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Řízení mobility uživatelů v bezdrátových sítích s malými buňkami

Mobility management in networks with small cells

Summary

To ensure continuous data connection for mobile users, handover between cells of a mobile network must be performed. However, the handover can be initiated very often if small cells, i.e., cells with low radius, are deployed in the network. This can lead to a drop in quality of service as an overhead is generated due to each handover. Moreover, the handover can cause a short interruption in data connection. To minimize these negative effects of the user's mobility, redundant handovers have to be eliminated or an advanced approach for mobility support, such as fast cell selection (FCS), has to be implemented. This lecture focuses on the FCS with management of active set suitable for networks with small cells. First, problems related to implementation of the FCS to future mobile networks are addressed. Then, the management of active set exploiting estimation of amount of radio resources required to serve the user is presented. This algorithm minimizes the problem of handover interruption and it also increases quality of service experienced by users.

Souhr

Pro zajištění kontinuity datového spojení uživatelů pohybujících se mezi buňkami bezdrátové sítě je nutné provést předání spojení, tzv. handover, mezi těmito buňkami. V případě, že jsou v síti implementovány i buňky s malým rozsahem oblasti pokryté signálem, nazývané "malé buňky", může docházet k častému handoveru. To vede k poklesu kvality služeb, jelikož každý handover vyžaduje určité množství signalizace. Zároveň může dojít i ke krátkému přerušení komunikace se sítí během handoveru. K potlačení těchto negativních vlivů je nutné eliminovat nadbytečné handovery nebo implementovat pokročilé metody řízení mobility, jako například rychlé přepínaní buněk. Tato přednáška je zaměřena na implementaci rychlého přepínání buněk s pokročilým managementem seznamu potenciálních obsluhujících buněk v sítích s malými buňkami. Nejprve je popsán způsob implementace rychlého výběru buněk do budoucích mobilních sítí. Poté je prezentován algoritmus výběru potenciálních obsluhujících buněk na základě množství přenosových prostředků spotřebovaných k obsluze uživatelů. Tento algoritmus umožňuje minimalizovat problém přerušení v důsledku handoveru a zároveň umožňuje zvýšit kvalitu služby uživatelů v síti.

Klíčová slova: rychlé přepínání buněk, handover, mobilita, malé buňky, budoucí mobilní sítě

Keywords: fast cell selection, handover, mobility, small cells, future mobile networks

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1 Introduction

Future generations of mobile networks are assumed to exploit frequencies in order of GHz (e.g., 2, or 3.5 GHz). Transmission at these frequencies leads to a significant attenuation of signal between a transceiver and a receiver. To cover potential gaps in coverage due to the attenuation, small cells (such as femtocells or picocells) are supposed to be deployed. Dense deployment of small cells introduces new challenges related especially to interference mitigation and users' mobility management for the closed and open/hybrid accesses [1], respectively. This lecture is focused on mobility management.

A user equipment (UE) has to perform handover from a serving cell to a target cell to guarantee a quality of service (QoS) for mobile users. If the user is moving close to the area with a dense deployment of small cells, large number of handovers can be performed within a short time interval. Then, a drop in QoS is introduced due to a short interruption, which is a consequence of handover. The amount of handovers can be adjusted by techniques used for elimination of redundant handovers, such as hysteresis or time-to-trigger [2][3]. Nevertheless, those techniques considerably decrease user's throughput in networks with small cells [4]. Enhancements of the handover decision for networks with small cells have been proposed, e.g., in [5][6][7]. All these papers targets so-called hard handover, which is characterized by disconnection of the UE from the serving cell before a new connection to the target cell is established [8]. Therefore, the interruption due to handover cannot be avoided.

To suppress the problem of the handover interruption and the QoS decrease in the networks with small cells, Fast Cell Selection (FCS) can be exploited instead of the hard handover. The FCS introduces an active set containing selected neighboring cells with which the UE can communicate. At every time interval, the UE can transmit/receive data to/from different cell included in the active set. The FCS introduces a gain in throughput especially at the cell edges where the interference is not marginal as shown, for example, in [9][10][11]. These papers investigate FCS in the scenario with macrocells only. Nevertheless, deployment of the small cells introduces several problems related to the limited backhaul capacity and low radius of coverage that could negatively influence performance of the FCS. Therefore, the algorithm for more efficient management of the active set respecting specifics of the small cells is introduced.

