Network Coding for Vertical Handoffs Between LTE and IEEE 802.11n: An Energy Perspective

Riccardo Bassoli[1,2], Hugo Marques[1,2], Jonathan Rodriguez[1], Seiamak Vahid[2], Rahim Tafazolli[2]

[1]Instituto de Telecomunicações, Aveiro, Portugal

[2]Centre for Communication Systems Research, Surrey, UK

$\{bassoli, hugo.marques, jonathan\}$@av.it.pt

$\{s.vahid, r.tafazolli\}$@surrey.ac.uk

Abstract

Wireless networks are evolving into a unique heterogeneous scenario. Moreover, mobile terminals with multiple wireless interfaces have the ability to roam between different access networks. Allowing seamless and efficient vertical handoffs is becoming a key requirement for future wireless environments. We discuss the application of recent kind of network codes called batched sparse (BATS) codes on HARD vertical handoffs between LTE and IEEE 802.11n to reduce packet loss and to increase performances. The first part of our analysis demonstrates a reduction of packet loss by applying network coding. However, the second part shows that the redundancy of the codes increases the energy per bit consumed by mobile terminals.

Index Terms

Network coding, LTE, IEEE 802.11n, vertical handoffs, energy consumption.

I. Introduction

In actual mobile networks, different technologies are coexisting and handsets with multiple wireless interfaces are moving under heterogeneous coverage. In this environment, vertical handoffs (VHO) are fundamental to augment performance of communications: the choice of the best network becomes important to improve user experience and efficiency of transmissions. In order to guarantee seamless handovers among technologies, a lot of research is focusing on designing new efficient mechanisms and protocols. To evaluate the quality of a vertical handoff many variables need to be taken into account such as delays, losses and costs. In terms of costs, a key objective for both telecommunication companies and

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customers is to achieve higher data rates and performances by reducing energy demand: in fact, that can respectively reduce the expenses of providers and it can increase the battery life of wireless devices.

During VHOs, errors due to erasures occur. If handoff is SOFT, the user changes network and IP address, all the packets sent to the previous network are forwarded by using the new technology and the previous interface keeps the connection. In this case, packet loss is mainly given by handoff delay and low signal time. On the other hand, if handoff is HARD, all the data packets sent to the previous IP address are lost. Losses result in more retransmissions, in delays and higher energy consumption. So, it is necessary to adopt techniques to avoid these issues caused by erasures. Link layer erasure codes have been developed to correct errors due to erasures. However, classical store-and-forward routing has been demonstrated not to be optimal in presence of erasure channels. In 2000, research in network coding [1] fully started and year after year it has continuously been growing by showing its many potentials. In presence of erasures, network coding can be used instead of classical link layer erasure codes, to achieve higher capacity and to correct errors. In order to reduce the decoding complexity of random linear network coding (RLNC), [2] proposed a novel approach by using LT codes [3]. Then, by extending Raptor codes and LT network codes, [4]–[6] designed a new class of fountain codes called batched sparse (BATS) codes to provide schemes with low computational complexity, more suitable for practical applications and large file transmissions.

In this paper, we develop a theoretical model to analyse packet loss and energy consumption of wireless devices during HARD VHOs between LTE and IEEE 802.11n. Then, a kind of BATS code is proposed to reduce erasures due to vertical handoffs. Finally, the energy consumption of the system is evaluated without and with BATS codes. The remainder of our work is organized as follows. First, it is described how LTE, IEEE 802.11n and the decision algorithm are modelled. Then, the mathematical description of the HARD VHO is shown. Finally, BATS codes are applied to the system and energy consumption is calculated.

II. System Model

This work is assuming eNodeB (eNB) coverage always available for user equipment (UE). Once UE is under the coverage of IEEE 802.11n access point (AP), it is possible to perform seamless VHO. Because of that, system discovery procedure can be avoided when LTE is the target network.

