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Handover Decision for Small Cells: Algorithms, Lessons Learned and Simulation Study

Dionysis Xenakis, Nikos Passas, Lazaros Merakos, and Christos Verikoukis

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1. INTRODUCTION

Small cell deployment is currently the main answer to the seamless transfer of the exponentially increased mobile data traffic throughout the cellular network infrastructure. Compared to macrocells, small cells are characterized by low deployment and maintenance costs as well as short transmit-receive range. Femtocells are a special case of small cells that are installed and managed by the end users, reaching the core network of the cellular operator through the customers' broadband backhaul [1]. To cope with their unplanned installation, small cells offers advanced capabilities for self-optimization and healing, combined with sophisticated radio resource, interference, and security management. The support of small cells is a key feature of the Long Term Evolution-Advanced (LTE-A) system, which enables flexible network deployment, improved spectral efficiency, better user experience and cost effectiveness [2].

The denser yet unplanned deployment of small cells in LTE-A complicates all individual phases of Mobility Management (MM) when the User Equipment (UE) is in the connected mode: cell search, cell identification, and cell handover (HO). Cell search and cell identification are the inextricable preludes to the cell HO process since, in combination, they enable the UE to discover and identify small cells within proximity. On the other hand, cell HO includes all the decision and signaling processes required to seamlessly transfer the user connections from the current serving to a neighbor cell.

Even though the LTE-A Standard addresses most of the fundamental issues for MM in the presence of small cells, certain implementation-dependent issues are yet to be solved to fully utilize their potential for enhanced Quality of Service (QoS) and low-power transmission of mobile data. LTE-A supports exciting new capabilities towards improving the cell HO process, such as optimization of cell-specific HO parameters, employment of cell and UE signal measurements, and mobility estimation. The utilization of such features during the HO decision stage is a key enabler for avoiding frequent yet unnecessary HOs in the small cell network and alleviating the negative impact of cross-tier interference on the Signal to Interference plus Noise Ratio (SINR) performance [3]. Since HO decision is outside the scope of the LTE-A Standard, the employment of intelligent HO decisions in the presence of small cells can be a big competitive advantage for an operator.

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In this paper, we summarize lessons learned from HO decision for small cells and present a novel LTE-A specific HO decision algorithm for small cells. The proposed algorithm alleviates network interference and prolongs the UE battery lifetime, given a prescribed target SINR for the uplink. In the sequel, we provide a quantitative performance comparison of the proposed and other existing state-of-the-art HO decision algorithms by using the widely accepted system-level simulation methodology of the Small Cell Forum [4]. To the best of our knowledge, this is the first work to quantitatively assess and compare the performance of the key design approaches for HO decision in the presence of small cells. This kind of analysis enables us to quantitatively validate the presented lessons learned from current state-of-the-art and derive useful design guidelines for HO decision tailored to the peculiar characteristics of the LTE-A small cell network.

2. CELL HANDOVER FOR SMALL CELLS AND OPEN ISSUES

Cell HO involves two main stages: HO decision and HO execution. In the presence of small cells, the short transmit-receive range brings the time horizon for cell HO closer to the one for Radio Resource Management (RRM), significantly increasing the processing and signaling overheads required for cell HO. HO decision for small cells typically involves the utilization of an enriched set of parameters on the network status [3], e.g., received signal strength (RSS), user speed, and interference. On the other hand, HO execution for small cells necessitates additional signaling to support the discovery of small cells (proximity indication), their unique identification (Physical Cell Identifier (PCI) resolution), and the employment of access control [2]. These challenges are unique to the small cell network and, if overlooked, they can increase the number of unnecessary HOs in the system, resulting in frequent service interruptions and deterioration of the QoS as perceived by the cellular users.

