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*Published in:*

I E E E Communications Magazine

*DOI (link to publication from Publisher):*

[10.1109/MCOM.2013.6515048](https://doi.org/10.1109/MCOM.2013.6515048)

*Publication date:*

2013

*Document Version*

Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*

Pedersen, K. I., Michaelsen, P. H., Rosa, C., & Barbera, S. (2013). Mobility enhancements for LTE-Advanced Multilayer Networks with Inter-Site Carrier Aggregation. *I E E E Communications Magazine*, 51(5), 64-71. <https://doi.org/10.1109/MCOM.2013.6515048>

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# Mobility Enhancements for LTE-Advanced Multilayer Networks with Inter-Site Carrier Aggregation

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## ABSTRACT

In this article we first summarize some of the most recent HetNet mobility studies for LTE-Advanced, and use these to highlight the challenges that should be further addressed in the research community. A state-of-the-art HetNet scenario with macros and small cells deployed on different carriers, while using inter-site carrier aggregation, is hereafter studied. Hybrid HetNet mobility solutions for such cases are derived, where macrocell mobility is network controlled, while small-cell mobility is made UE-autonomous. The proposed scheme is characterized by having the UE devices autonomously decide small cell addition, removal, and change without any explicit signaling of measurement events to the network or any signaling of handover commands from the network. Hence, the proposed solution effectively offloads the network from having to perform frequent small cell handoff decisions, and reduces the signaling overhead compared to known network controlled mobility solutions. Results from extensive dynamic system-level simulations are presented to demonstrate the advantages of the proposed technique, showing significant savings in signaling overhead.

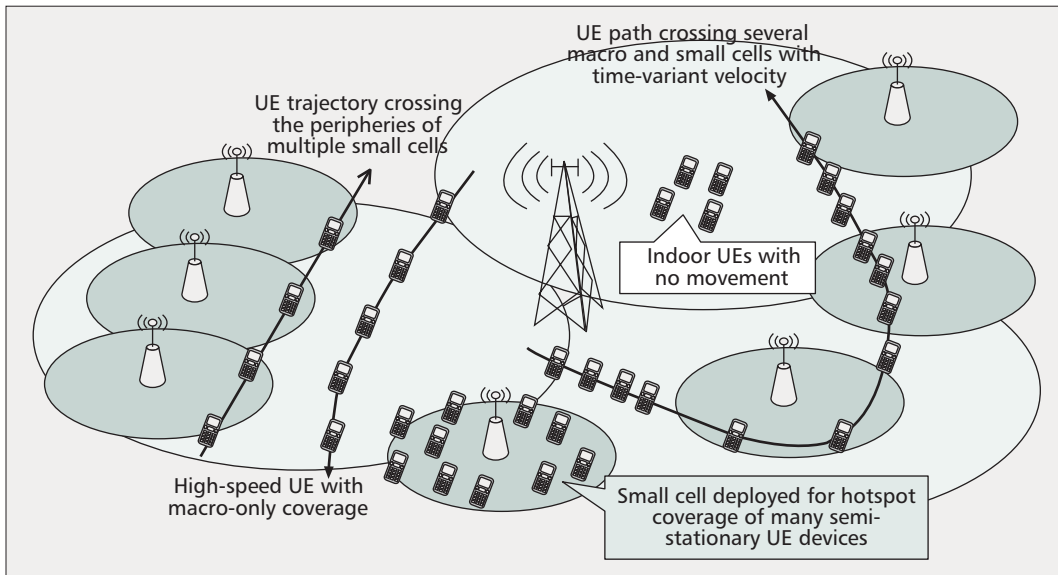
## INTRODUCTION

With the introduction of Long Term Evolution (LTE) and LTE-Advanced, several improvements have been introduced in Third Generation Partnership Project (3GPP) specifications to enhance both the link and system-level performance [1]. System-level performance enhancements in LTE-Advanced, among others, include mechanisms supporting efficient introduction of small cells (e.g., pico nodes) to supplement existing macrocells, also known as migration toward heterogeneous networks (HetNets). Increasing the number of small cells, and bringing them closer to the hotspot areas with many user equipment (UE) devices, naturally results in great improvements of capacity per area. An overview of the most recent 3GPP HetNet improvements is presented in [2], while a deployment study on

how to most efficiently introduce small cells to meet future traffic requirements is available in [3]. Despite the many advantages of migration toward HetNet scenarios, such a paradigm shift also introduces additional requirements and challenges. Among those, efficient self-organizing network (SON) features to enable low-cost zero-touch deployment of small cells are widely recognized as being of paramount importance [4]. Interference challenges for HetNet co-channel deployments also top the list, and have therefore attracted a lot of research in both academia and industry, and have, for instance, resulted in standardization of enhanced intercell interference coordination for LTE-Advanced [1, 5].