A. IEEE 802.11n Model

IEEE 802.11n is an amendment to IEEE 802.11 standards to achieve a higher throughput of at least $100Mb/s$. According to real measurements obtained by [7] in case of 2x2 MIMO, it is feasible to decide $200Mb/s$ as the rate of our IEEE 802.11n model. IEEE 802.11n aggregation mechanism is designed as a two-level scheme: there are two kinds of aggregation frames, called aggregate MAC protocol service unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU). In this paper only first aggregation mechanism is utilised.

The time the mobile host (MH) takes to connect to the AP (T_{WLAN}) is the sum between the time needed to scan the available networks (T_{scan}) and the time necessary to authenticate (T_{auth}) to the target AP: active scan procedure is implemented in this context. After these premises, scanning time becomes

$$T_{scan} = uT_u + eT_e \tag{1}$$

where T_u is the time to scan channels that are used, *u* is the number of channels used, T_e is the time to scan empty channels and *e* is the number of empty channels. Then,

$$T_u = T_{ProbeReq} + maxChannelTime \tag{2}$$

and

$$T_e = T_{ProbeReq} + minChannelTime \tag{3}$$

where $T_{ProbeReq}$ is the delay to send the *Probe Request* frame containing the broadcast address as its destination: a probe timer starts and MH waits for any *Probe Response*. If no response is received by *minChannelTime*, the next channel is scanned. However, if one or more responses are received by *minChannelTime*, the MH stops accepting *Probe Response* frames at *maxChannelTime* and processes all of the responses received by this time. The above steps are repeated for all the channels. Then, the transmission time for a *Probe Request* frame is

$$\begin{aligned} T_{ProbeReq} = aDIFSTime + \frac{aCWmin}{2} \cdot aSlotTime + \\ + PreambleHeader + \frac{length}{rate} \end{aligned} \tag{4}$$

where DIFS is the distributed inter-frame space, *aCWmin* is the maximum number of slots in the minimum contention window and *aSlotTime* is the length of a slot. By applying the characteristics specified by IEEE 802.11n, the values obtained are: $T_{ProbeReq} = 291.5\mu s$, $T_u = 15.3ms$ and $T_e = 0.97ms$. Finally, given two used channels and two empty channels (European channels), the scanning time becomes $T_{scan} = 32.54ms$. As security is outside of the scope of this work, an open-system authentication is considered, in which the AP always accepts a MH. According to real measurements obtained by [8], it is reasonable to simply choose $T_{auth} = 5ms$. So, $T_{WLAN} = T_{scan} + T_{auth} = 37.54ms$.

B. Long Term Evolution Model

LTE network is modelled by mainly focusing on the following components of the network. The eNB represents the point of access and connection to the LTE network. The Serving Gateway (S-GW)

TABLE I

LATENCIES OF LTE PROCEDURES TO ESTABLISH CONNECTION AND BEARERS.

Type of latency	Label	Delay
T_{RAC}	Contention-free random access procedure (RAC)	$13ms$
T_{RRCrs}	*RRCConnectionRequest* and *RRCConnectionSetup*	$19.8ms$
T_{RRCc}	*RRCConnectionSetupComplete*	$37.9ms$
T_{bearer}	Bearer establishment	$48.7ms$
T_{meas}	Measurement report	$6ms$
$T_{mobEUTRA}$	*MobilityFromEUTRACommand*	$3ms$

serves as local mobility anchor when UE is moving between eNBs. It also retains information about the bearers when UE is in idle state and temporarily buffers downlink (DL) data while Mobile Management Entity (MME) initiates paging of the UE to re-established bearers. A bearer is an IP packet flow with a defined quality-of-service (QoS) between the gateway and the UE. Finally, the PDN Gateway (P-GW) is responsible for IP address allocation for the UE, as well as QoS enforcement and flow-based charging. It is responsible for the filtering of DL user IP packets into the different QoS based bearers. It also serves as mobility anchor for inter-working with non-3GPP technologies. So, P-GW is responsible of delivering the packets to AP when VHO is performed. The P-GW is assumed to have the list of IEEE 802.11n APs and a direct link with them. The time to perform communications between S-GW/MME and P-GW is considered null in respect of the other times involved in the analysis.

