vT \leq d_1$, there is a RLF only after a previous HOF (and consequently, the set of angles that cause a RLF is $\Theta^v_{RLF} = [0, \theta_t]$); second, when $d_1 < vT \leq 2R$, only UEs with an entry angle below θ_R suffer from RLF (i.e. $\Theta^v_{RLF} = [0, \theta_R]$). Therefore,

$$P_{RLF} = \begin{cases} \frac{2}{\pi}\theta_t & \text{if } \frac{R-r}{T} < v \leq \frac{d_1}{T} \\ \frac{2}{\pi}\theta_R & \text{if } \frac{d_1}{T} < v \leq \frac{2R}{T} \\ 0 & \text{otherwise} \end{cases} \quad (22)$$

D. Ping Pong Probability

The Ping Pong probability (P_{PP}) is defined as the probability that, for a UE that has completed a successful handover to the small cell, the duration of the connection to the small cell is below the MTS, denoted as T_{min}. As the final expression of the P_{PP} is complex, let us define a set of conditions based on the definitions stated at the beginning of Section III.

$$C_1: \quad \frac{R-r}{T} \leq v \leq \frac{2r}{T_R} \quad (23)$$

$$C_2: \quad \frac{\sqrt{S^2-R^2}}{T+T_{min}-T'} \leq v \leq \frac{R+S}{T+T_{min}-T'} \quad (24)$$

$$C_3: \quad v < \frac{\sqrt{S^2-R^2}}{T+T_{min}-T'} \quad (25)$$

$$C_4: \quad v > \frac{R+S}{T+T_{min}-T'} \quad (26)$$

$$C_5: \quad v < \frac{\sqrt{R^2-r^2}+\sqrt{S^2-r^2}}{T+T_{min}-T'} \quad (27)$$

$$C_6: \quad v \leq \sqrt{\frac{S^2-R^2}{(T+T_{min}-T')(T_{min}-T')}} \quad (28)$$

$$C_7: \quad d_2 \leq d_4 \quad (29)$$

$$C_8: \quad \frac{d_3}{T} < v < \frac{d_4}{T} \quad (30)$$

The first condition, C_1, defines the range of v for which θ_R exists. Note that, if there is an RLF, there cannot be a PP. Condition C_2 guarantees the existence of θ_s. If C_2 does not hold, either C_3 or C_4 must be true. In particular, C_3 means that the ToS of the UE in the small cell is long enough (due to small v) to achieve $P_{PP} = 0$. As for C_4, the speed is too high and so $P_{PP} = 1$. When C_5 is accomplished, the trajectory of a UE with $\theta_e = \theta_s$ does not intersect the HOF circle. Condition C_6 is particularly important, since it means that $\theta_s \geq \theta_i$. It is worth noting that, for all $\theta_e \leq \theta_s$, there is not any PP, whereas for all UEs with $\theta_e > \theta_i$ there cannot be a HO. Hence, if C_6 holds, the $P_{PP} = 0$. Finally, C_7 is equivalent to $\theta_R \geq \theta_s$, whereas C_8 is equivalent to $\theta_t > \theta_s$.

In the following, we will denote the complement of a condition C_i as C'_i. For instance, when C_2 holds, neither C_3

nor C_4 do. Therefore, $C_2' = C_3 \cup C_4$. Based on the definitions, P_{PP} may be expressed as

$$P_{PP} = \begin{cases} 0 & \text{if } C_3 \\ 1 & \text{if } C_4 \\ 0 & \text{if } C_2 \cap C_6 \\ \frac{\frac{2}{\pi}(\theta_i - \theta_t)}{P_{HO}} & \text{if } C_1' \cap C_2 \cap C_5' \cap C_6' \cap C_8 \\ \frac{\frac{2}{\pi}(\theta_i - \theta_t)}{P_{HO}} & \text{if } C_1 \cap C_2 \cap C_5' \cap C_6' \cap C_7' \cap C_8 \\ 1 & \text{if } C_1 \cap C_2 \cap C_5' \cap C_6' \cap C_7 \\ \frac{\frac{2}{\pi}(\theta_i - \theta_s)}{P_{HO}} & \text{otherwise} \end{cases} \quad (31)$$