Mobility for ensuring continuous service of UE moving in the network is another important functionality of cellular systems. Mechanisms offering efficient mobility were included in the first LTE release (Rel-8), followed by various incremental enhancements in Rel-9 and Rel-10 [1]. LTE relies on a network-controlled UE-assisted mobility paradigm for UE in radio resource control (RRC) Connected mode.<sup>1</sup> This essentially means that the network explicitly informs RRC Connected mode UE devices via dedicated RRC signaling whenever they have to perform handover to another cell. The decision on when to initiate handover is based on measurement event feedback from UE. Today, field observations from live LTE macro-only networks have confirmed that mobility works very well with handover success rates of nearly 100 percent, and failure rates of only fractions of a percent [6, 7]. However, when migrating from macro-only to HetNet environments, recent studies have demonstrated that mobility becomes more challenging, due to potentially more challenging interference conditions, small cells appearing and disappearing more quickly as UE devices move, and so on [8, 9]. HetNet mobility improvements are therefore the topic of this study. In particular, we focus on schemes for improving the RRC Connected mode mobility performance for LTE HetNet scenarios where macro and small cells are deployed at different carrier frequencies, while assuming support for inter-site carrier aggregation between cell types

<sup>1</sup> In LTE, Idle mode mobility is UE controlled. Idle mode mobility is outside the scope of this article.



**Figure 1.** High-level sketch of LTE HetNet scenario with a three-sector macro base station and multiple small cells and UE devices.

*UE autonomous mobility decisions are advantageous for cases with many small cells, to offload the network from having to perform frequent mobility decisions, and as a remedy for reducing signaling overhead.*

with different transmit power levels. The HetNet scenario with macro and small cells at different carriers is especially relevant for cases with deployment of many small cells and availability of the required bandwidth. The outlined improvements represent a paradigm shift moving away from fully network-controlled mobility toward relying more on UE autonomous handoff decisions for small cells. As discussed in detail, UE autonomous mobility decisions are advantageous for cases with many small cells, to offload the network from having to perform frequent mobility decisions, and as a remedy for reducing signaling overhead.

The rest of the article is organized as follows. We present a short overview of recent LTE HetNet mobility studies with emphasis on the identified challenges for such scenarios that call for further improvements. In particular, we highlight the main observations from the recently concluded 3GPP LTE Rel-11 study item on mobility enhancement for HetNets. We outline the HetNet scenario addressed in this article. A novel UE autonomous mobility concept is presented as a simple solution to facilitate more attractive small cell handoffs without excessive signaling overhead. System-level performance results are presented, followed by concluding remarks.

## OVERVIEW OF RECENT HETNET MOBILITY STUDIES

Mobility performance is measured by several key performance indicators (KPIs). From an end-user perspective, the handover process shall offer a smooth transfer of the users' active connection when moving from one cell to another, while still maintaining the guaranteed quality of service (i.e., without interruptions and errors). The probability of radio link failures (RLFs) and handover failures (HOFs) are therefore commonly used KPIs for measuring mobility performance [9]. Furthermore, it is important that

mobility procedures are energy efficient, meaning that the UE energy consumption is not unnecessarily jeopardized from performing, say, neighbor cell measurements. From the network point of view, the mobility performance is also measured by the signaling cost associated with each handover, as well as the probability of unnecessary handovers, typically referred to as ping-pong (PP) events [9]. Thus, the objective is to have mobility procedures resulting in low probability of experiencing RLF, HOF, and PP, as well as low signaling overhead. Mobility solutions meeting those objectives are often said to be robust.

Figure 1 pictures a typical HetNet environment with a variety of different cell types, as well as a mixture of terminals that are either semi-stationary or moving along certain trajectories at different velocities. The macro and small cells may be deployed on the same carrier frequency (co-channel case) or on different carriers (dedicated carrier case). The challenge for the co-channel case is the interference between macro and small cells, which also influences the mobility performance. Typically, the path loss slope and the spatial correlation distance of shadow fading are different from macro and small cells to UE, generally resulting in a steeper gradient of the received signal strength at UE from small cells compared to macrocells. Timely and accurate handover between co-channel deployed macro and small cells is therefore essential for ensuring acceptable mobility performance. As reported in [8], outbound handover from small cells is especially challenging for high-velocity users, while good mobility performance for users at lower speeds can be achieved with basic LTE handover methods as standardized today. The same conclusion was reached by 3GPP in a recent study item on mobility enhancements in heterogeneous scenarios [9], where the co-channel HetNet mobility performance was found to be not as good as in macro-only scenarios, and especially challenging for higher UE speeds.

<sup>2</sup> The TTT parameter influences the UE measurement reporting process and has an impact on the overall handover time [1, 8].