2 Motivation

Handover can be initiated to ensure QoS for users, to improve coverage, or to balance load among base stations. According to originating standards for mobile networks, not only conventional macro base stations (MBS) but also small cells, represented by, e.g., femto access points (FAP), are expected to be deployed to improve network performance. However, by placing additional base stations to the network, new cell boundaries are introduced.

Since heavy deployment of the small cells is expected in future mobile networks, the handover procedure becomes initiated more frequently (see Figure 1). Therefore, more often scanning of a higher amount of cells in the UE's neighborhood has to be performed. Moreover, each handover generates management overhead and introduces interruption in user's communication. All these aspects lead to a drop in user's throughput and QoS [12]. To minimize this problem, common principles of mobility support have to be modified to preserve high level of QoS.

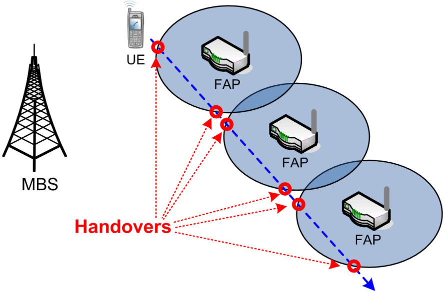


Figure 1. Problem related to the dense deployment of small cells.

The goal of this lecture is to provide solutions for suppression of the negative impact of the users 'mobility on the network performance and to improve user's experience.

3 Fast cell selection

A solution how to ensure seamless mobility of users consists in establishment of data connection with the target cell before connection with the current serving cell is released. In general, this approach is known as soft handover. In case of the soft handover, each UE can be connected to more than one cell at each time. A specific type of soft handover is the FCS. The FCS offers means for the UE and/or the network to decide which cell in the active set is really going to send data to the UE in the next transmission interval. To that end, the FCS selects and updates the best cell at each transmission interval. Then this cell performs data transmission to the UE. The same resources, which are used to serve the UE cannot be occupied by other cells included in the active set. This reduces interference and results in a gain in throughput of the UEs. To avoid delay due to delivery of data through backhaul, the same data are sent to all cells in the active set via their backhaul at the same time. Consequently, the FCS can even stress the limited backhaul capacity of FAPs as all data has to be delivered through the backhaul even if it is later transmitted to the UE through another FAP (see Figure 2).

The FCS is known as a code division multiple access (CDMA) specific technique. Thus, the FCS cannot be ported into the systems designed for future mobile networks based on orthogonal frequency division multiple access (OFDMA) unless particular algorithms are defined for control layer in order to achieve cooperation among the cells. Therefore, we first address problems related to implementation of the FCS to the networks with small cells. Then, novel management of active set is proposed and evaluated.

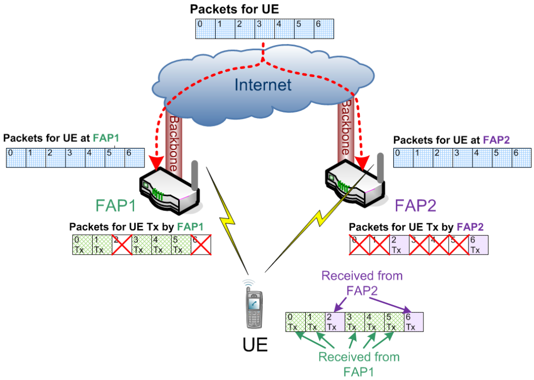


Figure 2. Backhaul limitation for FCS.

