Minimizing Packet Loss in High-mobility Radio-over-fiber Networks

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***Abstract*—The paper analyzes two handoff algorithms, i.e., the traditional handoff (THO) and the moving extended cell (MEC), respectively, both used in Radio-over-Fiber (RoF) networks at 60 GHz. The mathematical analysis and the corresponding simulation study are also presented, showing that MEC is a strong candidate handoff algorithm for packet loss minimization in high-mobility RoF networks at 60 GHz.**

Keywords—Radio-over-Fiber networks; handoff algorithms; high-mobility end-users; performance evaluation.

I. INTRODUCTION

End-users already produce or, at least, use large amounts of online data. Triple-play network services, HDTV, social networking and rich media file sharing are just few examples of bandwidth voracious services in our everyday life. Several solutions have been suggested, by using VDSL2, FTTx or xPONs technologies, to form hot-spots in conjunction with IEEE 802.11n, 60GHz and other wireless technologies, for either fixed end users or end users with limited mobility.

Another communication paradigm that attracts high attention recently is the use of Radio-over-Fiber (RoF) network architectures at 60GHz for delivering broadband wireless access services which combine the strengths of fixed optical and mobile millimeter-waveband technologies ([1], [2]). A strong advantage of the aforementioned architectures is that their basis are the low cost and complexity Remote Antenna Units (RAUs) located in remote sites and supporting the communication with the mobile end users, in conjunction with an intelligent and centralized unit, named Central Office (CO), which aggregates the entire network functionality and it is responsible to handle and execute complex signal processing and render passively the communication with RAUs, as depicted in Fig. 1. Several studies have adopt the RoF@60GHz approach ([2]-[4]), while initial performance results prove their effectiveness on supporting Gbps data rates in both indoor ([5], [6]) and outdoor ([7], [8]) environments.

In this paper we focus on the latter, i.e., on RoF networks at 60 GHz in outdoor environments, and specifically on presenting, analyzing and evaluating the performance of two handoff algorithms used in such networks allowing at the same time high end-user mobility. The rest of this paper is organized as follows: Section II describes the traditional handoff algorithm (THO) and the moving extended cell (MEC), respectively. Section III presents the mathematical analysis regarding packet loss by applying both the aforementioned handoff algorithms. Section IV describes the simulation testbed and provides the required details regarding the corresponding simulation scenarios used to verify the mathematical analysis presented in the previous section. The results are discussed in Section V and the paper concludes in Section VI.

II. HANDOFF ALGORITHMS IN RADIO-OVER-FIBER NETWORKS

Several handoff algorithms for RoF networks at 60 GHz have been proposed in the literature ([9], [10]). In this paper we present the most realistic two of them, i.e., THO and MEC, respectively.

A. *The Traditional Handoff Algorithm (THO)*

Handoff is the required process in wireless mobile cellular networks allowing end users to move from one network cell to another transparently to the network without loss or interruption of the end-user service. A thorough survey on handoff algorithms regarding several wireless mobile cellular networks, including GSM, UMTS, WLAN, LTE, Mobile WiMAX as well as 60 GHz based systems can be found in [10].

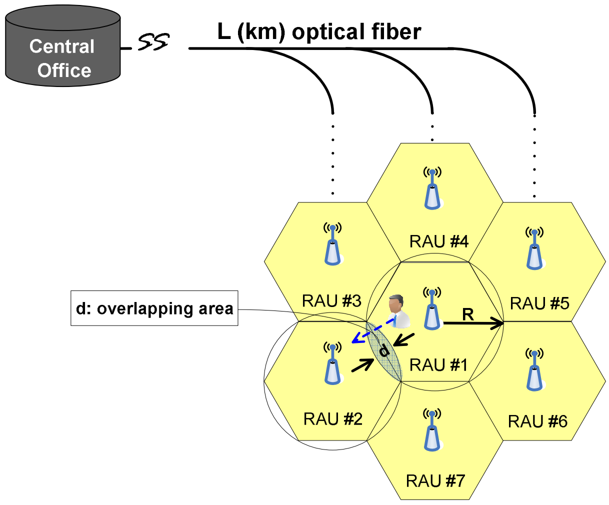

Fig. 1. The traditional handoff algorithm (THO).