*Given the outlined prior art studies of LTE HetNet mobility, there is a clear trend toward including additional mobility enhancements in future LTE releases to ensure smooth migration from macro-only to HetNet environments without jeopardizing the mobility robustness and UE power consumption.*

As HetNet mobility performance varies with UE speed (more challenging for higher speeds), it is first and foremost desirable to have reliable UE mobility state estimation (MSE). The UE MSE was already standardized in the first LTE Release (Rel-8) [1], where UE devices count the number of past cell crossings to roughly estimate their equivalent handoff rate and map it to a mobility state as either low, medium, or high. Depending on the UE's mobility state, handoff parameters such as time-to-trigger<sup>2</sup> are scaled to make the RRC Connected mode mobility performance more robust over the range of possible UE speeds. However, it was concluded in [9] that the currently defined UE MSE method is not as accurate for HetNet scenarios as for macro-only cases due to the larger variability of cell sizes and small cell density, thus calling for possible enhancements to achieve overall improvements in HetNet mobility performance. Examples of simple MSE enhancements include having the network provide information to the UE on the relative size of different cells, such that crossing smaller cells is weighted less than crossing larger macrocells when determining the mobility state. Having more accurate MSE can be used as a facilitator for further HetNet mobility robustness optimizations. As an example, the UE in Fig. 1 with only peripheral small cell crossings should only hand off to those small cells if it is moving at low to moderate speed, while otherwise be kept at the macro layer if it is traveling at high speed. Thus, a prerequisite for developing further UE mobility optimizations is a stable MSE.

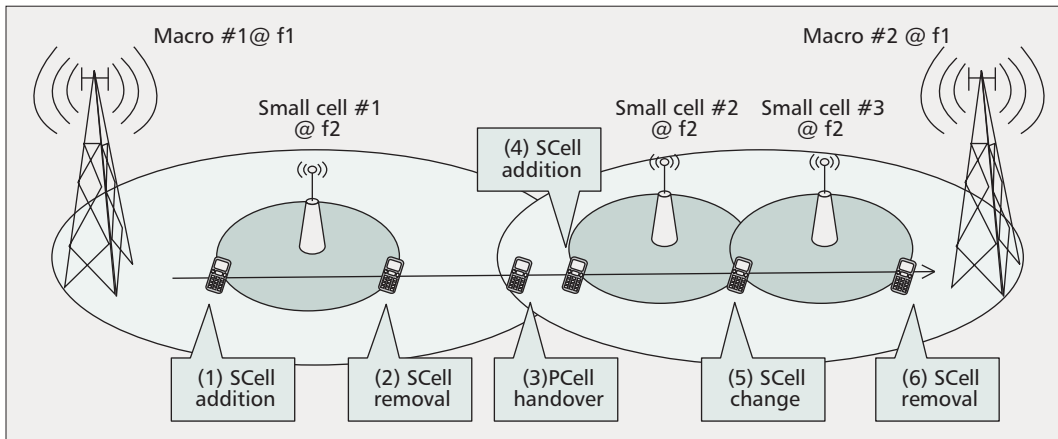
Extensive simulations were also presented in [9], showing that timely availability of UE radio resource management (RRM) measurements and signaling opportunities related to handover is more critical for HetNet scenarios than for macro-only cases. This translates to less robust HetNet mobility performance when using long discontinuous reception (DRX) [1] for users moving at speeds higher than approximately 30 km/h, since the UE does not report RRM measurements during DRX periods. This essentially means that handoffs do not happen for UE devices in long DRX periods as those do not report measurement events to the network for triggering handoffs; nor do UE devices in long DRX periods listen to downlink transmissions from their serving cell to, for example, receive handoff commands. So using a long DRX cycle length of 80 to 640 ms can cause too late handoffs, resulting in failures. DRX is an especially important feature for smart phone devices to minimize battery consumption; as an example, it was found in [9] that doubling the DRX cycle almost halves the power consumption for keep-alive traffic with 20 s interarrival time. Therefore, finding techniques for improving the use of long DRX without jeopardizing HetNet mobility performance and UE power consumption is a subject for further study. Possible enhancements to address such problems include, among others, amendments to current procedures such that UE devices in small cells perform more frequent RRM measurements for a limited time period (and related reporting of handoff events if triggering conditions are met) independent from the

configured DRX. By doing this, the probability of performing timely outbound handoff from the small cell is improved.