3.1 FCS in OFDMA networks with small cells

The first requirement, which the OFDMA system has to fulfill for FCS is time synchronization among cells in the network. Without proper synchronization, only the conventional hard handover is possible. Synchronizing the system allows to see the FCS as a specific case of joint scheduling, where a set of cells collaborates in a way that only the best cell in the set can schedule data toward the UE at each interval. In case of time division duplex (TDD), the time synchronization of the small cells can be derived from the umbrella MBS. Then each cell in the active set needs to receive the integral data to be scheduled toward the UE. This principle introduces redundancy. However, it allows reaching high rates of the cell switching, without flooding networks with handover events.

Because OFDMA systems, such as LTE or LTE-A, do not address the notion of the soft handover of FCS with the active set of cells serving a given UE, a solution is needed to allow several MBSs or small cells to participate in the active set in such systems. Once a radio bearer is established for a UE with one cell in the data path, it is necessary to add and remove additional contributing cells. This introduces the notion of a "serving" cell in the active set, which assumes a particular role, as opposed to a simple "contributing" cell. The serving cell is the one which is in charge of signaling and can also transmit data. Contrary, the contributing cell can deliver only data to the UE. Figure 3 illustrates required modifications for the FCS in LTE-A architecture with small cells.

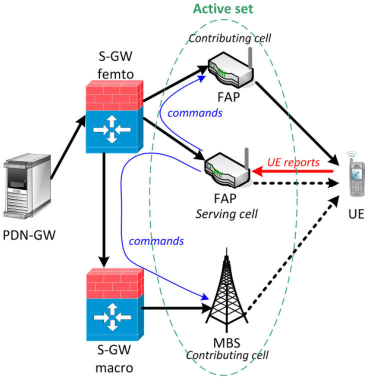


Figure 3. Architecture and principle of the FCS implemented into LTE-A networks.

New procedures should be defined in order to include or remove contributing cells to or from the active set, as listed in Table 1. When the contributing cell is added to the active set, the serving gateway (S-GW) should be notified and it should duplicate packets toward the new cell in the downlink. Similar mechanisms must be proposed for the uplink so that every contributing cells may take over a role of both data receiver/transmitter in uplink and downlink. In this lecture, we focus on downlink.

The serving small cell or MBS should be in charge of adding and removing the contributing cells to the active set. Conventionally, this decision is based on measurement reports received from the UE, as it is in the case for the hard handover decision itself. A novel algorithm for the active set management is proposed later in this lecture to improve efficiency of the FCS.

If the serving cell is shifted from a source one to a target one, then the set of contributing cells should be delivered from the source cell to the target cell as a part of the UE context. Once a successful handover has been achieved for a UE, then the target cell is free to maintain or modify the set of the contributing cells used by the former serving cell.

A solution should also be proposed in order to let the contributing cells know if they are elected to schedule data toward the UE for a given interval. The solutions defined in the context of 3GPP release 99 are CDMA specific and cannot be applied outside this context. The most natural solution is to let the serving cell communicate this information to the contributing cells on the basis of the UE measurement reports. Since we mainly assume slow moving UEs, reporting periodicity may be set low enough to maintain low overhead.

The serving cell should exploit measurement reports from the UE in order to decide, which cell in the active set will actually be in charge of scheduling data to the UE. Whenever a modification is done in this respect, the decision should be delivered to the involved contributing cells. This command from the serving cell to the contributing cells should just include the ON/OFF boolean value, together with the reference of the next interval where this update should be applied.

Table 1. Procedures for support of the FCS in OFDMA-based networks with small cells

From	**To**	**Message purpose**	**Message content**
Serving cell	S-GW	Add a contributing cell	ID of cell to be added
Serving cell	S-GW	Remove a contributing cell	ID of cell to be removed
Serving cell	UE	Define/update FCS measurement report *(same like for common handover)*	Measurement period Measurement content (as an index in a list)
UE	Serving cell	FCS measurement report *(same like for common handover)*	Measured value
Serving cell	Contributing cell	FCS command	ON/OFF value ID of next bit to be sent

3.2 Algorithm for active set management

The proposed algorithm for selection of proper members of the active set compares the current amount of radio resources consumed at the MBS with the radio resources of the MBS consumed if a cell would be added/removed to/from the active set. In addition, the backhaul limitation, in term of the limited capacity and higher delay, is introduced in the proposed active set management procedure.