But, RoF networks at 60 GHz have to overcome several innate limitations of the 60 GHz frequency band, in order to ensure a seamless mobile communication environment ([9], [10]). The strong air-propagation losses of the 60 GHz signals restrict cell radii to a few tens of meters yielding inevitably to picocellular configurations with small overlapping areas between neighboring cells. In outdoor environments, the radius (*R*) of a picocell in 60 GHz RoF networks fluctuates between

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15-20 meters, which results to an overlapping area (*d*) of 4-5 meters in the best case, as depicted in Fig. 1. If we assume that the mobile end-user moves from RAU#1 towards RAU#2, the handoff process will initiate when the beacon signal of RAU#2 will be received by the end user. It is obvious that the end-user can receive the beacon signal of RAU#2 only if he/she is in the range of RAU#2. In this case, the end user will then respond with an ACK signal to RAU#2 announcing its presence and initiating the handoff process. In other words, this means that, in order to achieve transparent and seamless connectivity for the end-user, the afore-mentioned procedure has to be initialized and also be completed, as far as the mobile end-user is still in the overlapping area between the neighboring cells. Thus, only a small time window is available for successfully completing a handoff process when a mobile end-user crosses the cell boundaries and moves to the neighboring cell, implying that only low moving speeds can be accommodated without losing connection [7]. In indoor environments, this time window is even further reduced, since the additional attenuation by the walls and furniture lead to the confinement of the radio cells typically to a single room, shaping directional and even narrower overlap areas only around the doors and windows [6]. The situation becomes even trickier due to corner effect phenomena, where a sharp turn movement of the mobile end user from the one room to another can cause a sudden loss of the line-of-sight with the present RAU, impeding the completion or even the initiation of a handoff.

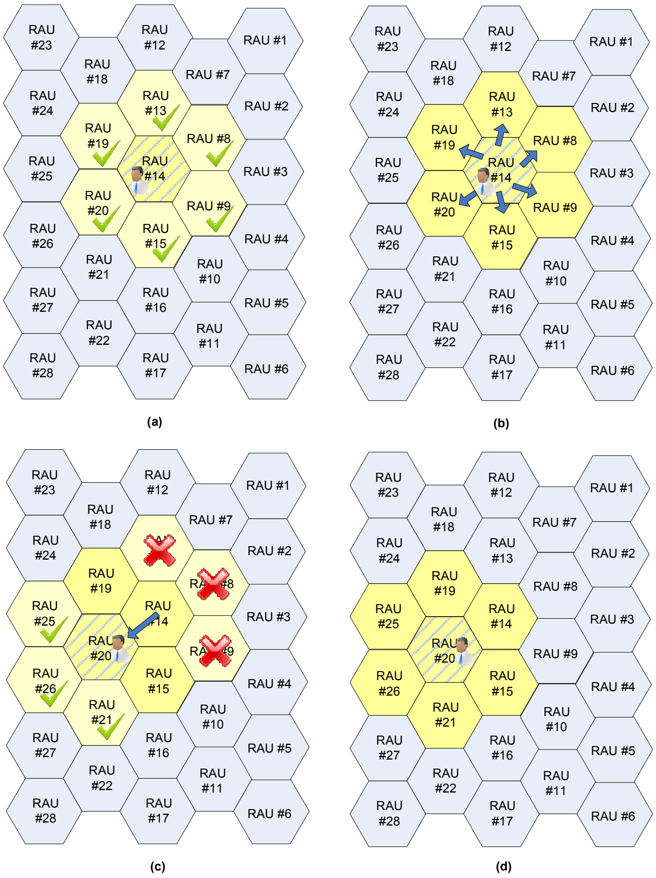
Last, but not least, the propagation delay contributed by the corresponding optical length (*L*) cannot be ignored, even if good performance has been observed in both uplink and downlink for optical length over 25 km [11]. In this case, the optical propagation delay can be even larger than the air-propagation delay and can possibly affect the handoff process.

B. *The Moving Extended Cell Handoff Algorithm (MEC)*

In indoor environments, the concept of Extended Cell (EC) structures, which can be characterized as a static clustering of neighboring cells, is an efficient technique used to increase the overlapping areas between neighboring cells and accommodate corner effect phenomena [6]. Inspired by EC concept, MEC handoff algorithm has been proposed for both indoor and outdoor environments [7].