The procedure used to model the access to LTE network and the establishment of bearers is the one fully described in [9]. The latencies involved in the procedure can be found in [10]. Table I summarises the values of the latencies used in the LTE model of this work. According to the delays in Table I, T_{LTE} results to be $125.4ms$. In the context of this paper, UE DL bit rate is fixed at $100Mb/s$ (20 MHz - 2x2 MIMO).

C. Handoff Decision Model

The handover decision problem is modelled by using Decision Theory (DT). Optimization of handoff decision is out of the scope of this article, then a simplified description follows. The notation of our model is inspired by the one realised in [11] in case of home heterogeneous networks.

The decision process consists in the evaluation of the reward obtained in each of the next state that occurs after an action. The decision is to choose action

$$\bar{a} = \arg \max_{a_{ij} \in A} \sum_{s_j \in S} P_{ij} U(s_j) \tag{5}$$

where $U(s_j)$ is the utility of each possible future state s_j, achieved after action a_i with probability P_{ij}. After that, a decision is represented by the quadruple $D = \langle P_i(s_i), A, P_{ij}, U \rangle$, where:

- P_i is the probability of initial state while making a decision.
- $A = \{a_i\}$ is the set of possible actions. Here, a_1 is the action that performs VHOs and a_2 is the one that keeps the device waiting after the end of the transmission.
- P_{ij} is the probability of each possible consequent state s_{ij}, while an action is performed.
- U is the utility function, which considers connection performance due to received signal strength (RSS) of AP and eNB.

The set of all the possible achievable states is $S = \{s_{11}, s_{12}, s_{21}, s_{22}\}$. Finally, the probabilities of future states are

$$\begin{cases} P_{11} = \Pr(RSS_{AP} \geq RSS_{eNB}) \\ P_{12} = \Pr(RSS_{AP} \leq RSS_{eNB}) \\ P_{21} = \Pr(s_{21} | RSS_{AP} \geq RSS_{eNB}) \\ P_{22} = \Pr(s_{22} | RSS_{AP} \leq RSS_{eNB}) \end{cases} \tag{6}$$

with $\sum_{i,j} P_{ij} = 1$.

III. Handoff Procedure

The mobile device is moving and suddenly enters in an area covered by an IEEE 802.11n AP. At this point, VHO decision algorithm performs action a_1 to move to state s_{11}. A first handoffs occurs: the UE is leaving LTE network to join IEEE 802.11n. Then, the MH changes state by moving to s_{21}. After that, MH is moving from WLAN and leaves the coverage of the AP so, action a_2 is performed to move to state s_{12}. All the handoffs performed are HARD backward handovers. Moreover, mobile user is receiving a file in DL from the internet so, handoffs is lossless in the sense that all the parts of the file has to be received without errors.

Handoff delay is analytically modelled following

$$T_{VHO} = T_{wireless} + T_{wire} \tag{7}$$

where $T_{wireless}$ is the time to prepare the VHO, to scan and to connect to the target radio technology, and T_{wire} is the delay of wired communications between AP and P-GW to prepare the handoff. According