IV. Numerical Results

The scenario under study consists of a small cell overlaid with a macro cell, with a distance between the macro cell site and the small cell site (D) that ranges from 40m to 240m. UEs are spread randomly over the layout moving at 60km/h (a very high speed in an urban scenario) and heading for the small cell coverage area with a random entry angle and moving on a straight line. The transmitted power of the macro and the small cell is 46 and 20 dBm, respectively [18][19]. Although a range of 16 possible TTT values are defined in [16], only the results (both simulated and analytical) for an illustrative subset of them have been included (specifically, TTT equal to 128, 256, 320 and 512 ms). The rest of the simulation parameters can be found in Table I.

TABLE I
Simulation Parameters

Bandwidth	10 MHz
Macro and Small Cell Frequency	2 GHz
Macro cell Path-Loss	128.1 + 37.6 $log_{10}(d\ km)$
Small cell Path-Loss	140.7 + 36.7 $log_{10}(d\ km)$
Macro cell transmitted power	46 dBm
Small cell transmitted power	20 dBm
HO A3 Hysteresis Margin	3 dB
TTT values	128, 256, 320, 512 ms
HO Preparation Time	50 ms
HO Execution Time	40 ms

Focusing on P_{HO} and P_{HOF}, depicted in Fig. 2 and Fig. 3, it is important to point out their dependency on θ_i, θ_t, R and r. In particular, the inspection of (20) reveals that P_{HO} grows when θ_i grows and/or θ_t falls. Thus, for a given v and T, θ_i rises when R grows (or in other other words, when D is increased) according to (8). Conversely, it may be observed in (9) that θ_t decreases as R rises. These two factors result in the upward trend shown in Fig. 2.

As for HOF probability, $P_{HOF} \neq 0$ if $\frac{R-r}{T} \leq v \leq \frac{R+r}{T}$. Therefore, it is tightly coupled with the size of the coverage area (R) and the HOF region (r). The numerical solution of (7) shows that in the simulated scenario the ratio $\frac{r}{R} = \beta$ remains approximately constant and equal to 0.73 for the whole range of D. Based on this, and making use of (21), the P_{HOF} will be different from 0 when

$$\frac{vT}{1+\beta} \leq R \leq \frac{vT}{1-\beta} \quad (32)$$

Fig. 3 displays the performance of P_{HOF} described in (32). Specifically, P_{HOF} presents an initial upward trend (commenced when $R = \frac{vT}{1+\beta}$) followed by a subsequent decreasing trend (that results in $P_{HOF} = 0$ when $R > \frac{vT}{1-\beta}$). This also explains the peaks observed in Fig. 2 for $D \simeq 50m$ when TTT equals 320ms, and $D \simeq 80m$ when TTT is 512ms. Initially, the P_{HO} for these TTT values has only the contribution of θ_i, since $vT < R-r$ (see the expression in (20)), thereby resulting in an abrupt increase. However, when $R = \frac{vT}{1+\beta}$ the increase of θ_i is counteracted by θ_t, causing the aforementioned peak.

Finally, Fig. 4 and Fig. 5 complement the analysis with the P_{RLF} and the P_{PP}, respectively. As expected, it may be observed that $P_{RLF} = 0$ as long as HOF region is not large enough to yield $vT_R \leq 2r$ (the necessary condition stated in (10) to have RLFs). Moreover, T must be long enough so that the UE does not complete successfully a HO, while the time spent inside the HOF region is at least equal to T_R. Therefore, $P_{RLF} \neq 0$ for large D and T.