For dedicated carrier HetNet deployments the mobility performance naturally does not suffer from interference between macros and smalls. However, for such cases the main challenge is for macro UE to discover small cells on other carriers in due time without performing unnecessary inter-frequency measurements. Here the dilemma is that while frequent inter-frequency measurement by macro UE would enable timely small cell discovery on neighbor carriers, it comes with a cost in terms of both UE power consumption and measurement gaps. Current LTE specifications only include options of performing periodical inter-frequency measurements every 40 or 80 ms, using measurement gaps of 6 ms. These options for inter-frequency measurements are largely sufficient to cover the needs for macro-only scenarios with multiple carriers, while not being sufficient to achieve fully optimized performance for HetNet scenarios with dedicated carrier deployments [9]. A list of eight candidate solutions for improving the inter-frequency small cell discovery for coming 3GPP releases has therefore been identified in [9], thus subject for further studies for LTE Rel-12. Among others, the solution candidates include new relaxed background small cell inter-frequency discovery measurements, and smart methods for automatic suspend and resume of small cell inter-frequency RRM measurements depending on whether the UE is likely to be in close vicinity of deployed small cells. The challenge of inter-frequency small cell discovery is less relevant for UE devices supporting carrier aggregation, as those may be able to perform concurrent reception on carrier A and inter-frequency measurements on carrier B (depending on the UE category and implementation).

## SCENARIO WITH INTER-SITE CARRIER AGGREGATION

Given the outlined prior art studies of LTE HetNet mobility, there is a clear trend toward including additional mobility enhancements in future LTE releases to ensure smooth migration from macro-only to HetNet environments without jeopardizing the mobility robustness and UE power consumption. In this study we therefore present further HetNet mobility enhancements for future scenarios with usage of inter-site carrier aggregation. Inter-site carrier aggregation can be realized based on the basic carrier aggregation functionality introduced for LTE-Advanced Rel-10. An overview of the LTE-Advanced carrier aggregation methods is available in [10, 11]. The considered scenario is pictured in Fig. 2, where it is assumed that a macro is deployed in carrier f1, while small cells are deployed on a separate carrier f2. RRC connected UE devices are assumed to always have a downlink connection from the macro layer. Adopting the 3GPP carrier aggregation terminology, this translates to assuming that UE devices are assumed to have their primary cell (PCell) configured on the macro layer. UE devices that are also in the cov-



**Figure 2.** Basic principle of mobility for a HetNet scenario with inter-site carrier aggregation.

erage area of a small cell can have that particular cell configured as their secondary cell (SCell), and thereby benefit from inter-site carrier aggregation to achieve a higher data rate due to the higher accessible bandwidth for the user. Thus, while the UE is moving under the same macro-cell it will always have a stable PCell connection, while adding, removing, or changing SCells on the small cell layer at f2. Macros and small cells are assumed to be interconnected, via either the X2 interface or fibers using other protocols [1]. Referring to Fig. 2, when the UE is entering the coverage area of small cell #1 at position (1), it will add this cell as an SCell, and when leaving the small cell coverage at position (2), the SCell connection is removed. At position (3), the UE will be subject to PCell handover from macro #1 to macro #2. An SCell change from small cell #2 to small cell #3 happens at position (5) while having the macro #2 as its PCell.

If using the current LTE-Advanced standardized carrier aggregation mobility functions as studied in, for instance, [12], the network will have to send a new RRC message to the UE whenever adding, removing, or changing an SCell. Such network actions are triggered by measurement reports from the UE (sent via uplink RRC signaling). For scenarios with many small cells, the RRC signaling from SCell operations can therefore be significant compared to managing PCell mobility. Second, frequent UE assisted and network controlled SCell management constitutes an additional burden (and signaling delays) on the network as non-stationary UE devices are likely to be subject to relatively frequent appearance and disappearance of small cells moving along certain trajectories. The aforementioned challenges are addressed in this article by proposing a solution where SCell management is instead performed using UE autonomous decisions with a certain degree of network control.

## UE AUTONOMOUS SCell MOBILITY PROPOSITION

A hybrid mobility solution is studied for the scenario in Fig. 2. As the PCell connection is assumed to be the most critical “lifeline” for the

UE to have basic service connectivity, we assume traditional network controlled, and UE assisted, mobility of the PCell as defined for today’s LTE-Advanced [1]. Thus, the network is in full control, and can perform active load balancing and mobility robustness optimization for PCell assignment for different UEs [4]. However, for SCell mobility management, we investigate a UE autonomous solution, where the more frequent SCell management actions are left for the terminals. This is achieved by configuring the UE devices with a list of candidate cells for autonomous SCell mobility. The aforementioned UE configuration could be facilitated via dedicated signaling from the network to the UE, or potentially be broadcast to jointly configure a group of UE devices with the same list of candidate cells for autonomous SCell mobility. This includes informing the UE of the system information parameters for those candidate cells, as well as which random access channel (RACH) preamble to use for them. At the network, the candidate cells for SCell mobility are prepared as well. In this context, preparing cells refers to providing those cells with the necessary information so that immediate service can be started after the UE requests it as SCell. Thus, the prepared cells are aware of the UE identity of potential terminals that may request them as SCells, and the prepared cell knows which macro is the UE’s PCell. As the UE moves to a new area (e.g., when experiencing PCell handoff to another macro base station), the network can supply the UE with an updated list of prepared cells for autonomous SCell mobility. Configuration of prepared cells can include a validity timer for which the configuration is valid, such that explicit signaling for later annulling such configurations is avoided.