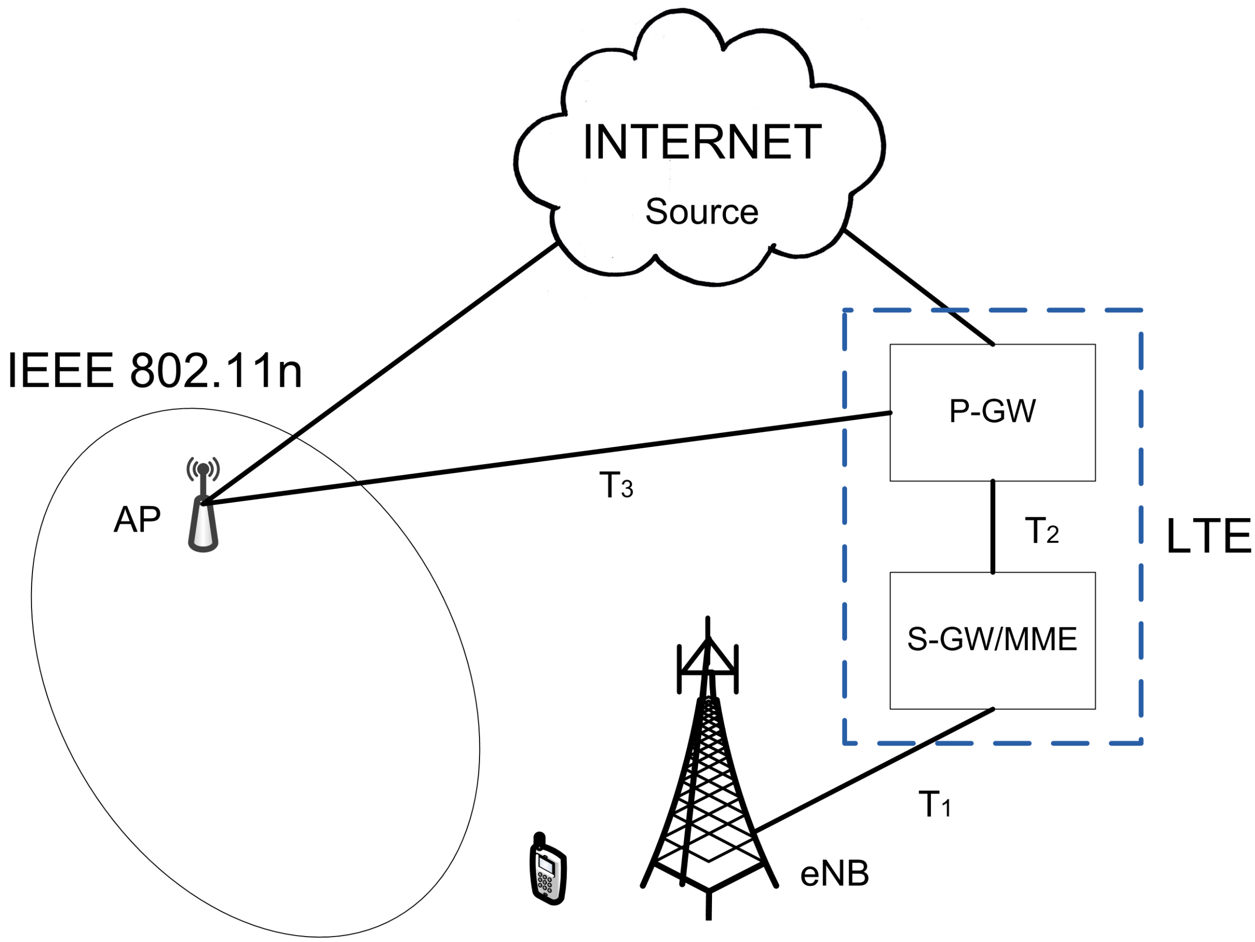

Fig. 1. VHO scenario analysed. IEEE 802.11n and LTE network are represented. For simplicity a direct link of 5km connects P-GW and AP. T_1, T_2, T_3 are respectively the delays for transmissions on wired links. In our case S-GW/MME and P-GW are located at the same place then, T_2 is neglected.

to the target radio technology chosen, $T_{wireless}$ is equal to either T_{WLAN} or T_{LTE}. On the other side, T_{wire} can be expressed as

$$T_{wire} = \sum_{i=1}^{N} (T_i^{proc} + T_i^{trans}) \tag{8}$$

where T_i^{proc} and T_i^{trans} are respectively the delays because of processing and transmission at each node i of the wired network. Figure 1 depicts the scenario considered in our analysis. By looking at that scenario, T_1, T_2, T_3 are the delays due to transmissions to which latencies for processing need to be added. In particular, $T_1 = 5ms$, $T_2 = null$ (S-GW/MME and P-GW are at the same place) and $T_3 = L/c$, where L is the distance and c is the speed of light. Furthermore, the processing delays of nodes of LTE wired network are assumed $T_i^{proc} = 5ms$ for $i = 1, .., 3$ and for AP node $T_4^{proc} = 1ms$ is considered.

