Energy Analysis of Network Coding in Hard Vertical Handovers

Riccardo Bassoli[1,2], Hugo Marques[1,2], Ayman Radwan[1], Jonathan Rodriguez[1], Seiamak Vahid[2], Rahim Tafaz
[1]Instituto de Telecomunicações, Aveiro, Portugal
[2]Centre for Communication Systems Research, Surrey, UK
$\{bassoli, hugo.marques, aradwan, jonathan\}$@av.it.pt
$\{s.vahid, r.tafazolli\}$@surrey.ac.uk

Abstract

In future mobile networks different technologies will coexist and wireless devices with multiple interfaces will move in a heterogeneous scenario. The capability to connect to different access radio technologies opens the way to vertical handover mechanisms. Then, allowing vertical handovers with low losses and costs will be a main requirement of future mobile networks. In this paper, we apply batched sparse (BATS) codes on hard vertical handovers to avoid packet losses due to erasures. The theoretical analysis shows that energy consumption per bit increases while BATS codes are used. In particular, the energy consumption per bit inversely grows with the size of the finite field of the code.

Index Terms

Energy consumption, network coding, LTE, IEEE 802.11n, hard vertical handovers.

I. Introduction

Future wireless networks will integrate a variety of heterogeneous wireless technologies. All these networks are called heterogeneous because of the different radio access technologies and communication protocols which they use. In such an environment, vertical handover (VHO) becomes a fundamental aspect with the aim of providing best connection to the users and seamless mobility among different technologies. The fact of guaranteeing a seamless handover means that users do not perceive any delay or interruption of services. So, actual research is focused on the design of protocols and techniques to reduce losses, latencies and costs. Regarding costs, an important goal for telecommunication companies and final users is to obtain higher performances by reducing energy consumption. In fact, the decreasing demand of energy can result in lower expenses for providers and in longer battery life of handsets.

Vertical handover mechanisms are classified into soft and hard handovers. In the former, packet erasures are mainly caused by delays and by periods with low signal. In the latter, all the packets sent to the old IP address are lost. Then, a lot of retransmissions are needed and consequently delays and energy consumption become bigger. [1] discusses weak aspects of existing approaches and presents a novel context-aware vertical handover framework to achieve higher energy-efficiency. Another the solution is the design of methods to avoid erasures to make VHOs more efficient. In order to avoid errors due to erasures, link layer erasure codes have been using for years. A decade ago, a new paradigm of code, called network coding, was started by [2]. Network coding is a coding process realised on packets at network layer. A first important property of network coding is to achieve higher capacity than classical store-and-forward routing in many scenarios. Among the various potentials of these codes, it has been demonstrated that network codes can substitute classical link layer erasure codes. The first issue that appears at the beginning was concerning the decoding complexity of random linear network coding (RLNC). To reduce that complexity, [3] proposed a novel network coding scheme based on LT codes [4]. Then, in 2011, [5]–[7] enhanced Raptor and fountain codes by designing the so called batched sparse (BATS) codes. The most important property of BATS codes is to have low decoding complexity so, to be more efficient in practical scenarios for large file transmission.

This work develops a theoretical model to study and to analyse the performances of hard VHOs between IEEE 802.11n and LTE. In particular, the model is focused on the evaluation of losses and energy consumption. Then, once the model is stated, BATS codes are applied to avoid packet erasures and retransmissions. Finally, an analysis in terms of energy consumption of the system without and with network coding is provided. Network coding for energy efficient automatic repeat request (ARQ) is shown in [8]. The remainder of the paper is organized as follows. First, the models to describe LTE and IEEE 802.11n are presented. Second, the decision algorithm of the VHO is provided. Next, the hard VHO is mathematically described. Finally, BATS codes are applied to the system and energy consumption id evaluated.