When the UE detects a preconfigured candidate cell fulfilling certain access criteria, it is allowed to directly access the cell via the RACH to request it as an SCell. The triggering criteria for requesting the SCell addition is configured by the network and could be based, for example, on event A4 (neighbor cell becomes better than threshold) [1, 11]. However, notice that as the SCell mobility is UE autonomous, the A4 event is not reported to the network. As illustrated in Fig. 3, after the UE has requested SCell addition

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Extensive dynamic system-level simulations are conducted in order to assess the performance and corresponding benefits of the proposed UE autonomous SCell mobility scheme. The simulator follows the general 3GPP guidelines for system-level simulations.

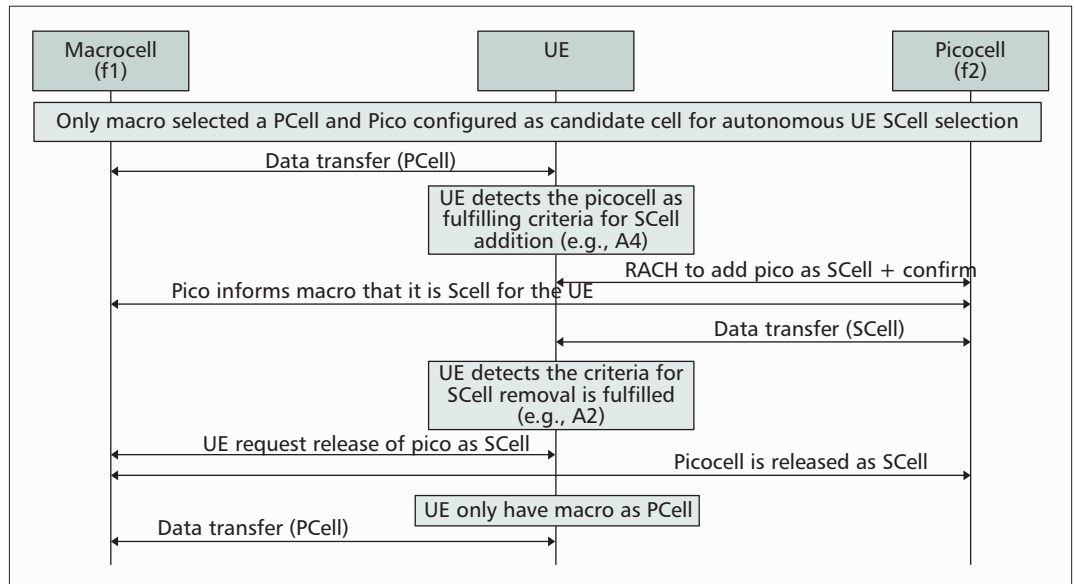


Figure 3. Example of UE autonomous SCell addition and removal.

via RACH, the pico (SCell) informs the master macro PCell that it now acts as SCell for the UE, and hereafter starts receiving data to be sent on the SCell in the downlink. The dataflow to the small cell acting as SCell for UE can be designed to come directly from the macro base station where the user has its PCell. As the UE starts to move away from the pico configured as SCell, the leaving criteria will eventually be triggered. The leaving criteria could be, say, A2 (cell becomes worse than threshold). When the SCell leaving criterion is fulfilled, the UE informs its master macro PCell to release the currently configured picocell as SCell, and the UE stops listening to transmissions from the pico. The macro informs the pico that it is no longer the SCell for the UE, as illustrated in Fig. 3. Note that having the UE send the SCell removal request to the macro (instead of the pico) is safer, as this will happen as the UE is moving away from the small cell's coverage region.