Finally, according to (8) the delay of wired network becomes $T_{wire} \simeq 21ms$.

Packet loss during HARD VHO is due to packets that are sent to the previous IP address that is not active anymore [12]. Then, this loss is expressed as

$$p_{loss} = \left\lceil \frac{rT_{VHO}}{p_{size}} \right\rceil \tag{9}$$

where r is the DL rate of UE/MH in the old network and 1500B is the IP packet size. Thanks to the delays calculated above,

$$p_{loss}^{LTE \to WLAN} = \left\lceil \frac{r(T_{meas} + T_{WLAN} + T_{wire})}{1500B} \right\rceil = 538 \tag{10}$$

and

$$p_{loss}^{WLAN \to LTE} = \left\lceil \frac{r(T_{LTE} + T_{wire})}{1500B} \right\rceil = 2440. \tag{11}$$

The errors that occur because of the HARD VHOs are modelled according to Figure 2: HARD handoffs are represented as erasure channels and the feedback considers that packets received are acknowledged to the source. However, the characteristics of the acknowledgement technique are not studied in this work.

A. Batched Sparse Codes for HARD VHOs

To reduce packet loss caused by HARD VHOs, BATS codes are deployed instead of link layer erasure codes. Given n source packets, a batch is a set of k coded packets, subset of the n source packets. Each packet is a vector of t symbols in a finite field $\mathbb{F}_q$. The source encodes its packets into K batches and sequentially sends them to P-GW. P-GW and AP are considered intermediate nodes that linearly combine packets belonging to the same batch. Once mobile user has received all the packets in a batch, it starts decoding them. The complexity of BATS coding [5] is $\mathcal{O}(tk), 2\mathcal{O}(tk), \mathcal{O}(k^2+tk)$, respectively at source node, intermediate node and destination node. The initial analysis in this work is focused on the energy consumption of the system. Because of that, the parameters of BATS codes are taken by results obtained in [4], [6]. The number of packets, which can be recovered by Belief propagation (BP) decoding, is $(1-\eta)n^*$. The sufficient condition for successful BP decoding is satisfied then, BP decoding ends with at most ηn packets erased. By these assumptions, decoding BATS code can recover all the packets lost during HARD VHOs.

Let consider a BATS code with $K = 32$ batches, over a finite field $\mathbb{F}_{16}$. The average rate the code can achieve is $C = 0.6818$. Then, once this BATS code is used in the system, data rates becomes

$$r_{DL-LTE} : 100Mb/s \to 68.18Mb/s \tag{12}$$

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*η is a value arbitrarily small. Example of values are $\eta = 0.01$ and $\eta = 0.08$ [4].