We consider three issues to be instrumental for HO decision in the presence of small cells: a) optimize the HO triggering procedure, b) employ interference-aware and energy-efficient HO decisions, and c) attain compatibility with the cellular standard. Referring to the first challenge, existing cellular systems support a plethora of RRM capabilities at the cells, including carrier aggregation and multi-antenna transmissions. Joint optimization of the HO triggering, in conjunction with the use of advanced RRM capabilities, will enable the operators to lower the HO probability and condense the signaling overhead required for cell HO. On the other hand, the HO decision stage is a key vehicle for improving the energy-efficiency of the network nodes and handling network interference at a macroscopic level. Besides, attaining compatibility with the cellular system is not trivial, given that most of the existing HO decision algorithms utilize parameters that are not (presently) available to the access network, requiring certain functional enhancements or additional network signaling to support them.

HO execution for small cells dictates a) smooth integration of all functions required for handing over to a small cell, and b) careful planning / dimensioning of all auxiliary network infrastructures required to support inbound/outbound mobility to small cells, e.g., femtocell gateway (F-GW) [2]. The employment of autonomous cell search, small cell identification, and access control, should be carefully re-designed to avoid over-engineering and reduce the HO execution delay. On the other hand, even though small cells can be deployed by the users in an unplanned fashion, the installation of traffic concentrators that handle the localized traffic of small cells should be (to a certain extent) subject to network planning. For example, the strategic deployment of F-GWs based on network or geographical data can significantly reduce the control burden required for handling the femtocell traffic in the core network, e.g., in a shopping mall.

3. HANDOVER DECISION FOR SMALL CELLS

The literature on HO decision algorithms for small cells is rich, e.g. [5]-[9]. Most of the existing works incorporate several parameters to reach the final decision, such as RSS, speed, and transmit power. In our previous work in [3], we have surveyed and classified the most prominent algorithms for femtocell-specific HO decision based on the primary criterion used. Below, we briefly introduce the key properties of each algorithmic class to launch the discussion on lessons learned from existing literature, followed by useful guidelines and best practices for the design of HO decision algorithms for small cells.

3.1 Classification of HO Decision Algorithms

RSS- based algorithms

RSS refers to the received power on the pilot or reference signals transmitted by a specific cell. In the presence of small cells, RSS is a decision parameter biased in favor of macrocells, since a) RSS is the product of the reference signal (RS) transmit power and the path loss [2], and b) different RS transmit powers are radiated between the macrocell and small cell tiers. There exist various approaches on how to use the RSS during the HO decision phase [5], mainly including RSS comparison of the candidate cells (relative RSS) either directly or with a HO hysteresis margin (HHM), and RSS comparison of the cells with absolute thresholds (absolute RSS). The HHM is typically used to avoid frequent handovers and mitigate the ping-pong effect. The ping-pong effect refers to the situation where the cell edge user is repeatedly handed over between neighboring cells.

Speed-based algorithms

In this class of algorithms [6], the decision is reached by comparing the user speed to algorithm-specific thresholds. The user speed is typically used to reduce the number of unnecessary HOs for medium to high speed users, while it is frequently combined with other metadata on the UE mobility pattern. Speed-based algorithms incorporate other decision criteria as well, such as the RSS and the traffic type of the user connections.

Interference-aware algorithms

Algorithms in this class directly or indirectly account for the interference at the UEs or the cell sites [7]. The main decision parameters include the Received Signal Quality (RSQ) at the UEs or the Received Interference Power (RIP) at the cells. The RSQ refers to the ratio of the RSS from a target cell to the interference at the UE site, while the RIP refers to the total received power from all cells or non-associated users in proximity. RSQ-based algorithms compare the RSQ of the serving and the neighbor cells, or allow inbound mobility to a small cell whenever the respective RSQ is higher than a fixed threshold [7]. RIP-based algorithms emphasize on reducing interference in the uplink direction.

Energy-efficient algorithms

Energy-efficiency is critical for the LTE-A network nodes, which are required to support advanced radio capabilities, e.g., carrier aggregation and multi-antenna transmissions. Existing energy-efficient algorithms use the mean UE energy consumption or the mean UE transmit power to reach to a final decision, e.g., [8].

Cost-function based algorithms

These algorithms use a single cost-function calculated from various parameters (e.g., multi-parameter functions or weighted summations) [9]. The decision is reached by comparing the outcome of the cost-function for the serving and the neighbor cells. Apart from the criteria mentioned before, the cost-function may also employ the available bandwidth at the neighbor cell, the UE membership status, or the path loss between the UE and the neighbor cell.