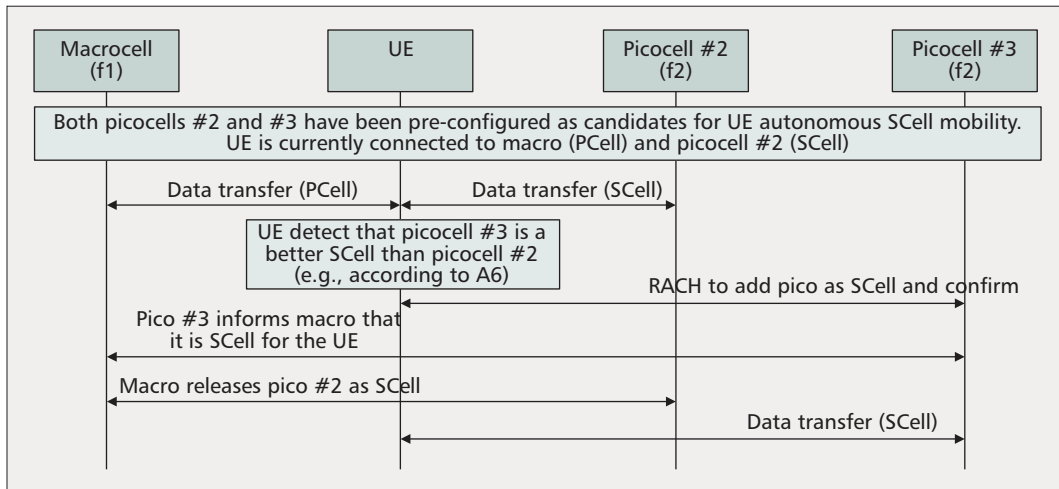
An example of UE autonomous SCell change is illustrated in Fig. 4. Here the UE first has the macro as its PCell and pico #2 as its SCell. Assuming that picocells #2 and #3 are located so that they have overlapping coverage areas, as in the example in Fig. 2, the UE can request SCell change. The criterion for SCell change is configured by the network, and can, for instance, be event A6, which indicates that the signal level from another SCell candidate has become a threshold better than current SCell [11]. As illustrated in Fig. 4, changing the SCell involves network signaling to inform the master macro PCell of this update. Notice from Figs. 3 and 4 that one of the advantages of the proposed UE autonomous SCell mobility framework is that no RRC events are reported from the UE to the network for SCell management; nor does it require any RRC messages from the network to the UE as is the case for normal network controlled mobility [1, 12]. Second, as the candidate picocells for UE autonomous SCell mobility are all prepared, addition of SCells is faster than traditional SCell addition. According to [9], the

composite handover delay for LTE Rel-10 equals the sum of preparation and execution delays, taking values of typically 50 and 40 ms, respectively. The cost of the proposed scheme is that multiple cells need to be prepared for each UE, as well as that UE devices should be configured with the same list of allowed candidate cells for autonomous SCell mobility.

## PERFORMANCE RESULTS

Extensive dynamic system-level simulations are conducted in order to assess the performance and corresponding benefits of the proposed UE autonomous SCell mobility scheme. The simulator follows the general 3GPP guidelines for system-level simulations. An LTE-Advanced HetNet scenario with regular three-sector macro sites operating at 1.8 GHz and omnidirectional picos at 2.6 GHz is simulated. The downlink transmit power equals 46 and 30 dBm for macro and picos, respectively. The basic network layout and propagation models follow the 3GPP models as defined in [13]. For the downlink,  $2 \times 2$  single-user multiple-input multiple-output (MIMO) with rank adaption is assumed in coherence with basic LTE functionality [1]. UE devices follow the large-scale mobility model defined in [9], where UE devices move at constant speed in a random direction selected independently for each UE device. Simulations are conducted for different UE velocities. Cases with 2 and 10 picos per macrocell are considered, assuming random placement of these, subject to a minimum inter-distance constraint between different base station types as defined in [13].

The major RRM algorithms are simulated, including detailed modeling of handoff related mechanisms in coherence with assumptions outlined in [9]. This means that UE RRM measurements and the corresponding physical layer measurement imperfections are explicitly modeled, as well as UE layer 3 filtering of them, and associated delays when adding, removing, or



**Figure 4.** Example of SCell change while maintaining the same PCell.

changing cells. The PCell management is assumed to follow the currently defined mechanisms, where the PCell is restricted to the macro layer only. PCell change from one macrocell to another is executed if the UE reports an A3 event (neighbor cell becomes offset better than PCell) based on reference signal received power (RSRP). The value of the offset is set to 3 dB, and the time to trigger equals 160 ms in coherence with one of the recommended parameter settings in [9]. The criteria for UE autonomous addition and removal of SCell are assumed to be based on UE reference signal received quality (RSRQ) measurements. RSRQ is defined as the RSRP divided by the total received power on the carrier, also known as the received signal strength indicator (RSSI) in 3GPP terminology [1]. When event A4 (RSRQ on cell becomes better than threshold) is met, SCell addition is triggered. Similarly, event A2 (RSRQ on cell becomes worse than threshold) is used as SCell removal criteria. The thresholds for A2 and A4 are selected so that they correspond to approximately adding an SCell when the signal-to-interference-plus-noise-ratio (SINR) is above 0 dB, and removing it again when it is below -5 dB. Thus, whenever the UE experiences reasonable quality on the pico layer, the pico is added as an SCell for improved performance. UE autonomous SCell change is based on A6 (neighbor cell on f2 becomes Y dB stronger than current SCell) with  $Y = 1$  dB.