Let $UE = \{UE_1, UE_2, \ldots, UE_u\}$ denotes the set of u users in the network and $C = \{C_1, \ldots, C_m, C_{m+1}, \ldots C_{m+f}\}$ represents the set of $k = m + f$ cells in the network, where m and f is the amount of MBSs and FAPs, respectively. Further, $N^i = \{N_1^i, N_2^i, \ldots, N_{nc^i}^i\}$ represents the set of the neighboring cells of the *i-th* UE. Each N^i consists of nc^i neighboring cells. The set $A^i = \{A_1^i, A_2^i, \ldots, A_{ac^i}^i\}$ is composed of cells included in the active set of the *i-th* UE. Note that the A^i is always a subset of the N^i, i.e., $A^i \subseteq N^i$. The amount of cells included in the active set of UE_i is denoted as ac^i. The parameter ac^i is also known as active set size.

Principle of the proposed algorithm can be explained as follows. If $C_j \in N^i$ and $C_j \notin A^i$, then the cell can be included into the A^i if:

$$\alpha R_{j \in A^i}^i < R_{j \notin A^i}^i \tag{1}$$

where $R_{j \in A^i}^i$ represents the amount of radio resources of the MBS consumed by the UE_i if the C_j would be included in the A^i, $R_{j \notin A^i}^i$ represents the amount of the MBS's radio resources consumed by the UE_i if the C_j would not be included in the A^i, and α represents a gain required for inclusion of the C_j in the A^i. Resources of the MBS are considered in this equation rather than resources of the FAP since each FAP is supposed to serve only low amount of users comparing to the MBS. Thus, any change in an active set influences large amount of the macrocell users but only couple femtocell users.

Both $R_{j \in A^i}^i$ and $R_{j \notin A^i}^i$ are derived from the reports on signal quality (e.g., SNR, RSS, etc) measured by the UE_i from all cells included in the N^i (see, e.g., [13]). If SNR of all cells included in the N^i is measured, signal to noise plus interference ratio (SINR) can be determined. Then, SINR is mapped to a modulation and coding scheme (MCS) according to, for example, [14]. Each MCS defines a modulation and a coding rate. Therefore, the amount of bits per resource element (RE) carried on the physical layer, denoted as b_{RE}, can be derived as the multiplication of the coding rate (cr) and amount of bits per symbol of the modulation (bps), i.e., $b_{RE} = cr \times bps$. Knowing amount of the radio resources required by the UE_i and $b_{RE,i}$ of appropriate channel between the UE_i and the C_j, the amount of the consumed resources is determined as a simple ratio of data intended to be sent by the UE_i ($d_{UE,i}$) and the b_{RE}; $R^i = d_{UE,i}/b_{RE,i}$. Difference in derivation of $R^i_{j\in A^i}$ and $R^i_{j\notin A^i}$ consists in consideration of the C_j in the interference evaluation. For $R^i_{j\in A^i}$, the signal from the C_j is not taken into account since no cell included in the A^i can transmit at the same frequencies as the serving cell. Contrary, the signal from the C_j is included in the interference for $R^i_{j\notin A^i}$.

Once inclusion of the C_j in the A^i is profitable from the point of view of the amount of consumed radio resources at the MBS, the quality of backhaul of the C_j is evaluated. The problem of packet delay due to transmission via backhauls with different quality is fixed as follows. To cope with the delay, we suggest an additional condition for inclusion of a cell into the A^i as defined by the next formula:

$$D_j \leq D_s^i \tag{2}$$

where, D_j is the delay of data delivered though C_j, and D_s^i is the maximum acceptable delay for the service exploited by the EU_i (we assume this delay can be met by all cells already included in the A^i). Note that this problem is common problem of the handover procedure. Therefore, it should be considered even in the conventional hard handover. However, the backhaul of the MBS typically provides high quality of the connection with low delay and this condition is fulfilled always.

