Packet Loss Optimization by applying Efficient Handoff Algorithms in High-mobility Radio-over-fiber Networks: A Mathematical Analysis

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ABSTRACT

The paper analyzes three handoff algorithms which are used in Radio-over-Fiber (RoF) networks at 60 GHz. Specifically, the Virtual Cellular Zone (VCZ) and the Moving Extended Cell (MEC), are presented, against the Traditional Handoff (THO) algorithm, which is the simplest proposed solution in such networks. The mathematical analysis regarding packet losses for all three handoff algorithms is presented and it is verified by the corresponding simulation study. The result is that both VCZ and, especially, MEC could be two strong candidate handoff algorithms for packet loss minimization in high-mobility RoF networks at 60 GHz.

Keywords

Radio-over-Fiber networks, handoff algorithms, moving extended cell, high-mobility end-users, performance evaluation.

1. 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 VDSL, 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 Figure 1. Several studies have adopt the RoF at 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. First of all, we present in detail the rationale of the most common handoff algorithm used in RoF networks at 60 GHz, i.e., the Traditional Handoff (THO) algorithm, as well as two dominant handoff algorithms, which provide high flexibility to the mobility of the end-user in such networks, namely the Virtual Cellular Zone (VCZ) and the Moving Extended Cell (MEC), respectively. The main contribution of the paper is the introduction of a mathematical analysis, which calculates the packet losses observed in end-users with high-mobility in a RoF at 60GHz environment using either THO, VCZ or MEC handoff algorithm, respectively. The packet loss mathematical models for all three algorithms are verified through simulation scenarios, thus, these algorithms can be safely applied in high-mobility RoF networks, in order to optimize (minimize) the corresponding packet losses to the end users.

The rest of this paper is organized as follows: Section 2 describes the THO, as well as the VCZ and the MEC handoff algorithm, respectively. Section 3 presents the mathematical analysis regarding packet loss by applying all three aforementioned handoff algorithms in RoF at 60 GHz networks with high mobility users. Section 4 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 5 and the paper concludes in Section 6.

2. 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 three of the dominant ones, i.e., THO, VCZ and MEC, respectively.

2.1 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].

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 15-20 meters, which results to an overlapping area (d) of 4-5 meters in the best case, as depicted in Figure 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.

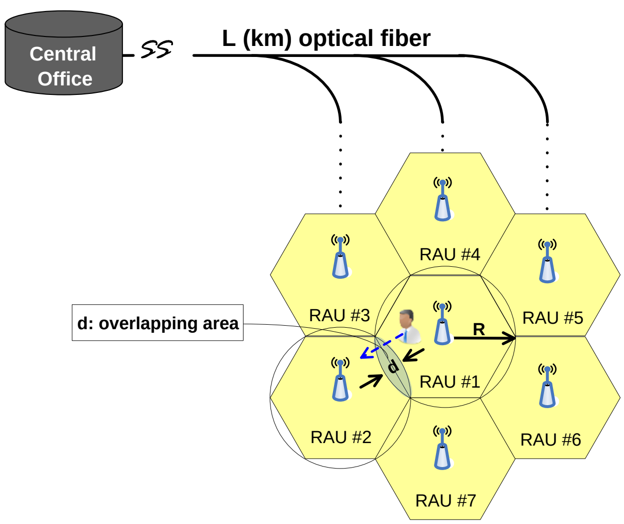

Figure 1. The traditional handoff algorithm (THO)

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.

2.2 The Virtual Cellular Zone Handoff Algorithm (VCZ)

The Virtual Cellular Zone (VCZ) handoff algorithm has been proposed for outdoor vehicular 60GHz RoF networks [8]. Assuming that the Central Office manages N RAUs, the latter are divided into S groups ($1 \leq S \leq N$) where a set of RAUs in the same group must be contiguously deployed. The area covered by each group is called "Virtual Cellular Zone (VCZ)". A schematic representation is depicted in Figure 2, in which 33 RAUs have been divided into 5 VCZs. VCZ-1 consists of RAUs #1, #2, #7 and #12, VCZ-2 consists of RAUs #3, #4, #8, #9, #13, #14, #18 and #19 and so on.