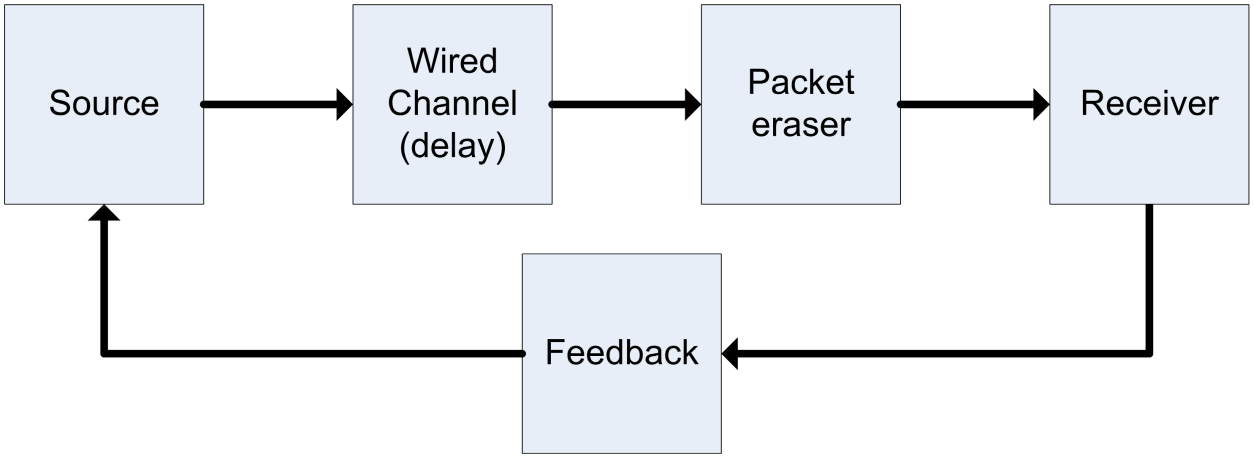

Fig. 2. The packet loss is only due to HARD VHO and is modelled as a packet erasure channel (PEC). The wired network is described as a delay element that does not have any loss. A feedback element represents the acknowledgement process once the mobile user successfully decodes a batch.

TABLE II

ENERGY CONSUMPTION MEASUREMENTS OF IEEE 802.11N BY CONSIDERING UNIT TIME $1s$.

MAC state	Energy Consumption $[mJ]$
Off	0
Sleep	100
Listen	1130
Receive	1270
Transmit	1990

and

$$r_{WLAN} : 200Mb/s \rightarrow 136.36Mb/s. \tag{13}$$

IV. ENERGY ANALYSIS

The analysis of UE energy consumption during transmission of two files, follows. Two HARD VHOs occur during the transmissions. Table II shows the energy consumption of IEEE 802.11n during the possible different states of the system based on measurements done by [7]. On the other hand, Table III provides the energy consumption of LTE based on measurements done by [13], [14]. Figure 3 depicts the sequence of events, which occur during the handover.

TABLE III

ENERGY CONSUMPTION MEASUREMENTS OF LTE BY CONSIDERING UNIT TIME $1s$.

UE model	Energy Consumption $[mJ]$
Off	0
Idle	594
Connected	1680
Receiving	420
Transmitting	550
Rx + Tx	160
Two codewords	70

First, evaluation of energy consumption of the system without coding follows. Let consider the download from the internet of the first file (64000 IP packets). At time t_0, UE starts receiving the first data packet in DL at fixed rate of $100Mb/s$. Once a batch is decoded, packets received are acknowledged. The total energy consumed per second is

$$E_{1s}^{LTE} = E_{con} + E_{rec} + E_{Tx} + E_{Rx} + E_{Tx+Rx} + E_{TC}. \tag{14}$$

Then, energy consumption by $t_1 = 5s$ results in $E_{t_1}^{LTE} = 14.4J$. The respective energy consumption per bit is $E_c^{LTE} = 28.8nJ/bit$. At t_1, LTE radio interface switches off and the HARD VHO is performed: $p_{loss}^{LTE \to WLAN} = 538$ packets need to be retransmitted. Once MH is authenticated to WLAN AP, at t_2 starts receiving packets at $200Mb/s$ from the last one acknowledged during previous LTE communication till MH finishes the download of the file ($\Delta t_{23} = 1.37s$). The WLAN connection consumes per second