The backhaul of the MBSs is projected to be able to serve all the data transmitted via the radio interface. It means the bottleneck does not appear on the backhaul of the MBSs. In case of the FAPs, the situation is exactly the opposite. Since the FAPs are supposed to be connected to the networks via the backhaul with limited capacity, previous conditions (1) and (2) are complemented by additional one focused on the backhaul capacity. The femtocell C_j can be potentially included in A^i only if:

$$b_{j,av} - b^{i,req} \geq 0 \tag{3}$$

where $b_{j,av}$ is the available backhaul capacity of the *j-th* FAP and $b^{i,req}$ represents the backhaul capacity requested by the UE_i. If (3) is fulfilled, the C_j is included in a temporary active set A^i_{temp}. The A^i_{temp} is composed of all cells that should be included in A^i as those meet (1), (2), and (3). If only one UE is supposed to include the C_j into the A^i, then the temporary active set can be added to the A^i, i.e., $\{A^i\} = \{A^i\} + \{A^i_{temp}\}$. However, if more UEs would like to include the C_j in their A^i, then the backhaul limit is reconsidered. The cell C_j should be added to more active sets only if the FAP will be still able to serve all UEs as expresses the following equation:

$$b_{j,av} - \sum_{i,i|j\in A^i_{temp}} b^{i,req} \geq 0 \tag{4}$$

If (4) is not fulfilled, only A^i of the selected UEs will be updated. A procedure for selection of the most appropriate UEs, whose active set should be enhanced by the C_j is proposed as follows. We define new parameter κ^i_j, which represents a ratio of the gain caused by the inclusion of the C_j into A^i to the requested backhaul capacity:

$$\kappa^i_j = \frac{R^i_{j\notin A^i} - R^i_{j\in A^i}}{b^{i,req}} \tag{5}$$

The C_j is included only to the A^i of the UEs that leads to the highest κ^i_j. For this purpose, the cells are sorted according to κ^i_j in descending order, i.e., $\kappa^n_j > \kappa^m_j$ if $n>m$.

Then the C_j is sequentially added to the A^i for $i = 1, ..., b_{max}$. The b_{max} is determined as $max(b)$; $b = (1,...,u)$ for which the following formula is still valid:

$$b_{j,av} - \sum_{i=1}^{b} b^{i,req} \geq 0 \tag{6}$$

A specific situation, when (1) and (2) are fulfilled while (3) is not can occur. In this case, a FAP can provide higher throughput even if other UEs with this FAP in the active set could suffer from the inclusion of the FAP into the A^i. Nevertheless, the drop in throughput of the UEs served by the FAP can be insignificant and the throughput of all of these UEs can be still above the one provided by the MBS. Therefore, the cell C_j is included into A^i even if not enough available backhaul is provided by the C_j. The inclusion is conditioned by fulfilling subsequent equation:

$$T^i_{j,j\in A^i} > T^i_S \tag{7}$$

where $T^{i}_{j,j\in A^{i}}$ is the throughput of UE_i if the C_j would be added to A^i and T^{i}_{S} represents the throughput experienced by the UE_i from the current serving cell. To add the C_j to the A^i, all UEs currently served by the C_j must still be experiencing higher capacity than the capacity provided by the MBS.

Description above focuses on conditions and algorithm for inclusion of a cell into an active set. The opposite case, that is, removal of a cell from the active set must be defined. In our algorithm, the C_j is deleted from the A^i if it results in a lower amount of radio resources consumed at the MBS. In other words, the C_j is removed if condition (1) is no longer met. Of course, the cell is also removed if its backhaul capacity or delay changes and either (2) or (3) becomes not fulfilled.

Selection of the serving cell is based on comparison of the signal levels measured by the UE. If the cell with the strongest signal measured by the UE_i can fully serve this particular UE_i by means of signaling, then the cell is selected as the serving.

4 Performance Evaluation of Active Set Management

The results obtained by the simulations in MATLAB are presented in this section. In, the first subsection, a set of appropriate values of α for the proposed algorithm is identified. Then, performance of the proposed algorithm is compared with competitive approaches.