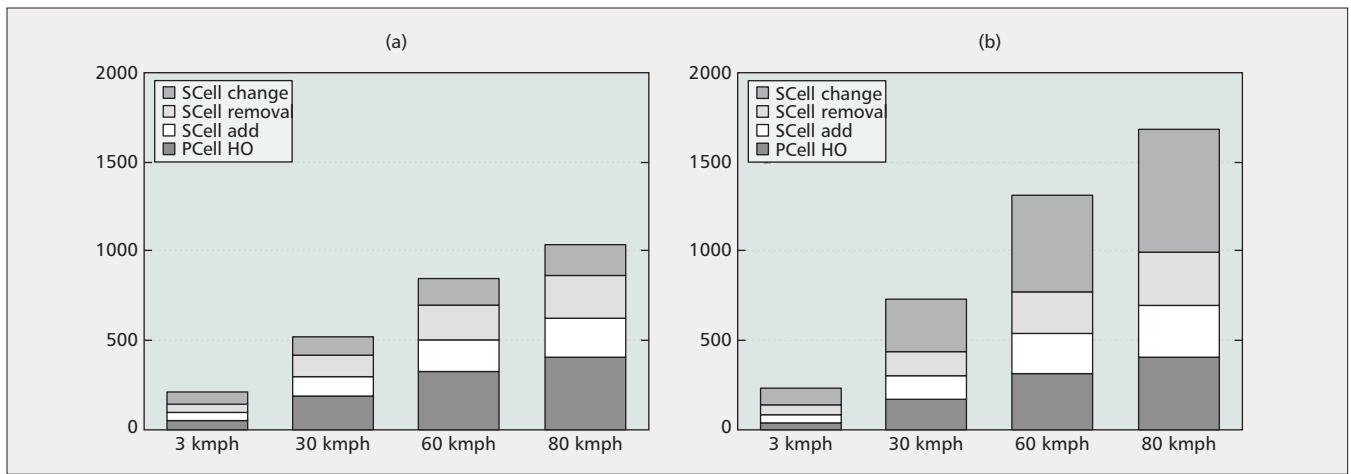
Figure 5 pictures the statistics for the possible PCell and SCell operations per UE device per hour for different speeds and numbers of picos per macrocell area. The first observation is that the number of PCell operations is significantly lower than the sum of SCell operations. This behavior is simply observed because the picos have a much smaller coverage area than the macrocells used for PCells. In fact, PCell mobility operations only represent ~20 percent of the total sum of PCell/SCell management operations (for the case with 10 picos), thus showing that using the proposed UE autonomous SCell mobility scheme is promising for lowering the number of RRC reconfigurations related to handoffs. For the case with only two picos per macrocell

area, the SCell mobility operations are primarily dominated by SCell addition and removal, while it is relatively seldom that SCell change is triggered due to sparse small cell density, and therefore there is a low likelihood of overlapping small cells. However, for the dense small cell deployment with 10 picos per macrocell area, the relative ratio of SCell changes is naturally higher. As expected, the number of mobility operations for both PCell and SCell increases with higher UE speed.

Following the mobility KPIs outlined earlier, the RLF event is declared if the downlink SINR on the PCell has been below -8 dB ( $Q_{out}$ ) and stayed below -6 dB ( $Q_{in}$ ) for the duration of 1 s [9]. Similarly, HOF is declared if RLF occurs during the handover execution time, and PP is counted if a user experiences handover from cell A to B and back to A within a time period of 1 s. PP events represent unnecessary handovers, and are therefore desirable to minimize. As the RLF and HOF are only related to PCell quality according to the 3GPP definitions [10, 11], which in our case is always on the macro layer, it is found from the simulations that the probability of RLF and HOF is practically zero (less than 0.6 percent). For cases without inter-site carrier aggregation, inter-frequency PCell handovers would need to be conducted between macro and pico, resulting in potentially higher RLF and HOF rates depending on the settings for inter-frequency measurements and so on. Thus, this shows one advantage of always keeping the PCell on the macro layer for the considered scenario. Similarly, the PP rate for PCell at the macro layer is found to be only 0.2 percent. The SCell PP rate on the pico layer for the case with 10 picos per macrocell area is on the order of 5 percent, despite the rather aggressive setting of the A6 offset to only 1 dB. By increasing the A6 offset to 3 dB (similar as used for A3 offset for PCell), the PP rate is lowered to around 2 percent.