$$E_{1s}^{WLAN} = E_{Tx} + E_{Rx}. \tag{15}$$

After Δt_{23}, $E_{t_3}^{WLAN} = 4.5J$. The respective energy consumption per bit is $E_c^{WLAN} = 16.4nJ/bit$. The MH enters in sleep mode. At t_4, MH initiates the download of another file. At $t_5 = 3s$, IEEE 802.11n interface turns off to perform HARD VHO to LTE network: MH has consumed $E_{t_5}^{WLAN*} = 9.8J$. So, $E_c^{WLAN*} = 16.3nJ/bit$. The HARD VHO results in $p_{loss}^{WLAN \to LTE} = 2440$ packets, which need retransmissions. Finally, at t_6, eNB retransmits the packets not acknowledged and the remaining packets to complete the download: $E_{t_7}^{LTE*} = 5.8J$ and $E_c^{LTE*} = 28.9nJ/bit$.

When BATS codes are applied the packet erased can be recovered: so, retransmissions are avoided. Nevertheless, the price to pay is a reduction of data rate, as shown by (12) and (13). In a coded system,

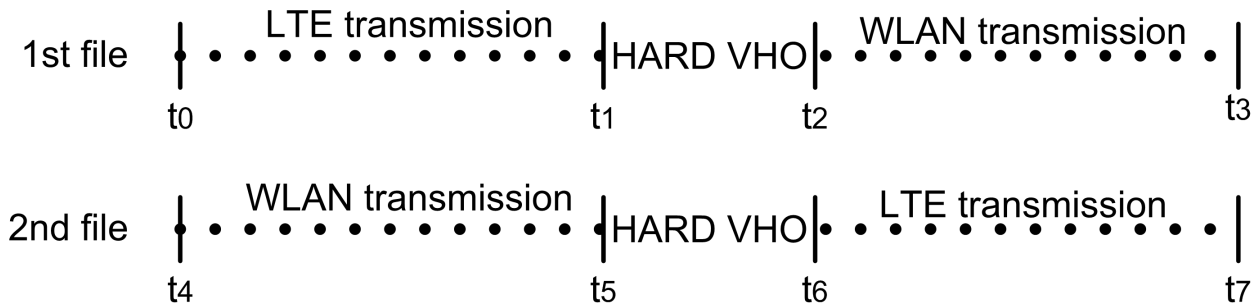

Fig. 3. Representation of the example that simulate the reception of two files during two HARD VHOs. This particular case helps to evaluate the energy performance of the system with and without BATS codes.

at t_0 UE starts to receive the file in DL. This time the data rate is less than before. Then, respective energy consumption per data bit becomes $E_c^{LTE} = 42.2nJ/bit$. At t_1, LTE radio interface switches off and the HARD VHO is performed: $p_{loss}^{LTE \to WLAN} = 367$ packets are erased. Once MH is authenticated to WLAN AP, at t_2 just starts receiving packets left because the BATS code is able to recover all the lost packets: MH finishes the download of the file in ($\Delta t_{23} = 3.14s$) and $E_{t_3}^{WLAN} = 10.2J$. The energy consumption per data bit is $E_c^{WLAN} = 24nJ/bit$. At t_4, MH initiates the download of another file after a time in sleep mode. At $t_5 = 3s$, IEEE 802.11n interface turns off to perform HARD VHO to LTE network. The HARD VHO results in $p_{loss}^{WLAN \to LTE} = 1664$. Finally, at t_6, UE receives the remaining packets to complete the download: $E_{t_7}^{LTE*} = 15.2J$. Figure 4 compares the energy consumption per bit of LTE and IEEE 802.11n without coding and while BATS coding is applied.

V. Conclusion

This work studies BATS codes in VHO scenarios: in particular, the presented analysis focuses on HARD backward VHOs between LTE and IEEE 802.11n. At the best of authors' knowledge this is the first paper investigating in network coding for vertical handoffs. First, we developed a theoretical framework to fully describe the problem by modelling the actions, the latencies and the losses involved in the process. Second, BATS codes are used to recover lost packet due to HARD VHO. Next, the energy consumption of mobile terminal during vertical handoffs with and without coding is shown. The results in the paper described how BATS codes can be useful in HARD VHOs to reduce packet erasure. On the other hand, the redundancy introduced by coding operations slightly increases energy consumption of mobile devices. Future work will include the research on how coding operations and complexity impacts on latencies, how different sizes of the finite field influence energy consumption and how to design efficient acknowledgement procedure when BATS coding is applied.