3.2 Lessons Learned from the Design of HO Decision for Small Cells

RSS-based algorithms are in general of low-complexity and easier to validate through performance analysis. Minimum network interventions are also required to support them, unless more sophisticated capabilities are deployed, e.g., mobility prediction. However, this kind of algorithms are in general interference-agnostic and do not consider the impact of interference on the SINR, throughput, or energy consumption performance. On the other hand, speed-based algorithms reduce the HO probability and mitigate the number of unnecessary HOs for medium to high speed users. However, in most of the cases, existing algorithms compare the user speed with arbitrarily chosen thresholds, which are not the outcome of simulation or analysis. Another weak aspect of existing speed-based algorithms is that they do not consider the monetary, signaling, or energy consumption overhead, required for evaluating the UE speed and its transfer to the serving cell.

Interference-aware algorithms improve the SINR and allow for interference handling at a macroscopic level. However, algorithms that are based on relative RSQ comparisons are required to optimize their HHM both to lower the HO probability and reduce the ping-pong effect. On the other hand, the incorporation of the RIP at the cell sites, or the RS transmit power, dictates the deployment of more complex signaling procedures, which are typically outside the scope of the respective works. Energy-efficient algorithms reduce the energy expenditure and typically improve the SINR performance in the uplink. However, they also increase the signaling and processing overhead to keep track and evaluate the energy-efficiency at the cellular nodes. Cost-function based algorithms incorporate a wide set of parameters to reach a HO decision. The integration of bandwidth-related parameters often enables preliminary admission control or load balancing. Nevertheless, cost-function based algorithms typically do not provide a detailed methodology for calculating the optimal weights or adjustment factors of the cost-function, which, however, may have a major impact on the final decision outcome. In Table 1, we summarize the strong and weak aspects of the aforementioned algorithmic classes.

	RSS-based	**Speed-based**	**Interference-aware**	**Energy-efficient**	**Cost-function based**
Strong aspects	(+) Low-complexity	(+) Reduce HO probability	(+) Enhance SINR performance	(+) Reduce energy expenditure	(+) Enable preliminary admission control
	(+) Easier to analyze	(+) Mitigate unnecessary HOs for medium to high speed users	(+) Enable interference handling	(+) Improve SINR performance in the uplink	(+) Load balancing
	(+)Minimum network interventions				
Weak aspects	(-) Interference-agnostic	(-) Arbitrary speed thresholds	(-) Require HHM optimization	(-) Increase complexity	(-) Require optimization of the weights and adjustment factors
	(-) Do not account for SINR, interference and energy energy-efficiency	(-) Increase monetary and signaling cost for estimating the UE speed	(-) Increase complexity	(-) Increase network signaling	
			(-) Increase network signaling		

Table 1: Comparison of HO decision classes

3.3 Design Guidelines and Best Practices

Based on the previous discussion, we identify four key design principles for robust HO decision algorithmic design in small cell networks: a) focus on the multiple-macrocell multiple-small cell HO scenario, b) be compatible with the cellular system, c) optimize decision-related parameters, and d) use widely-accepted evaluation methodologies.

Most existing algorithms consider a single-macrocell single-small cell HO decision scenario, e.g., [5] [6]. Nevertheless, existing reports foresee that the number of small cells will surpass that of deployed macrocells by up to six times within the next few years [10], transforming the operator-planned network of medium to large radii cells to a multi-tier network with numerous user-deployed small sized stations. In such an environment, the robust support of inter-cell mobility asks for HO algorithms that are optimized to operate under the multiple-macrocell multiple-small cell HO scenario.

Referring to the issue of compatibility, existing solutions incorporate a rich set of parameters to improve the cell HO performance. However, only a few describe the additional network functionality and signaling procedures required to support them. Specifying in detail all necessary architectural and functional enhancements is critical, as it guarantees the smooth integration of the proposed solution and provides stimulus for further research, innovation, and standardization.