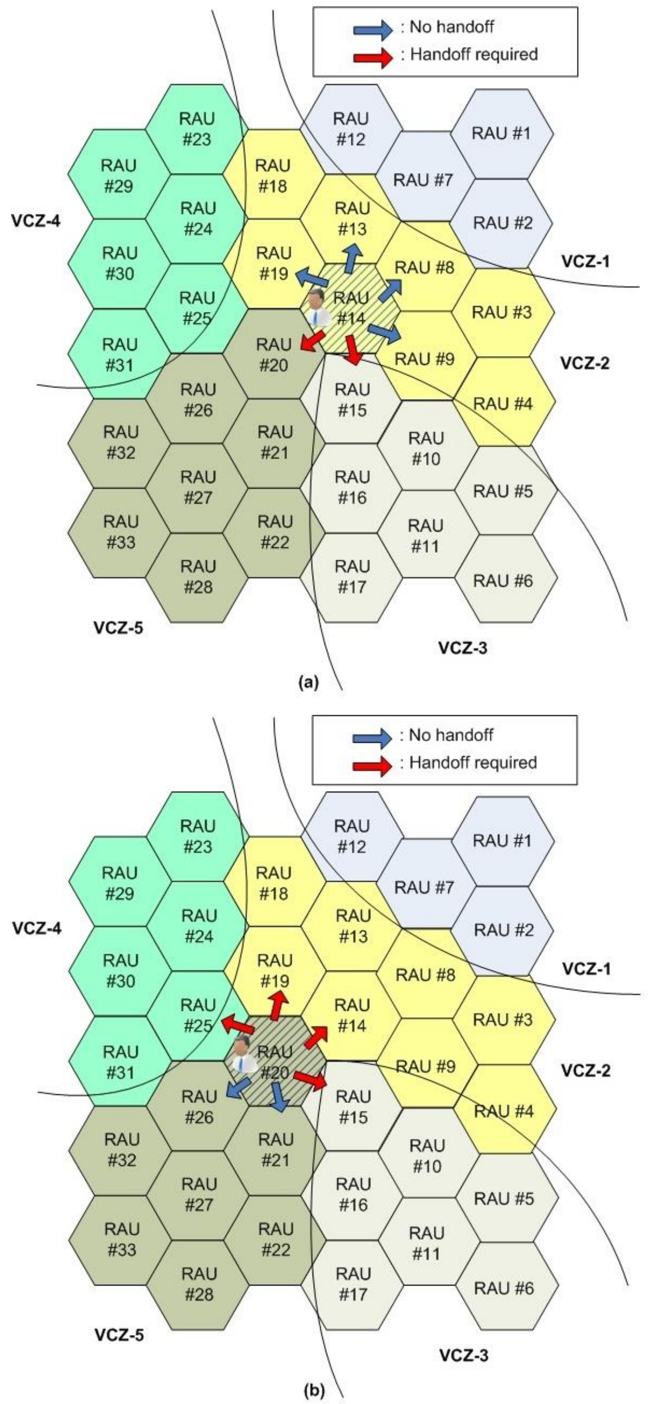

Figure 2. The Virtual Cellular Zone handoff algorithm (VCZ)

TDMA is utilized in the system and divides each frequency channel in fixed time frames, while each fixed time frame consists of X timeslots. The X timeslots of each fixed time frame of the same frequency channel are allocated in each VCZ.