II. Long Term Evolution

LTE network is modelled as shown in Figure 1. The eNodeB (eNB) is the point of access and connection and its coverage is always available for user equipment (UE). Then, system discovery of targeted LTE network can be avoided. The Serving Gateway (S-GW) is the local mobility anchor when UE is making horizontal handovers between eNBs. It also keeps 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 an assigned quality-of-service

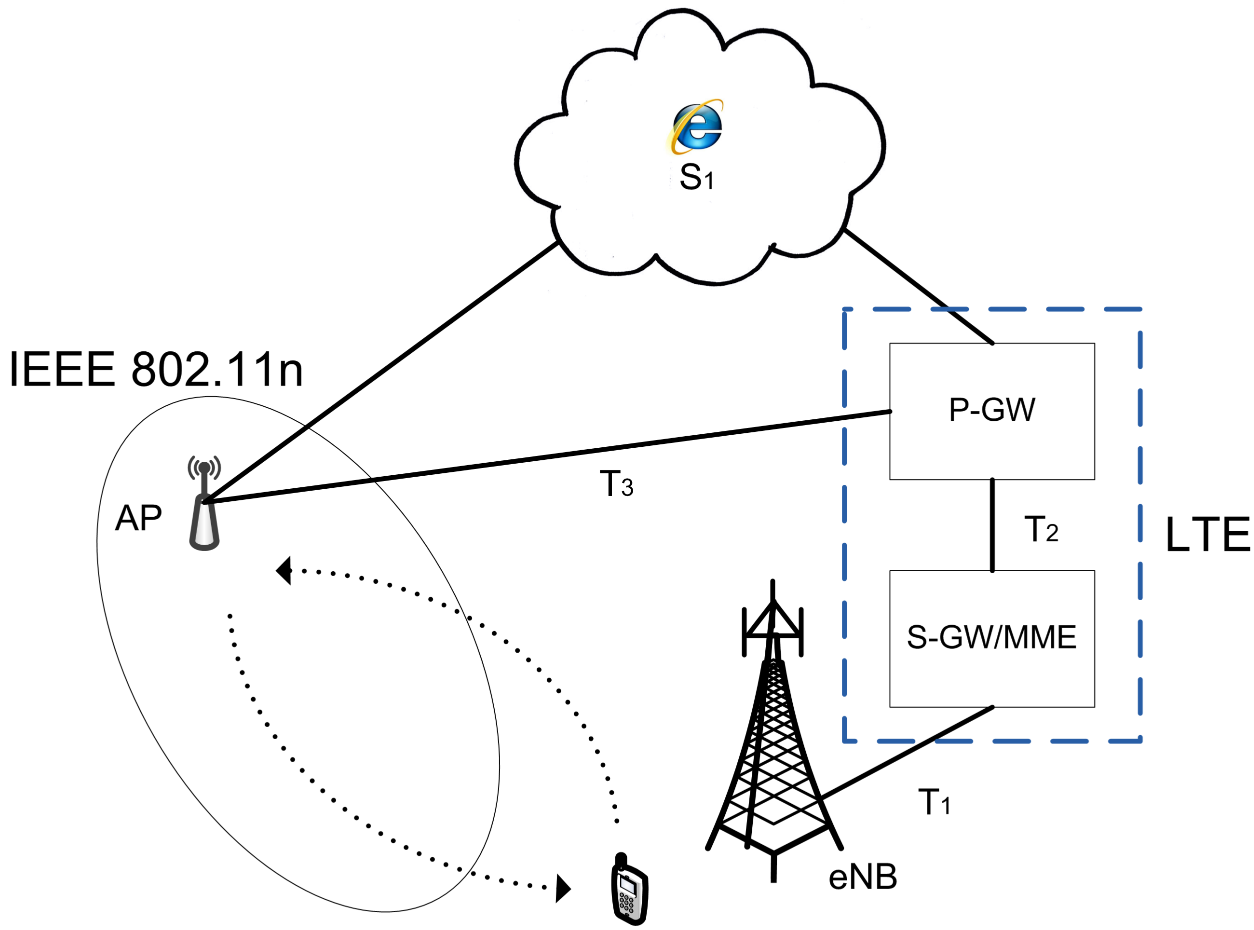

Fig. 1. Scenario analysed in which IEEE 802.11n and LTE networks are depicted. A direct link of 5km connects P-GW and AP. T_1, T_2, T_3 are respectively the delays for transmissions on wired links. S-GW/MME and P-GW are located at the same place so, T_2 can be neglected.

(QoS) between the gateway and the UE. The PDN Gateway (P-GW) allocates IP address for UE, as well as QoS enforcement and flow-based charging. It filters DL user IP packets into different QoS based on bearers. Furthermore, it serves as mobility anchor for inter-working with non-3GPP technologies. In the context of this work, S-GW/MME and P-GW are stated in the same place so, the time to perform communications between them is considered null.