A schematic representation of MEC is depicted in Fig. 2. The Extended Cell structure transmits the same user-specific data content over the same radio frequency and consists of the current cell serving the mobile end-user (RAU#14 in Fig. 2a) and the six surrounding cells ensuring connectivity for all possible directions when the user leaves his/her current cell (Fig. 2b). However in the case of user's entry in a new cell, the Extended Cell is dynamically recomposed so as to form a new user-centric seven-cell group following the user's motion. This is clearly illustrated in Fig. 2c, where the mobile end-user leaves RAU#14 and moves into RAU#20. The dynamic reconfiguration of the Extended Cell takes place once the mobile end-user receives the beacon signal of RAU#20. Then, the initial Extended Cell is reformed so that RAU#20 becomes the new central cell. The capacity of RAUs #8, #9 and #13 is released, while the corresponding capacity of RAUs #21, #25 and #26 is reserved (Fig. 2c). The result is a new Extended Cell formation that consists of RAUs #14, #15, #19, #20, #21, #25 and #26 (Fig. 2d). To this end, the Extended Cell is always formed around user's current location and it is adaptively restructured when the user enters a new cell.

As a result, the end-user is continuously surrounded by cells that transmit the same data content, offering in this way seamless communication conditions for all possible subsequent movements. Co-channel interference problems in the overlapping areas between neighboring cells could be overcome by implementing the medium access control scheme proposed in [12].



(a) (b)

(c) (d)

Fig. 2. The Moving Extended Cell (MEC) handoff algorithm.

III. MATHEMATICAL ANALYSIS

This section presents the mathematical analysis used in order to calculate the packet losses observed in end-users with high-mobility in a RoF at 60GHz environment using either THO or MEC handoff algorithm, respectively. We assume a network of N successive cells placed on a straight line, as depicted in Fig. 3. R is the cell radius of each cell, while d is the distance of the overlapping area between successive cells. T_b is the period of the beacon packets. The leftmost edge of the first cell is assumed to have distance $D = 0$. We assume that a user starts at $t = 0$ from point D_{init} (which is randomly selected within the interval $[0,2R\text{-}d]$) and moves with constant velocity v. We also assume that the first beacon packet is transmitted at $t = 0$.

The interval of the overlapping area of each pair of neighboring cells is given by the interval:

$$[k(2R-d), k(2R-d)+d], \quad k=1,2,\ldots,N-1$$

where k is the number of successive cell. E.g, for $k = 1$, the overlapping area between the first and second cell is located within *[2R-d, 2R]*.

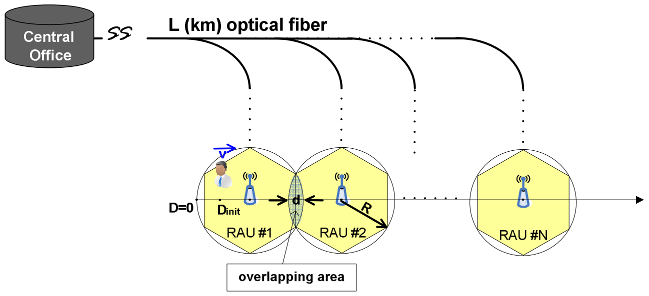


Fig. 3. Experimental topology.

The total number of beacons (M) that have already been transmitted when the user receives a beacon for the first time after passing the left edge of the overlapping area of the k^{th} cell is: $M = \left\lceil \frac{k(2R-d)-D_{init}}{vT_b} \right\rceil, \quad k=1,2,\ldots,N-1$

Therefore, the distance between the right edge of the k^{th} overlapping area and the position in which the user will receive the beacon packet is expressed by:

$$MvT_b + D_{init} - k(2R-d) - d$$

In addition, when the user receives the beacon packet, a total time of T_{HO} is required, in order the reconfiguration process to be completed [7]. T_{HO} is expressed by:

$T_{HO} = T_{update} + \frac{L}{c/n}$, where T_{update} corresponds to the propagation delay of the ACK signal sent by the terminal after receiving the beacon frame, in order to travel through the new RAU and inform the CO about the reconfiguration request and $\frac{L}{c/n}$ is the time required by the data packets routed by the CO to the new $(k+1)^{th}$ RAU for propagating through the respective fiber link. Thus, T_{update} includes both the propagation delay of the wireless link as well as the delay through the fiber of length L. Therefore T_{update} is expressed by:

$T_{update} = \frac{\left|k'(2R-d)+R-MvT_b-D_{init}\right|}{c} + \frac{L}{c/n}$, where $k' = \left\lfloor \frac{MvT_b + D_{init}}{(2R-d)} \right\rfloor$. Therefore, the distance between the right edge of the k^{th} overlapping area and the position in which the user will receive the first data packet is expressed by: $MvT_b + D_{init} + T_{HO} - k(2R-d) - d$.

If the user receives the first data packet into the k^{th} overlapping area, the aforementioned quantity will be negative, while in the case that user will receive the first data packet after passing the k^{th} overlapping area the quantity will be positive. Therefore, the distance in which the user terminal is possible to lose connectivity with the $(k+1)^{th}$ cell after passing the right edge of the k^{th} overlapping area is expressed by:

$$D_{PNC} = \max\left(MvT_b + D_{init} + T_{HO} - k(2R-d) - d, 0\right)$$

In addition, if the beacon signal is received in the next, i.e., the $(k+1)^{th}$, overlapping area or after the next overlapping area, then this term must be decreased in order not to be evaluated more than once in the final aggregation. Therefore, the final distance that the end-user loses connectivity within the cell is expressed by:

$$D_{NC} = \begin{cases} \max\begin{pmatrix} MvT_b + D_{init} + T_{HO} \\ -k(2R-d)-d,\ 0 \end{pmatrix} & ,if \quad MvT_b + D_{init} + T_{HO} \leq (k+1)(2R-d) \\ 2R-d & ,otherwise \end{cases}$$

We assume that the video server generates constant bit rate (CBR) video flow with a rate of P frames per seconds, while each frame is encapsulated in an application layer packet. The video transmission starts at $t=0$ and continues as far as the user has not reached the N^{th} cell. The number of packets (PL) in application layer that will be lost, because of the aforementioned temporal loss of connectivity, is expressed by:

$$PL = \left\lceil \frac{D_{NC}P}{v} \right\rceil$$

In this expression we assume that not contention is emerge during the packet transmission, while the queue size of the cell is zero. Thus, the total number of lost packets for all N cells is: $PL_{total} = \sum_{k=1}^{N} \left\lceil \frac{D_{NC}P}{v} \right\rceil$, while the percentage of lost packets against all transmitted packets is expressed by:

$$PL_{total,\%} = \frac{\sum_{k=1}^{N} \left\lceil \frac{D_{NC}P}{v} \right\rceil}{\left\lfloor \frac{N(2R-d)+d-D_{init}}{v} P \right\rfloor} \times 100$$

In the case of MEC handoff algorithm, the only difference in all the above is the distance in which the user terminal loses connectivity with the cell, which is expressed by:

$$D_{NC,MEC} = \begin{cases} \max\begin{pmatrix} MvT_b + D_{init} + T_{HO} \\ -(k+1)(2R-d)-d,\ 0 \end{pmatrix} & ,if\ MvT_b + D_{init} + T_{HO} \leq (k+2)(2R-d) \\ 2R-d & ,otherwise \end{cases}$$

IV. SIMULATION SCENARIOS

In order to verify and evaluate the aforementioned mathematical analysis regarding packet loss in both THO and MEC handoff algorithms in RoF networks at 60 GHz, we have implemented a set of simulation scenarios based on the experimental topology of Fig. 3, by using OPNET simulation environment.