With regard to P_{PP}, it is correlated with P_{HO}, since there cannot be a PP if there is not any previous HO. Fig. 5 reveals that, for a given v, the performance in terms of PP depends on two key parameters: D and T. In particular, when the small cell is deployed close to the macro cell site (small D values) and there is a successful HO, both R and S are small and so the UE is prone to short ToS and the consequent PP. On the contrary, P_{PP} falls for the same reason when the distance between the macro and the small cell rises. The impact of T on P_{PP} is in turn the opposite, since larger T leads to longer HO delay, and therefore shorter ToS in the small cell (Fig. 5).

Fig. 2-Fig. 5 demonstrate that the appropriate selection of TTT, as a function of v and D, presents important challenges to cope with the conflicting trends experienced by the different HO performance probabilities. Note that these challenges are not addressed by related works where TTT remains constant for different inter-site distances. In more detail, the TTT selection should start with the limitation of the maximum P_{RLF} (limited to 2% according to [8]). Then, the final TTT value should be selected based on the maximum acceptable P_{HOF} and P_{PP}. It is worth noting that there is a degree of freedom in the selection of the TTT. This degree of freedom allows the possibility to manage the usage of the small cell. Thus, in a scenario characterized by high mobility, an increase of P_{HO} of UEs moving at high speed results in a higher small cell usage. Conversely, in low mobility scenarios, P_{HO} for high v should be decreased to reduce the small cell usage (in case of overload in the small cell).

V. Conclusions

In this work, a Handover performance analysis in terms of P_{HO}, P_{HOF}, P_{RLF}, and P_{PP} was carried out. Specifically, we have proven the dependency of the Handover on the inter-site distance between the small cell and the overlaid macro

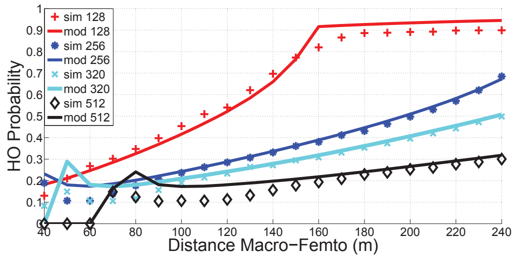

Fig. 2. HO probability (P_{HO})

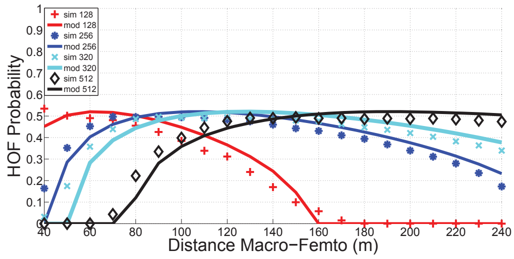

Fig. 3. HOF probability (P_{HOF})

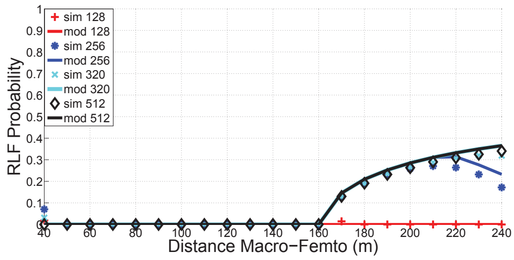

Fig. 4. RLF probability (P_{RLF})

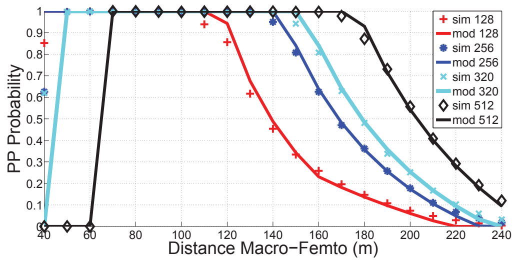

Fig. 5. PP probability (P_{PP})

cell center in a two-tier scenario Furthermore, closed-form expressions for the aforementioned probabilities were derived as a function of inter-site distance and speed of the UEs. Finally, it has been shown that the appropriate TTT selection, based on inter-site distance and UE's profile, is essential for maintaining the conflicting trends of different HO performance probabilities. Therefore, it should be selected in a more flexible way, on a UE basis, and adjusted to network's characteristics and objectives to enhance HO performance.

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