4.1 Impact of α on active set management

Impact of the threshold for inclusion of the cell to the active set, α, on the active set update rate is shown in Figure 4. The active set update rate represents the average amount of changes in the active set of one user per simulation step (one second). Each inclusion or removing of a cell into the active set represents one change. As Figure 4 shows, the update rate of active set decreases with the amount of traffic offered by the UEs. This is due to the limited capacity of the backhaul of the FAPs. Once the backhaul is fully utilized, the FAP is included into other active set(s) only if it improves the throughput of the UE and ensures enough capacity even for all UEs with the FAP in current active set. Furthermore, higher value of α lowers the update rate since lower profit must be achieved at the side of the MBS to include a FAP into the active set (see (1)). Besides active set, α influences user's throughput as depicted in Figure 5. All cells, even FAPs, are able to serve high amount of users without reaching backhaul limit for low bitrate required by the UEs. Thus, no impact of α on throughput is observed for a low level of the offered traffic. However, if the offered traffic increases, high α leads to selection of only considerably profitable cells as candidates to be included in the active sets. Thus, the average throughput is slightly increasing with α. Note that we assume proportional fair sharing of the FAPs backhaul capacity among all UEs (indoor as well as outdoor) connected to it.

Based on the presented results, $\alpha > 2$ is considered as the appropriate value of gain since high throughput and low update rate of active set are generated. Thus, $\alpha = 2$ and $\alpha = 3$ are selected for comparison of the proposal and competitive schemes in the next subsection.

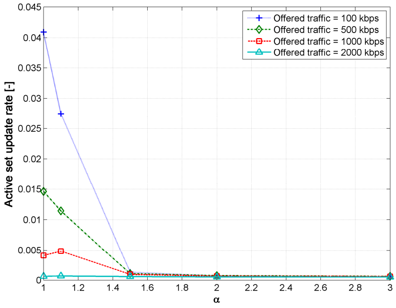


Figure 4. Impact of α on frequency of active set updates.

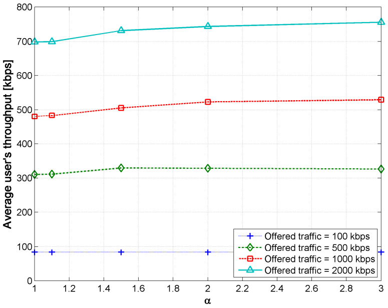


Figure 5. Impact of α on users' throughput.

4.2 Comparison of active set management approaches

The proposal is compared with two algorithms: conventional FCS active set management [15] and the capacity based FCS active set management proposed in [13].

As shown in Figure 6, the proposed active set management algorithm improves throughput of the UEs comparing to the conventional and the capacity based FCS. The gain in throughput rises with the amount of traffic offered by the UEs and it is nearly independent on α. The throughput gain introduced by the proposed algorithm is up to roughly 23%, 14%, and 37% comparing to the capacity based FCS, conventional FCS with $\Delta_{HM} = 3\ dB$ and conventional FCS with $\Delta_{HM} = 5\ dB$, respectively.

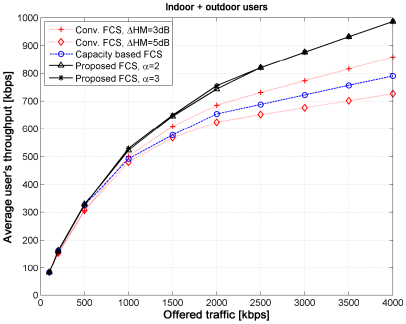


Figure 6. Average throughput of users.

Frequency of the active set updates is presented in Figure 7. Each event in the active set is linearly proportional to the management overhead. Therefore, the figure can be understood as the amount of overhead generated due to the active set management. The update rate of the proposed scheme decreases with a higher values of α and with an increase in offered throughput. Lower frequency of the active set updates for a higher α is due to a lower probability of fulfilling condition (1). At the same time, a higher offered traffic leads to less often update of the active set due to limitation of the FAP's backhaul. The proposed scheme outperforms the conventional FCS and the capacity based FCS roughly by 58% - 65% and by 20% - 43% (depending on the amount of the offered traffic), respectively, in terms of the active set update rate and consequently in terms of overhead for management of the active set comparing to both competitive scheme.