Another critical issue is the optimization of all parameters involved in the HO decision. The use of a HHM during the RSS / RSQ comparison plays a key role in handling the fast variations of the wireless medium and mitigating the ping-pong effect. This effect is even more prominent in the presence of small cells due to the overlapping cell coverage. Combined with speed-based parameters, the utilization of a HHM can significantly reduce the HO probability, especially for medium to high speed users. However, optimizing the HHM is cumbersome and should be based on robustly handling the (negative) impact of user mobility while, at the same time, making the most out of the short transmit-receive range.

Since the evaluation of a HO decision algorithm is integral part of its design, validating the performance of the proposed algorithms using realistic system assumptions and simulation setups is also important. Even though some of the existing proposals conduct mathematical analysis, the assumption of simplistic network layouts raises questions about their scalability in real-life systems. Besides, recent trends for performance evaluation of multi-tier networks, such as the Small Cell Forum evaluation methodology or stochastic geometry [3], should be integral part of future proposals for HO decision in a small cell network.

4. PROPOSED ALGORITHM

In view of the above discussion, we propose a novel HO decision algorithm for the LTE-A small cell network. The proposed algorithm applies to the multiple-macrocell multiple-small cell scenario, is compatible with the LTE-A Standard and utilizes two of its key features: the enhanced cell measurements and the so-called private mechanism for non-standard use [11] [12]. The former feature enables the LTE-A cells to assess their radio status by performing local measurements, e.g., cell RIP and downlink RS transmit power; the latter feature enables the exchange of measurements either directly (X2 interface) or through the core network (S1 interface). The proposed algorithm uses measurements from all candidate cells to optimize two HHMs. The first HHM is used to avoid cells that can compromise service continuity, due to poor channel conditions, while the second HHM is used to identify the cell with the minimum required UE transmit power, given a prescribed SINR target.

Let $\boldsymbol{C}$ denote the set of candidate cells for the tagged user and s the current serving cell. Furthermore, let $RIP(c)$ and $P_{RS}(c)$ denote the RIP and the downlink RS transmit power measurements performed at cell c, respectively, and $RSRP(c)$ the RS Received Power (RSRP) measurement performed at the user, i.e., the RSS from cell c. The aforementioned parameters are standard cell measurement capabilities in LTE-A [11]. Given a prescribed mean SINR target for the user connections, denoted by γ_t, and a minimum RSRP requirement for sustaining service continuity, denoted by $RSRP_{th,}$ the set of candidate cells that sustain a minimum required channel gain, denoted by $\boldsymbol{M}$, can be identified using Eq. (1):

$$\boldsymbol{M} \coloneqq \{c | RSRP(c) > RSRP_{th} + HHM_1(c),\ where\ \mathrm{c} \in \boldsymbol{C}\ and\ HHM_1(c) = P_{RS}(c) - T(c)\} \qquad (1)$$

where $T(c)$ denotes the maximum transmit power of the candidate cell c (typically 20 dBm for femtocells and 43 dBm for macrocells). Eq. (1) is derived by considering that a) the channel gain between the UE and the target cell equals the ratio of the RSRP and the actual RS transmit power of the cell, and b) the minimum required channel gain can be computed as the ratio of the RSS threshold $RSRP_{th}$ to the maximum transmit power of the target cell.

Focusing on the adaptation of the second HHM, let $P(c)$ denote the mean transmit power of the user in the target cell c. Aiming to reduce the uplink transmit power, i.e., $P(c) < P(s)$, the cell with the minimum required UE transmit power is given by Eq. (2).

$$\arg\max_{c \in \boldsymbol{M}} RSRP(c) \coloneqq \{c |\ RSRP(c) > RSRP(s) + HHM_2(c), where\ HHM_2(c) = P_{RS}(c) - P_{RS}(s) + I(c) - Is \qquad (2)$$