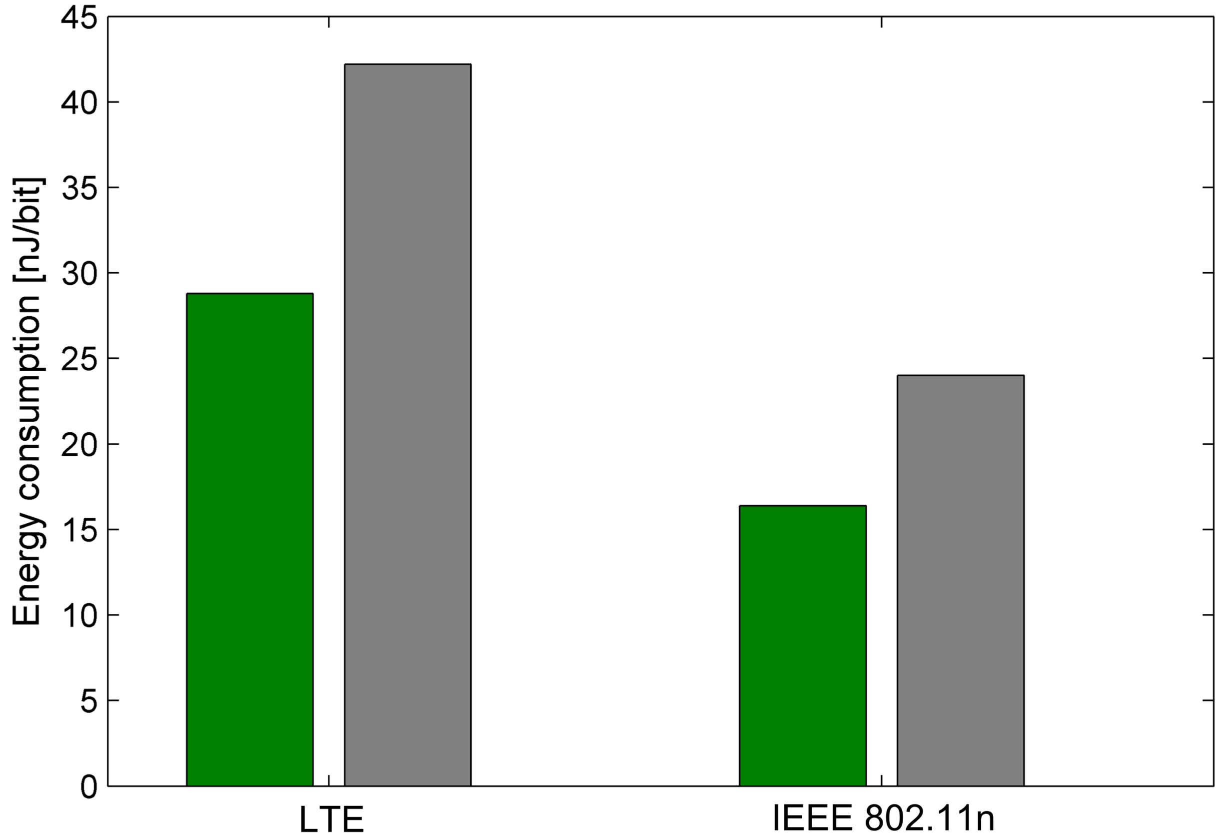

Fig. 4. Figure compares energy consumption per bit of LTE and IEEE 802.11n without coding (green bars) and with coding (grey bars). By applying BATS coding, the capability to recover erased packets is paid in terms of higher energy consumption.

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