Thus, the mobile end-user does not change frequency channels as far as he/she moves within the VCZ (e.g. if he/she is in RAU#14 that belongs to VCZ-2 and moves following the "blue arrows" of Figure 2a, i.e., towards RAU #9, #8, #13 or #19, which all belong to VCZ-2, too). Frequency channel change needs to take place only if the mobile end-user moves enters to a new VCZ (e.g. if he/she moves from VCZ-2 towards VCZ-5, e.g., from RAU#14 to RAU#15 or RAU#20, in Figure 2a). Neighboring VCZs do not use the same frequency channel to avoid co-channel interference, while the avoidance of co-channel interference in the overlapping areas between cells within the same VCZ is assured either by implementing the medium access control scheme proposed in [12]-[14] or by using both TDMA/CDMA multiplexing for each frequency channel [15].

If the user is free to move randomly, the possibility of whether frequency change is required (or not) depends only on the initial VCZs' deployment and on his/her current cell. For example, if the user is currently in RAU #14 the possibility of a required handoff is 2/6 (Figure 2a), while if he/she is in RAU#20 the corresponding possibility is 4/6 (Figure 2b). This is one of the main disadvantages of this algorithm, which however is mitigated if the end-user movement is deterministic, e.g., trains in railways or cars in highways.

2.3 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]. Based on a futuristic idea that proposes RAUs moving physically with the railway or across the highway [16], the Moving Cell (MC) handoff algorithm has been proposed for outdoor environments in [17]. Inspired by the combination of EC and MC concepts, MEC handoff algorithm has been proposed for both indoor and outdoor environments [7].

A schematic representation of MEC is depicted in Figure 3. 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 Figure 3a) and the six surrounding cells ensuring connectivity for all possible directions when the user leaves his/her current cell (Figure 3b). 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 Figure 3c, 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 (Figure 3c). The result is a new Extended Cell formation that consists of RAUs #14, #15, #19, #20, #21, #25 and #26 (Figure 3d). 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 [13].

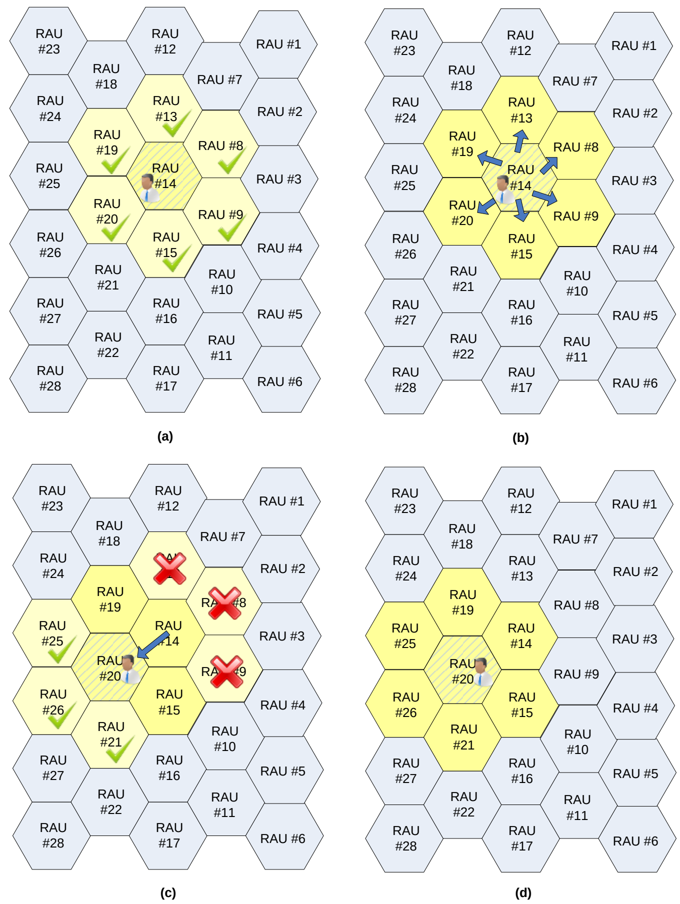

Figure 3. The Moving Extended Cell handoff algorithm (MEC).