The rationale behind Eq. (2) is that the mean UE transmit power for the target cell is equal to the product of the SINR target times the RIP at the target cell divided by the channel gain between the UE and the cell. The proposed algorithm is summarized as follows:

```
Proposed HO decision algorithm for small cells
(1)  Handover Triggering
(2)  Acquire $RIP(c)$, $P_{RS}(c)$, and $T(c)$ for every cell $c$ in $\boldsymbol{C}$
(3)  Calculate $HHM_1(c) = P_{RS}(c) - T(c)$ and $HHM_2(c) = P_{RS}(c) - P_{RS}(s) + I(c) - I(s)$ for every candidate cell in $\boldsymbol{C}$
(4)  Identify the candidate cell set $\boldsymbol{M} \coloneqq \{c | RSRP(c) > RSRP_{th} + HHM_1(c)\}$
(5)  Handover to the cell that satisfies Eq. (2)
(6)  Terminate HO decision phase
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Upon HO decision triggering (step 1), the serving cell (decision entity) acquires the maximum transmit power, the cell interference and the downlink RS transmit power for all candidate cells, by using the private mechanism for non-standard use (step 2). The two adaptive HHMs are subsequently evaluated for all candidate cells (step 3) and the (sub) set of cells that sustain service continuity is identified (step 4). The cell that requires the minimum UE transmit power is subsequently selected (step 5) and the HO decision stage terminates (step 6).

5. SIMULATION STUDY

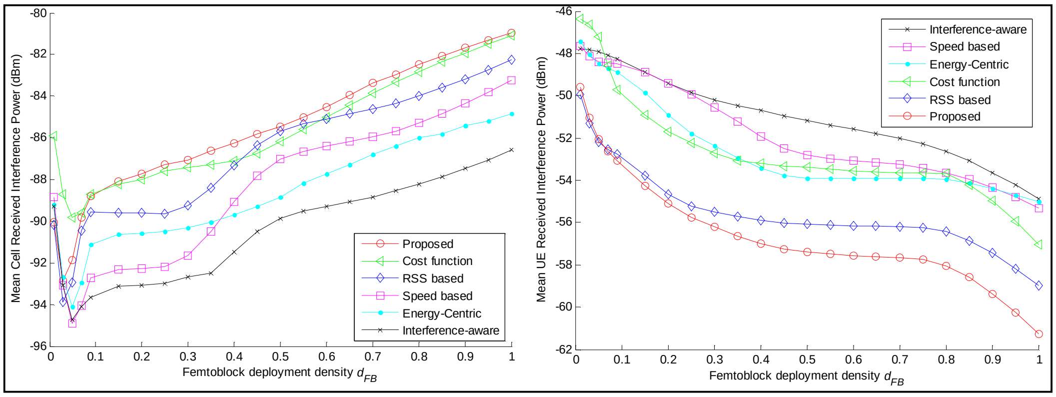
In this section, we assess the performance of the proposed algorithm and one representative algorithm from each HO decision class (Section 3.1). The emphasis is given both on revealing the strong and weak aspects for each HO decision approach, as well as on algorithm performance comparisons. The HO algorithms under scope are the ones in [5], [6], [7], [8], and [9], which will be referred to as RSS-based, speed-based, interference-aware, energy-efficient, and cost-function, respectively. The system-level simulations are conducted according to the Small Cell Forum evaluation methodology [4]. Given that the simulation model and parameters are in line with [4, pp. 107-110], below, we only briefly discuss some key features of the simulation setup.

We consider a hexagonal LTE-A network with a main cluster composed of seven macrocells. The network is extended by using the wrap-around technique, while a certain number of blocks with apartments, referred to as *femtoblocks*, are uniformly dropped within the LTE-A network area in accordance with the femtoblock deployment density parameter, denoted by d_{FB}. This parameter adjusts the percentage of the network area covered with femtoblocks and takes values in [0, 1]. Each femtoblock consists of two stripes of apartments, each having 2x10 apartments of 10mx10m size (dual stripe model [4]). In between and around the stripes, we consider a street with 10m width, leading to an overall block size of 120m x 70m. Femtocell stations and users are uniformly dropped within the apartments, where each femtocell initially serves one associated user. Each apartment is equipped with a femtocell with probability 0.2. All femtocells support one Closed Subscriber Group (CSG) [2], i.e., closed access only, where three CSG are considered for the entire network. All LTE-A users are members of up to one CSG. Each macrocell initially serves thirty users (ten users per sector), which are uniformly dropped within it. Aiming to guarantee a minimum QoS, all algorithms are evaluated using the same mean SINR target 3dB (fixed user throughput). User mobility is modeled in accordance with [8]. Note that apart from increasing the femtocell density in the network, a higher d_{FB} also increases the number of users in the system, i.e., one additional user per femtocell.