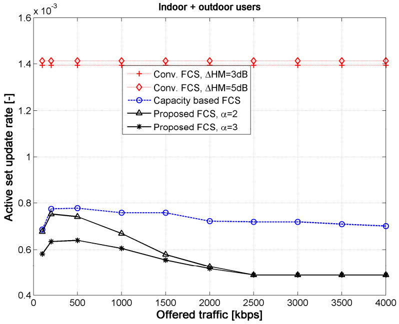
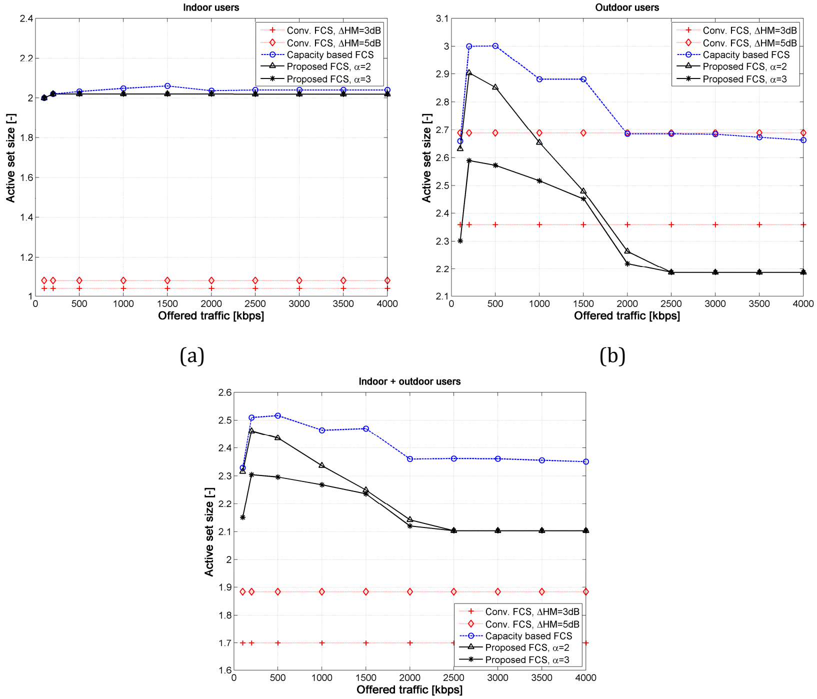


Figure 7. Average amount of changes in active set.

In Figure 8, the average size of active set per UE is depicted. For indoor UEs (Figure 8a), roughly one cell is included in the active set for the conventional FCS. This cell is typically the FAP deployed in the same house as the UE. The signals from other cells are usually attenuated due to intervening walls. Hence, these cells do not provide signal with sufficient quality to be included in the active set. For the capacity based FCS and the proposed FCS, roughly two cells are included in the active set on average. This is typically the MBS and the local FAP. Other FAPs provide weak signal (at least two walls are between the FAP and the UE) to be included in the active set.

For outdoor users (Figure 8b), the active set consists of the MBS and several closest FAPs. The exact number of the FAPs included in active set depends on offered traffic load for the capacity based FCS. In case of the proposal and the conventional FCS, the number of FAPs in active set is further influenced by α and by hysteresis level, respectively. Figure 8c shows average of both results for indoor as well as outdoor UEs weighted by the ratio of user indoor and outdoor.



(a)

(b)

(c)

Figure 8. Average amount of cells included in active set for: (a) only indoor users; (b) only outdoor users; (c) all users

5 Conclusions

To minimize negative impact of users' mobility on the overall performance of network and on QoS of users, the fast cell selection enhanced by advanced active set management is proposed. The new management is based on the comparison of the amount of radio resources consumed at the MBS if a cell is included to the UE's active set or not. In addition, also consideration of backhaul delay and capacity is considered to avoid bottleneck in backhaul in case of FAPs. The simulation results show significant gain in throughput for all users (up to roughly 37%). At the same time, the proposed algorithm reduces signaling overhead related to the active set management (up to 65%).