Figure 6a shows the percentage of time that a UE device has SCell configured for different UE speeds and number of picos per macrocell area. Figure 6b pictures the empirical cumulative distribution function of SCell time of stay (ToS) to show the time each UE typically spends per

*As the presented concept of UE autonomous SCell mobility looks promising, further studies of such solutions are recommended. Details related to the exact requirements and complexity of network elements and terminals from using HetNet inter-site carrier aggregation with UE autonomous SCell mobility require further analysis.*



**Figure 5.** Number of PCell and SCell mobility actions per UE, per hour: a) case with two picos per macrocell area; b) case with 10 picos per macrocell area.

picocell. It is generally observed that for the low UE speed (3 km/h), UE devices have higher probability of having SCells, and higher SCell ToS, compared to the case with higher UE speed (60 km/h). At the higher speed, UE devices naturally move faster through the small cells and therefore do not always have sufficient time to fulfill the SCell addition criteria, leading to the effect that UE devices spend slightly less of their time with enabled SCells. Whenever a UE device has an SCell, it experiences a significant data rate boost due to higher available scheduling bandwidth. In addition, the experienced SINR on the small cell layer is typically rather good, combined with only having a few simultaneous active users per pico, resulting in further throughput gains compared to having the UE only connected to the macro layer. Thus, the end-user throughput gain relative to only having a PCell at the macro layer is orders of magnitude higher than the percentage of time for which each UE device has an SCell configured. It should be noted that the statistics presented in Fig. 6 naturally depend on the assumed settings of events A2 and A4, as used for SCell addition and removal here.

## CONCLUDING REMARKS

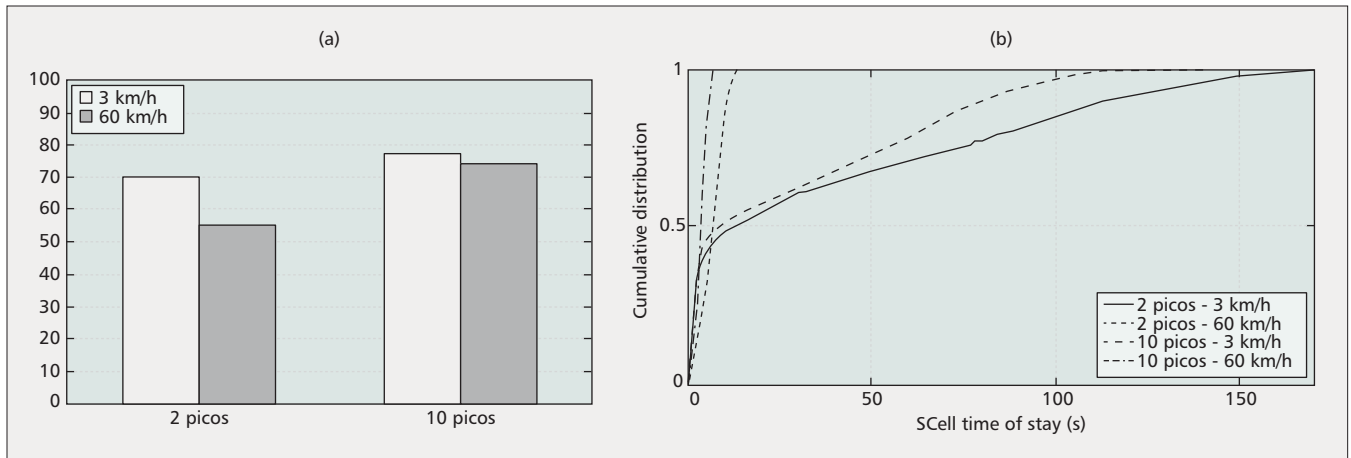
The migration from macro-only to HetNet scenarios introduces new challenges that call for additional innovations to harvest the full potential of introducing small cells. Among those, mobility challenges are high on the list to ensure robust handoff performance without having excessive signaling overhead, and without jeopardizing UE power consumption. The presented summary of recent observations from a rather extensive 3GPP study of HetNet mobility enhancements gives valuable pointers to HetNet mobility problems that need further research to have a fully optimized system. These include enhanced MSE, optimization of long DRX for mobility, and improved inter-frequency small cell discovery. The presented HetNet scenario with inter-site carrier aggregation is one of the promising configurations for boosting the end-user experienced performance, offering higher

data rates. For such scenarios, a hybrid mobility solution with network controlled handoff for PCell and UE autonomous mobility management for SCells is derived and motivated. By using the UE autonomous SCell mobility for the layer of small cells, the frequent RRC signaling for small cell mobility management can be reduced by partly delegating such management actions from the network to the UE. The presented performance results demonstrate that the signaling for mobility management can be significantly reduced by using the proposed scheme, given the considered HetNet scenario. This is achieved while still having low probabilities of experiencing RLF, HOF, and PP events.

As the presented concept of UE autonomous SCell mobility looks promising, further studies of such solutions are recommended. Details related to the exact requirements and complexity of network elements and terminals from using HetNet inter-site carrier aggregation with UE autonomous SCell mobility require further analysis. Among others, it is on the 3GPP agenda to have further research and standardization of HetNet mobility improvements during the Rel-12 timeframe, including technical innovations for small cell enhancements.

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**Figure 6.** Small cell offloading statistics: a) percentage of time UE devices have SCells configured; b) cumulative distribution function of SCell ToS.

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