3. 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, VCZ or MEC handoff algorithm, respectively. We assume a network of N successive cells placed on a straight line, as depicted in Figure 4. 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, $2R$-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 described in eq. (1).

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

where k is the number of successive cell. For example, for $k = 1$, the overlapping area between the first and second cell is located within $[2R\text{-}d, 2R]$.

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 given by eq. (2).

$$M = \left\lceil \frac{k(2R-d)-D_{init}}{vT_b} \right\rceil, \quad k = 1,2,\ldots,N-1 \tag{2}$$

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 the following formula.

$$MvT_b + D_{init} - k(2R-d) - d \tag{3}$$

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 eq. (4).

$$T_{HO} = T_{update} + \frac{L}{c/n} \tag{4}$$

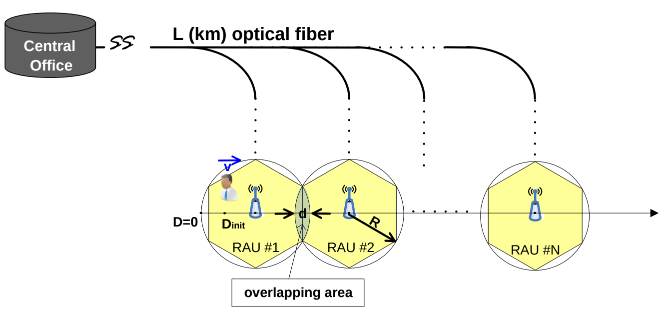

Figure 4. Experimental topology

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 eq. (5), while k' is provided by eq. (6), respectively.

$$T_{update} = \frac{\left|k'(2R-d)+R-MvT_b-D_{init}\right|}{c} + \frac{L}{c/n} \tag{5}$$

$$k' = \left\lfloor \frac{MvT_b + D_{init}}{(2R-d)} \right\rfloor \tag{6}$$

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 the formula in eq. (7).

$$MvT_b + D_{init} + T_{HO} - k(2R-d) - d \tag{7}$$

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 eq. (8).

$$D_{PNC} = \max\left(MvT_b + D_{init} + T_{HO} - k(2R-d) - d, 0\right) \tag{8}$$

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 eq. (9).

$$D_{NC} = \begin{cases} \max\begin{pmatrix} MvT_b + D_{init} + T_{HO} \\ -k(2R-d)-d, 0 \end{pmatrix} & \text{, if } MvT_b + D_{init} + T_{HO} \le (k+1)(2R-d) \\ 2R-d & \text{, otherwise} \end{cases} \tag{9}$$

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 given by eq. (10):

$$PL = \left\lceil \frac{D_{NC}P}{v} \right\rceil \tag{10}$$

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 expressed by eq. (11), while the percentage of lost packets against all transmitted packets is expressed by eq. (12), respectively.

$$PL_{total} = \sum_{k=1}^{N} \left\lceil \frac{D_{NC}P}{v} \right\rceil \tag{11}$$

$$PL_{total,\%} = \frac{\sum_{k=1}^{N} \left\lceil \frac{D_{NC}P}{v} \right\rceil}{\left\lfloor \frac{N(2R-d)+d-D_{init}}{v} P \right\rfloor} \times 100 \tag{12}$$

In the case of VCZ handoff algorithm, we assume that all the virtual cells consist of Z cells. Then, the S parameter describes the number of cells that are in front of the current overlapping area and they are transmitting the same data with the previous cell and it is expressed by eq. (13).

$$S = Z - (k \bmod Z) - 1 \tag{13}$$

Thus, in the VCZ case, the distance that the user terminal loses connectivity with the cell is expressed by eq. (14):

$$D_{NC,VCZ} = \begin{cases} \max\begin{pmatrix} MvT_b + D_{init} + T_{HO} \\ -(k+S)(2R-d) - d, 0 \end{pmatrix} & \text{, if } MvT_b + D_{init} + T_{HO} \leq (k+S+1)(2R-d) \\ 2R-d & \text{, otherwise} \end{cases} \quad (14)$$