In the future, the algorithm can be combined with control of transmitting power of small cells to enable partial utilization of resources among neighboring cells.

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Work experiences

Since 01/2011	**CTU in Prague, FEE, Dept. of Telecommunication Engineering** Assistant professor
2008 - 2010	**CTU in Prague, FEE, Dept. of Telecommunication Engineering** Researcher
2009	**Vodafone RDC at CTU in Prague, Czech Republic** PhD student - development of testbed for wireless networks
2006 - 2007	**Sitronics R&D centre, Prague, Czech Republic** PhD student - VoIP speech quality improvement

Education

2005 – 2010	**CTU in Prague, FEE** Ph.D. in Telecommunications
1999 – 2005	**CTU in Prague, FEE** M.Sc. in Telecommunications

Internship

01-06/2013	**CEA-Leti, Wireless Telecommunications Lab** Six month research visit in Grenoble, France
04/2007	**Budapest Politechnic, FEE, Dept. of Telecommunication** One month CEEPUS internship in Budapest, Hungary

Research interests

Radio resource management in mobile networks, mobility support in wireless networks, power control, femtocells, small cells.

Academic activities

Lectures and laboratory exercises in Mobile Communication Networks.

Supervisor of two PhD and more than twenty BSc and MSc students.

Miscellaneous

Representative of CTU in Prague in 3GPP and ETSI standardization bodies.

Member of more than 15 conference committees.

Reviewer for many top journals indexed by WoS such as IEEE Transactions on Wireless Communications, IEEE Transactions on Mobile Computing, IEEE Transactions on Vehicular Technology, IEEE Communications Letters, IEEE Wireless Communications, etc

Publication activities

More than fifty papers published in journals and international conferences.

Three published book chapters.

Contributions to 3GPP and IEEE 802.16m.

Selected papers:

[1] Z. Becvar, P. Mach, M. Vondra, "Self-optimizing Neighbor Cell List with Dynamic Threshold for Handover Purposes in Networks with Small Cells," *Wireless Communications and Mobile Computing*, early view, 2013.

[2] Z. Becvar, P. Roux, P. Mach, "Fast cell selection with efficient active set management in OFDMA networks with femtocells," *EURASIP Journal on Wireless Communications and Networking*, 2012:292.

[3] Z. Becvar, P. Mach, B. Simak, "Improvement of Handover Prediction in Mobile WiMAX by Using Two Thresholds," *Computer Networks*, Elsevier, Vol. 55 No. 16, 2011.

Research projects

09/2012 – 02/2015	**Project TROPIC** (www.ict-tropic.eu) FP7 project (No. ICT-318784) founded by European Commission WP leader (Scenarios, Architecture, and Market Analysis), member of coordination and technical project committees.
01/2012 – 12/2014	**Prediction Algorithms for Efficient Mobility Management in Wireless Networks** Research project no. P102/12/P613 funded by Czech Science Foundation (GACR)
01/2010 – 12/2011	**Project FREEDOM** (www.ict-freedom.eu) FP7 project (No. ICT-248891) founded by European Commission WP leader (Control procedures for RRM), member of coordination and technical project committees.
12/2008 – 12/2009	**Project WiMATE** (http://www.rdc.cz/en/projects/WiMate) Vodafone RDC project.
01/2008 – 12/ 2009	**Project ROCKET** (www.ict-rocket.eu) FP7 project (No. ICT-215282) founded by European Commission.
09/2007 – 12/2007	**Feasibility study of national radio access network based on WiMAX** Project founded by Ministry of the Interior of the Czech Republic.
01/2006 – 12/2007	**Project FIREWORKS** (http://fireworks.intranet.gr) FP6 project (No. IST-027675) founded by European Commission.
01/2006 – 12/2007	**Improvement of VoIP speech quality** Project founded by Sitronics R&D centre, Prague.

Language skills

Czech	Native
English	Fluent
French	Basic
German	Basic