Table 2: Femtocell utilization

Algorithm	**Number of femtocell users / Total number of users**						
	$d_{FB} = 0.01$	$d_{FB} = 0.05$	$d_{FB} = 0.1$	$d_{FB} = 0.25$	$d_{FB} = 0.5$	$d_{FB} = 0.75$	$d_{FB} = 1$
Proposed	11/171	22/181	33/194	58/231	100/312	112/381	135/462
Cost-function based	11/171	18/181	32/194	54/231	88/312	95/381	95/462
Energy-Centric	11/171	22/181	30/194	47/231	67/312	81/381	100/462
RSS-based	3/171	8/181	14/194	30/231	68/312	70/381	79/462
Speed-based	3/171	7/181	11/194	23/231	66/312	74/381	86/462
Interference-aware	3/171	5/181	10/194	20/231	49/312	50/381	68/462

Table 2 depicts a concrete measure of femtocell utilization: the number of users associated with a femtocell. Note that the proposed algorithm considerably increases femtocell utilization compared to the other algorithms, as it accounts for the actual interference and path loss between the UE and the neighbor cells. Increased femtocell utilization is also observed for the cost-function based algorithm, which uses an enriched set of parameters to allow inbound mobility to femtocells. High femtocell utilization is shown for the energy-centric algorithm as well, as it tends to utilize the energy saving potential of femtocells. On the other hand, the speed-based algorithm reduces femtocell utilization due to the use of speed thresholds, whereas low utilization is also observed for the interference-aware algorithm, which limits inbound mobility to femtocells to mitigate cross-tier interference.



(a) (b)

Figure 1: Mean Received Interference Power: (a) at the cells (eNBs and HeNBs) and (b) at the UEs

Fig. 1 demonstrates the mean received interference power at the cells (Fig. 2a), including both eNBs and HeNBs, and the UEs (Fig. 2b) versus the femtoblock density d_{FB}. Interestingly, even though the proposed algorithm increases the interference at the cells (Fig. 2a), it offers a considerable reduction of the UE interference at the same time (Fig. 2b). The former property follows from the high offloading gain towards the small cells, which increases the number of uplink interferers operating within the small cell tier. On the other hand, the former property follows from the high utilization of small cells, which reduces the mean inter-site distance between the devices and the serving base station. The cost-function based algorithm increases the cell interference as well. However, at the same time, it results in medium to high UE interference for the same reasons. Similar, yet slightly worse, performance is observed for the RSS-based algorithm, whereas the speed-based and energy-centric algorithms show roughly the same performance. In contrast, the interference-aware algorithm attains the lowest cell interference and the highest interference at the UEs, which is quite the opposite behavior compared to the proposed one.

The results in Fig. 1 reveal an important performance trade-off for the LTE-A small cell network. Even though HO algorithms with high small cell utilization increase the interference at the cells, they simultaneously result in considerable interference mitigation at the UEs and increased offloading gain for the macrocell tier. Thus, apart from interference and load handling at the LTE-A cells, small cell specific HO decision can also complement the interference management in the downlink direction.

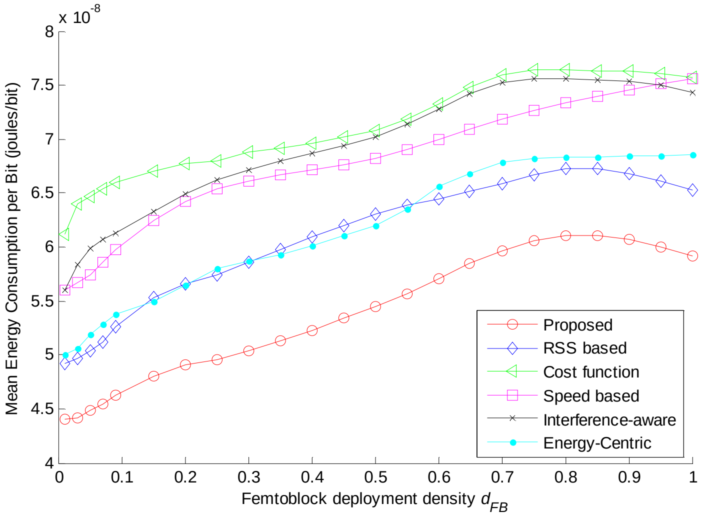


Figure 2: Mean UE Energy Consumption per Bit (Joules / bit)