Finally, in the case of MEC handoff algorithm, the only difference by the THO case is the distance in which the user terminal loses connectivity with the cell, which is expressed by eq. (15).

$$D_{NC,MEC} = \begin{cases} \max\begin{pmatrix} MvT_b + D_{init} + T_{HO} \\ -(k+1)(2R-d) - d, 0 \end{pmatrix} & \text{, if } MvT_b + D_{init} + T_{HO} \leq (k+2)(2R-d) \\ 2R-d & \text{, otherwise} \end{cases} \quad (15)$$

4. SIMULATION TESTBED

In order to verify and evaluate the aforementioned mathematical analysis regarding packet loss in THO, VCZ and MEC handoff algorithms in RoF networks at 60 GHz, we have implemented a set of simulation scenarios based on the experimental topology of Figure 4, by using OPNET simulation environment [18].

Each simulation scenario realizes a 60GHz RoF network topology comprised of N=300 successive cells placed on a straight line (Figure 4). The user moves with a constant velocity (v) starting from $D_{init} \in [0, 2R\text{-}d]$ 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 3) 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 [19] 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 [19].

The scenarios are repeated for THO, VCZ 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, while in VCZ scenarios, all Virtual Cellular Zones consist of $Z=3$ cells. The main objective of the executed simulation scenarios is on one hand to compare the three 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 3. The corresponding results are presented in the following section.

5. 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, VCZ and MEC handoff algorithms' comparison. Figure 5 depicts the real-time monitoring of the traffic received from the high-speed mobile end-user, when THO, VCZ 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 Figure 5 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.

In Figure 5 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.

In the same time window, VCZ presents fewer disconnection times (specifically three) and therefore higher rate of successful handoff processes. This is because of the algorithm's nature, since the same data is transmitted into a group of RAUs forming the Virtual Cellular Zone explained in Section 2.2. Therefore an unsuccessful handoff process is more probable when the mobile terminals move between two different zones. In this case, as the virtual cellular zone consists of Z=3 cells, the probability of an unsuccessful handoff process is higher every 3 cells. The rationale is clearly observed in Figure 5, in which unsuccessful handoff processes are observed around 2s, 4s and 6s, i.e., the times that mobile terminal is moving between different Virtual Cellular Zones. Furthermore, VCZ presents shorter periods of disconnection against THO and this can be explained by the fact that – because of the high user velocity – in case of THO there is always a probability for a terminal to lose connectivity even between two consecutive RAUs. In this case the period of disconnection is very high (about 2 secs). On the contrary, in case of VCZ because of the Virtual Cellular Zone formulation the same probability equals zero and therefore the periods of disconnection are limited to an upper bound.