Each simulation scenario realizes a 60GHz RoF network topology comprised of $N=300$ successive cells placed on a straight line (Fig. 3). The user moves with a constant velocity (v) starting from $D_{init} \in [0,2R-d]$ of the first cell and moving through the 300 cells towards the right edge of the last one, following the line that intersects the centers of all cells. A Video Server generating 200 Mbps CBR video traffic flows (according the characteristics described in Section III) injected into the RoF network and a CO infrastructure, in which the RAUs and the Video Server is connected via fiber links (all of length $L=6km$) are also used in all simulation scenarios. The traffic flow is one-directional following the downstream direction, i.e., from the video server to the mobile terminal. The frame rate is set to 50p (frames per seconds), which is a typical rate for HDTV services, while the frame size is set to 500 Kbytes. The cell radius is set to $R=20m$ and the successive cells are appropriate located to form overlapping areas of $d=5m$. The period of the beacon frames equals to $T_b=1sec$, while, in order to avoid synchronization issues, the time moment that the RAUs starts sending beacon signals is randomly chosen within the interval [0.0, 1.0] sec. All wireless transmissions are realized on a 2.16 GHz band, (out of the four 2.16 GHz frequency bands that ECMA Standard [13] defines in total, each one spanning from 57.24 – 59.4 GHz, 59.4 – 61.56 GHz, 61.56 – 63.72 GHz and 63.72 – 65.88 GHz, respectively). All radio transmitters are configured to transmit at 20mW, all radio receivers are configured to reception with a -95dBm threshold, while the 16QAM modulation is selected for all radio transmissions. Regarding the MAC layer, the IEEE 802.11 RTS/CTS was used and reconfigured to enable efficient transmission in 60 GHz. Regarding its timing parameters, the pMIFS is selected to 888 ns, while the pSIFS is selected to 2666 ns [13].

The scenarios are repeated for both THO and MEC handoff algorithm for five different end-user velocities, i.e., 100, 150, 180, 200 and 220 km/h, respectively, which are typical trains' velocities values. The main objective of the executed simulation scenarios is on one hand to compare the two aforementioned handoff algorithms in terms of packet losses in application layer for different end-user velocities and, on the other hand, to verify the correctness of the mathematical analysis presented in Section III. The corresponding results are presented in the following section.

V. RESULTS AND DISCUSSION

We first analyze the real-time monitoring of mobile terminal's handoffs throughout time, in order to have a first indication regarding THO and MEC handoff algorithms' comparison. Fig. 4 depicts the real-time monitoring of the traffic received from the high-speed mobile end-user, when THO or MEC is used, respectively. In this scenario the velocity of the mobile end-user is set to 220 km/h, assuming that end-users are located in either high-speed trains or cars in highways, while the bit rate of the traffic load is set to 200 Mbps. In order to render Fig. 4 as readable as possible, without loss of generality we present a time window of the first 6.5 seconds of the experiment (i.e. the required time for the vehicle to go through the first 10 RAUs of the system), since a similar pattern is repeated for the rest of the experiment.

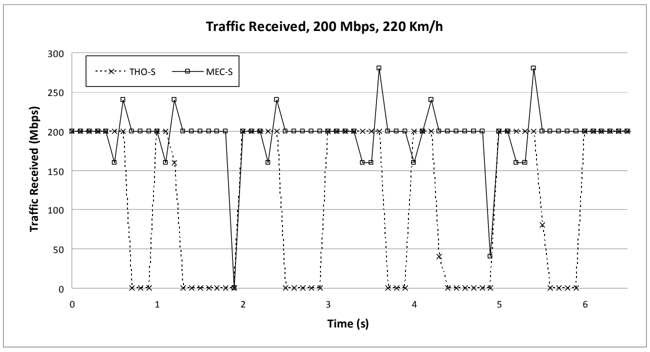


Fig. 4. Real-time received traffic (traffic load: 200Mbps, end-user velocity: 220km/h).

In Fig. 4 we can see that THO is inadequate for high mobility, since the mobile end-user is totally disconnected 6 times, while large periods of disconnections are observed. Actually, the disconnection phenomenon is observed in 6 out of the 9 (in total) overlapping areas between the first 10 RAUs, which means that only 3 out of 9 handoff processes are successful. This happens because of the limited overlapping area between the neighboring cells in conjunction with the high speed of the mobile end-user. Remind that the overlapping area is, in the best case, about 5m, so the available time for a successful handoff process is something more than 80ms (i.e., 5m/220km/h), in the best case, too. The best case occurs if the mobile end-user receives the beacon signal of the next RAU in the leftmost point of the overlapping area between the adjacent cells.