Fig. 2 illustrates the mean energy consumption per bit at the user, owing to transmit power, for all algorithms. Although the cost-function algorithm results in high femtocell utilization (Table 2), it simultaneously requires the highest UE energy expenditure per bit (Fig. 2). This result reveals that even though prioritizing femtocell over macrocell access enhances femtocell utilization, the smart selection of a target femtocell plays a key role for sustaining low cross-tier interference (Fig. 1), and utilizing the energy saving opportunities offered by the femtocells (Fig. 2). As expected, the speed-based and the interference-aware algorithms show relatively high energy consumption per bit compared to other algorithms, mainly due to the high macrocell utilization (Table 2). Interestingly, the energy-centric and RSS-based algorithms demonstrate roughly similar performance, whereas the proposed algorithm reduces the energy expenditure per bit by 10% to 29% compared to all algorithms, depending on the femtocell deployment density. This performance improvement follows from the proposed algorithm’s tendency to drastically increase the utilization of small cells, which in turn reduces the (average) distance between the UEs and their respective serving cells.

From Fig. 2, it follows that even though a higher femtocell utilization increases the mean cell interference in the system (Fig. 1), comparably lower energy expenditure per bit can be achieved if the actual cell interference and path loss between the UE and the target cells are taken into account. This is one of the key design differences between the proposed and the cost-function based algorithms.

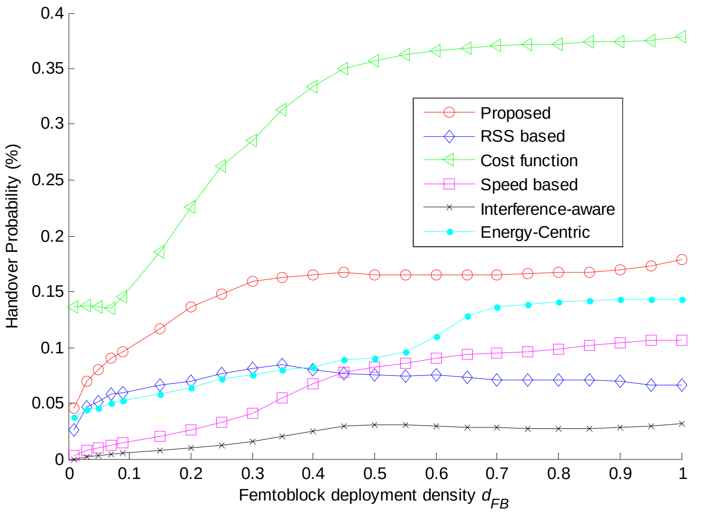


Figure 3: Average HO probability (%)

As expected, the HO probability strongly depends on the actual utilization of femtocells, given that HO algorithms that increase the femtocell utilization also result in higher HO probability (Fig. 3). Note that even though the proposed algorithm achieves the highest femtocell utilization, it attains significantly lower HO probability compared to the cost-function algorithm. Moreover, the RSS-based algorithm shows roughly constant HO probability for increasing femtocell density, whereas the HO probability for the speed-based and energy-centric algorithms is proportional to the femtocell deployment density. As expected, the interference-aware algorithm attains the lowest HO probability, owing to the increased macrocell utilization.

Table 3: Performance comparison for $d_{FB} = 0.5$

Algorithm **Measure**	**Proposed**	**RSS-based**	**Cost-function based**	**Speed-based**	**Interference-aware**	**Energy-Centric**
Small Cell Utilization (%)	Very High (32)	Medium (22)	High (28)	Medium (21)	Low (16)	Medium (22)
Uplink Capacity per User (Mbps)	High (14.5)	High (14)	Low (12.6)	Medium (13.7)	Medium (13.5)	High (15)
Energy per Bit (nJ/bit)	Very Low (54)	Medium (63)	Very High (71)	Medium (68)	High (70)	Medium (63)
UE Transmit Power (dBm)	Very Low (17)	Low (18)	Very High (19.5)	Medium (18.5)	High (19)	Very Low (17)
Cell Transmit Power (dBm)	Very Low (29)	Low (32)	Medium (33)	Medium (33)	High (34)	Low (32)
UE Interference (dBm)	Very Low (-58)	Low (-56)	Medium (-54)	High (-53)	High (-51)	Medium (-54)
Cell Interference (dBm)	High (-85)	Medium (-87)	High (-86)	Medium (-87)	Very Low (-91)	Low (-89)
HO Probability (%)	High (15)	Medium (8)	Very High (35)	Low (7)	Very Low (4)	Medium (9)
HO Failure Probability (%)	Very Low (0.1)	Very Low (0.1)	Very High (30)	Low (5)	Very Low (0.3)	Low (3)
Signaling Rate (signals/sec)	High (2220)	Low (880)	Very High (5350)	Very Low (380)	Very Low (270)	Medium (1160)

In Table 3 we summarize and compare the performance of all HO algorithms for $d_{FB} = 0.5$ under different performance measures. Note that the results refer to mean values while the signaling rate refers to the number of signals per second exchanged within both the core and the access network. The