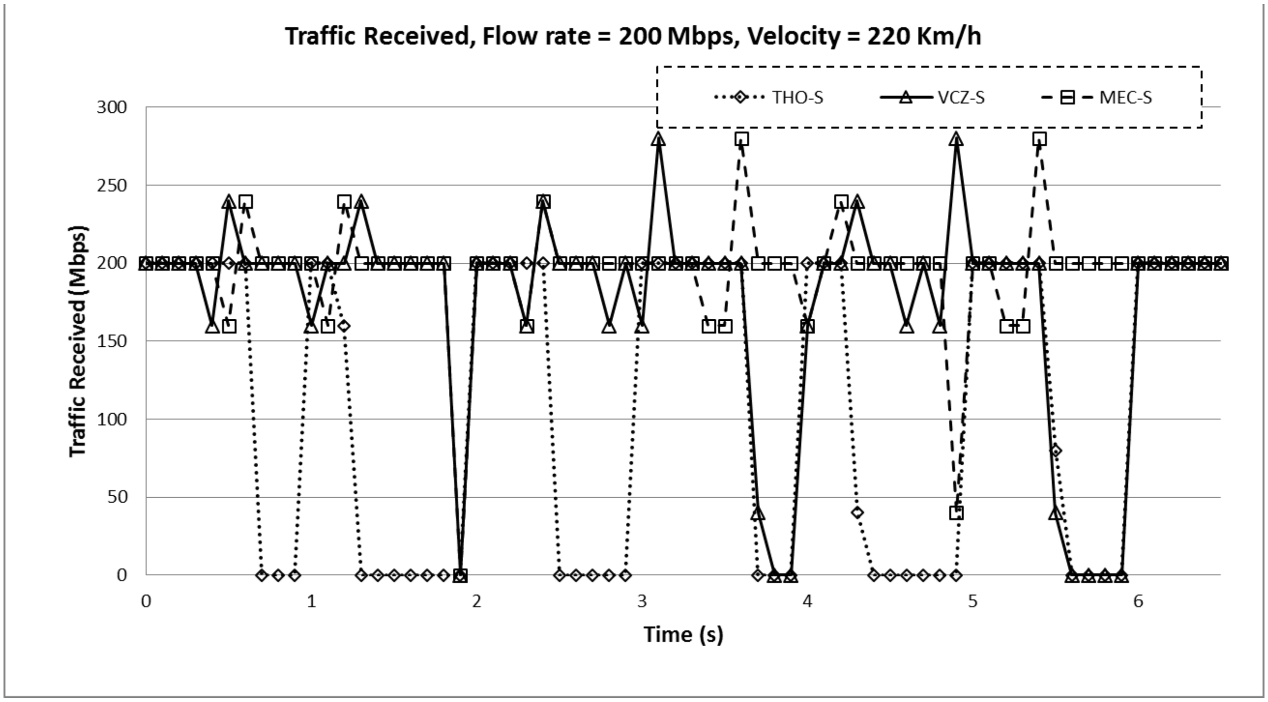

Figure 5. Received traffic (traffic load: 200Mbps – end-user velocity 220km/h)

MEC on the other hand 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 can be explained since 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 3, Figure 6 depicts the average packet loss against different values of end-user velocity for THO, VCZ 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 all three 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 $D_{init} \in [0,2R\text{-}d]$, 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 $D_{init} \in [R, 2R\text{-}d]$, 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.

In case of VCZ, the higher/lower theoretical performance observed in specific times for medium velocities is explained by the selection of the Virtual Cellular Zone size Z, i.e., 3. Thus, because of the experimental topology, for some values of velocity (e.g., 126 km/h and 144 km/h) the probability of receiving the beacon signal in the small overlapping area (d=5m) between different Virtual Cellular Zones becomes higher, so the observed packet loss rate becomes lower. On the contrary, for specific velocity values (e.g., 112 km/h and 168 km/h) the same probability is lower, and this is the reason for the higher observed packet loss rate.

Regarding the three handoff algorithms, Figure 6 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. The performance of VCZ in terms of packet loss is better for all end-user velocities, but it remains unsatisfactory as in all cases the packet loss is higher than 5%. In case of VCZ the packet loss values fluctuate between 7% (for 100 km/h) to 20% (for 220 km/h). Therefore, both THO and VCZ are inappropriate to support end-users moving with medium/high speed in vehicular RoF networks at 60 GHz.