On the other hand, MEC seems to be only slightly affected and short inconsistencies, which cannot be treated by higher traffic rates of the new cell, are emerged in only two (out of nine) overlapping areas, even for such a high velocity. In case of MEC, there are also small periods, in which the amount of traffic received is observed to be higher than the flow rate (i.e., 200Mbps). This is explained by the fact that after a successful handoff procedure the new serving RAU continues to deliver packets to mobile terminal that are not delivered by the previous cell due to handoff delay.

In order to verify the mathematical analysis presented in Section III, Fig. 5 depicts the average packet loss against different values of end-user velocity for THO and MEC handoff algorithms, respectively, while at the same time it depicts both the average packet loss values coming by the mathematical analysis (for end-user velocities in [100 km/h, 220km/h] with a step of 1km/h) as well as the corresponding values coming by the simulation executions (for end user velocities 100, 150, 180, 200 and 220 km/h, respectively).

The first observation is that the theoretical model seems to be in accordance with the simulations results, since only slight deviations are presented in average packet loss values between the mathematical analysis and the simulations results for either THO or MEC handoff algorithm. The better theoretical performance observed in THO for 128 km/h (i.e., 35,5m/sec) against other, even higher, values of velocity is not accidental, but it is related to our experimental topology. Remind that $D_{init} \in [0,2R-d]$, while $R=10m$ and $d=5m$, thus the distance between the leftmost edge of a RAU (e.g., RAU_k) and the rightmost edge of the following RAU (e.g., RAU_{k+1}) is 35m. So, it is quite easy to observe that almost every second the end-user will be in the overlapping area between adjacent RAUs, with a probability of 33% (roughly estimated if $D_{init} \in [R, 2R-d]$, since $R=10m$ and $d=5m$). Thus, if the end-user receives the beacon signal in the first overlapping area between RAU_2 and RAU_3, he/she will receive most of the beacon signals in the overlapping areas between RAU_k and RAU_{k+1} and, in this case, the probability for a successful handoff is increased, which leads to packet loss reduction.

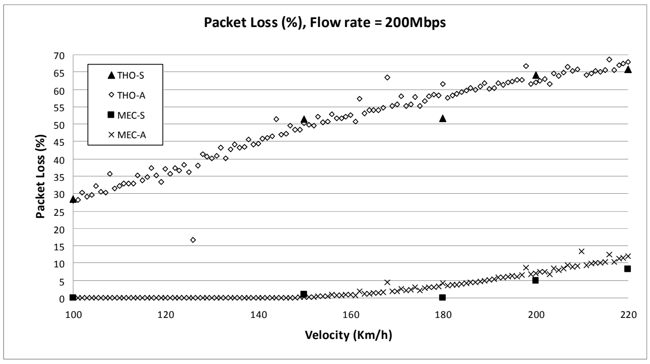


Fig. 5. Packet loss vs. user velocity (analysis vs. simulations).

Regarding the two handoff algorithms, Fig. 5 shows also that THO could not be applied even for end-users moving with medium speed (e.g., 100 km/h), since it performs more than 28% packet loss. Furthermore, the value of packet loss increases dramatically as the velocity increases, reaching to very high values and up to 65% for 220 km/h. Thus, it is clear that THO handoff algorithm is not suitable in RoF networks at 60 GHz, because of the unacceptably high values of packet losses both in medium and high velocities. On the other hand, the packet loss in MEC case is decent, since it is less than 0.2% for velocities up to 150 km/h, while for higher velocities the packet loss rate is kept below 8%. The observed negligible value of packet loss for MEC handoff algorithm in simulations (for end-user velocity equals to 180km/h=50m/sec) is due to similar experimental topology reasons explained above. Therefore, MEC is suitable for packet loss sensitive applications for medium or high velocities and for higher velocities could be applied only to applications tolerant to medium packet loss rates.

VI. CONCLUSION

We presented and analyzed the packet loss models for THO and MEC handoff algorithms, respectively, used in Radio-over-Fiber (RoF) networks at 60 GHz. We verified the mathematical analysis by a set of simulation scenarios and we evaluated their packet loss performance. The results verified that THO fails to accommodate fast moving mobile terminals because of prohibitive values of packet losses, while MEC exhibits negligible or reasonable packet losses for low/medium and high speeds, respectively, rendering it a strong candidate handoff algorithm for packet loss minimization in high-mobility RoF networks at 60 GHz.

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