RSS-based algorithm achieves a relatively medium small cell utilization, energy consumption and interference performance, while it sustains low HO probability and signaling rate as well. On the other hand, even though enhanced small cell utilization is shown for the cost-function algorithm, the results indicate that the cost-function weights should be carefully selected to improve its uplink capacity, interference, and HO probability/signaling performance. The incorporation of user mobility criteria enables the speed-based algorithms to significantly reduce the cell interference and attain very low HO probability / signaling. However, further enhancements are required to lower the interference at the UEs and improve their energy-efficiency. Interference-aware algorithms greatly reduce the cell interference and keep the HO probability / signaling low. However, they result in poor utilization of the low power operation of small cells, leading to enlarged energy consumption and interference at the user terminals. The energy-centric algorithm substantially enhances the mean uplink capacity and reduces the energy expenditure for both the cells and the UEs. Nevertheless, the use of higher HHM should be considered to further reduce the HO probability / signaling required for monitoring the UE energy consumption.

Based on the results in Table 3 we can conclude that compared to all other algorithms under scope, the proposed algorithm attains superior performance in terms of energy expenditure per bit, uplink capacity, cell and UE transmit power, and mean UE interference. These performance improvements follow from the exchange and utilization of the LTE-A measurements, which allow for an accurate estimation of the actual cell interference and path loss between the UE and the target cells. Nevertheless, even though the utilization of measurements from other cells enables this robust performance, i.e., increased small cell utilization combined with smart selection of cells, it is also the origin for increased cell interference and HO probability/signaling.

6. CONCLUSION

We have overviewed the main open issues for cell HO in the presence of small cells, with emphasis on the implementation-dependent HO decision stage. We have reviewed existing design approaches for HO decision in order to discuss lessons learned and practices for the algorithmic design of HO decision in small cell networks. Based on this discussion, we have proposed a HO decision algorithm that addresses most of the design guidelines under consideration. Using the Small Cell Forum evaluation methodology, we have validated our views on lessons learned for HO decision in the presence of small cells, and have revealed the key advantages and main weaknesses of existing design approaches. The simulation study has shown that the utilization of standard LTE-A measurements allows the proposed algorithm to double the macrocell offloading gain, enhance the uplink capacity (around 0.5 Mbps per user) and reduce the interference at the UEs (up to 7 dB). On the other hand, the intense utilization of the small cell infrastructure combined with the exchange of the standard LTE-A measurements have been shown to increase the cell interference (up to 8 dB) and the HO probability / signaling requirements. Our results highlight the need for small cell specific interference mitigation and novel cell HO protocols tailored to the specific characteristics of the small cell network.

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