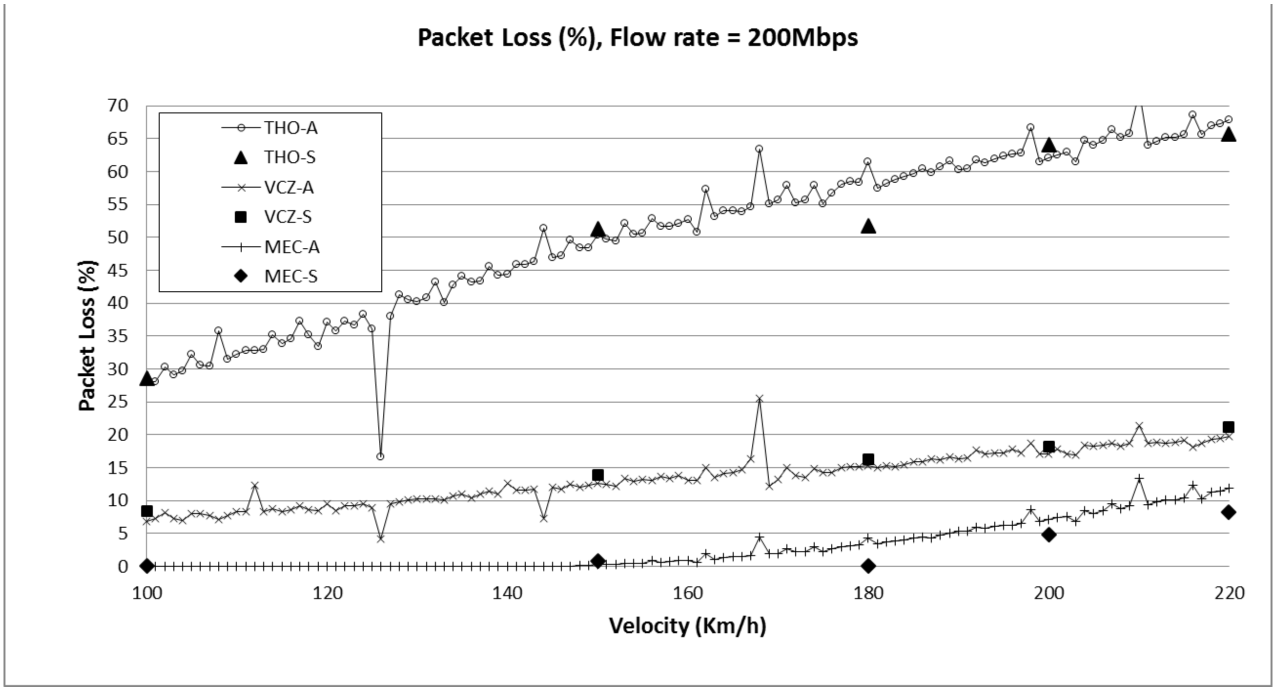

Figure 6. Packet loss vs. user velocity (analysis vs. simulation)

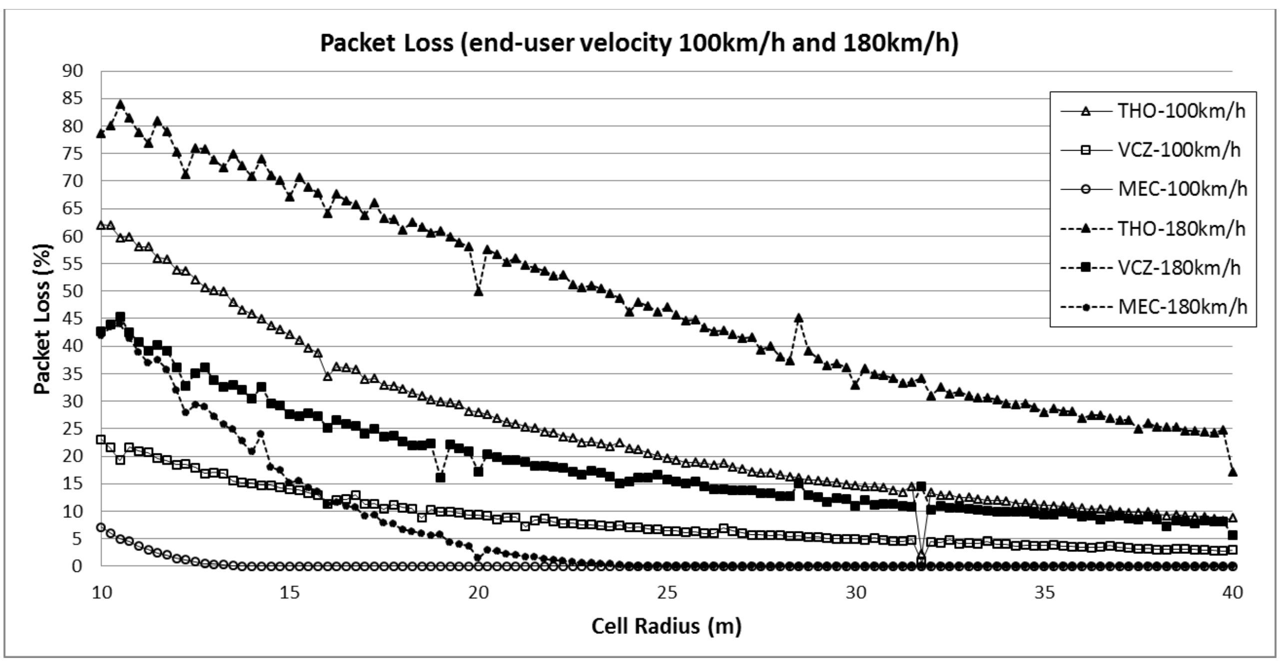

Figure 7. Packet loss vs. cell radius (*v*=100km/h and *v*=180km/h)

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 even 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.

In addition, another set of numerical scenarios has been generated, in order to study how the cell radius affects packet losses for all three handoff algorithms. Remind that in the presented analysis as well as in the simulation experiments the cell radius for all RAUs was set fixed to 20 m, but in practice cell radius may fluctuate, since it depends on the transmitted power value. Specifically, the set of numerical scenarios (derived from the analytical model) was created for different cell radii spanning between 10 m and 40 m with a step of 0.25 m and for different end user velocities. In order to render the corresponding diagram as clear as possible we present the results only for a medium velocity (i.e., v=100km/h) as well as for a higher one (i.e., v=180km/h), which are typical medium and high speeds, respectively, for trains in railways or cars in highways. The results are depicted in Figure 7 and it is obvious that for very low values of cell radius, i.e., less than 12.5 m, all three handoff algorithms retain very high values of packet losses for both medium and high velocities, except from the combination of medium velocity and MEC handoff algorithm. So, for such small cell radii the MEC algorithm is the only solution, but only for medium end-users speeds and applications that could afford up to 7% packet losses. In addition, Figure 7 illustrates that packet loss rate decreases as the cell radius increases, for all three algorithms. In detail, THO algorithm presents only prohibited values for packet losses (i.e., up to 84%) for both medium and high speeds and even in the case of the maximum cell radius it is higher than 8%. VCZ algorithm presents high values of packet losses even for high velocities, which fluctuates between 10% and 45% for the maximum and the minimum cell radius, respectively. But VCZ could be a candidate handoff algorithm for medium speeds, since it presents very low packet losses (i.e., less than 1%) for cell radii more than 22 m. Finally, MEC algorithm presents affordable packet loss values for high speeds, i.e., less than 10% for cell radius between 20 m and 30 m, and less than 5% for cell radius more than 30 m, while packet loss is negligible (less than 0.3%) for medium speeds and cell radius more than 12.5 m.

6. CONCLUSION

We presented and analyzed the packet loss models for THO, VCZ 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, while further fine-tuning on packet loss could be also achieved by fluctuating cells' radii. The results verified that THO fails to accommodate fast moving mobile terminals because of prohibitive values of packet losses even for medium speeds. On the other hand, for medium speeds VCZ could be a good choice especially for applications tolerable to up to 7% packet loss. Finally, MEC exhibits negligible or reasonable packet losses for medium and high speeds, respectively, rendering it the strongest candidate handoff algorithm for packet loss optimization in high-mobility RoF networks at 60 GHz.

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