The procedure that models the access to LTE network and the establishment of bearers is described in [9]. The values of latency can be found in [10]. Table I summarises the values of the latencies used in the LTE model of this work. By using the values listed in Table I, T_{LTE} results in $125.4ms$ by having chosen UE DL bit rate equal to $50Mb/s$ (20 MHz - 2x2 MIMO).

LTE deploys Hybrid Automatic Repeat Request (HARQ) in acknowledge mode. So, NACKs and ACKs

TABLE I

LATENCIES OF LTE PROCEDURES.

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*	$3ms$

are deployed.

III. IEEE 802.11N

IEEE 802.11n achieves a throughput of at least $100Mb/s$. The real measurements in [11] regarding 2x2 MIMO, show that $250Mb/s$ is a suitable rate for our model. IEEE 802.11n has a two-level aggregation mechanism: there are two aggregation frames, called aggregate MAC protocol service unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU). For the scope of this paper only first aggregation mechanism is taken into account.

Once mobile host (MH) tries to connect to the access point (AP), it takes T_{WLAN} ms. This time is the sum between the time T_{scan} for scanning and the time T_{auth} for authenticating. Active scan is used in our context. Then,

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

where T_u is the time to scan channels in use, u is the number of channels in use, T_e is the time to scan empty channels and e is the number of empty channels. So, T_u and T_e are respectively

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

and

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

The mobile host transmits a 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. Finally, the latency of *Probe Request* frames is

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

By applying the requirements specified by amendment IEEE 802.11n, $T_{ProbeReq} = 290.7\mu s$, $T_u = 15.29ms$ and $T_e = 0.96ms$. Finally, according to European organization of channels, there are two used channels and two empty channels. Then, the scanning time becomes $T_{scan} = 32.5ms$. Security is not in the analysis of this work, an open-system authentication is considered. The real measurements in [12], allow to choose $T_{auth} = 5ms$. Because of that, $T_{WLAN} = T_{scan} + T_{auth} = 37.5ms$.

IEEE 802.11n implements acknowledgement. When an A-MPDU from one station is experiencing errors, the receiver sends block acknowledgement, to only acknowledge correct MPDUs. The source needs to retransmit the non-acknowledged MPDUs. This mechanism only applies to MPDUs. If a MSDU is received incorrectly or is not received, the whole A-MSDU has to be retransmitted.

IV. Handover Decision Model

Handover decision is modelled by using Decision Theory (DT), inspired by [13] (for home heterogeneous networks). A simple description is provided since optimizing the handover decision process is not the aim of this work.

The first step the system does is to collect the information on user preferences, network characteristics and condition of the environment. The decision theoretic model consists in:

- 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.
- $\Delta U(s_{ij})$ is the utility degradation, which considers connection performance, the received signal strength (RSS) and energy consumption.

The states of the system are:

- s_{11}, performing VHO from LTE to IEEE 802.11n.
- s_{12}, performing VHO from IEEE 802.11n to LTE.
- s_{21}, device is in waiting mode connected to IEEE 802.11n after ending the transmission.
- s_{22}, device is in waiting mode connected to LTE after ending the transmission.

Then, the probabilities are defined as

$$\begin{cases} P_{11} = \Pr(RSS_{AP} \geq RSS_{eNB}) \\ P_{12} = \Pr(RSS_{AP} \leq RSS_{eNB}) \\ P_{11} = \Pr(s_{21}|RSS_{AP} \geq RSS_{eNB}) \\ P_{21} = \Pr(s_{22}|RSS_{AP} \leq RSS_{eNB}) \end{cases} \tag{5}$$

with $\sum_{i,j} P_{ij} = 1$. The utility degradation of each possible consequent state can be defined as

$$\begin{cases} \Delta U(s_{11}) = T_{WLAN} \cdot r_{WLAN} \cdot E_c^{WLAN} \\ \Delta U(s_{12}) = T_{LTE} \cdot r_{LTE} \cdot E_c^{LTE} \\ \Delta U(s_{21}) = T \cdot E^{WLAN} \\ \Delta U(s_{22}) = T \cdot E^{LTE} \end{cases} \tag{6}$$

Given the two available actions, the expected utility degradation is formulated as

$$\begin{cases} \Delta U_{a_1} = P_{11}\Delta U(s_{11}) + P_{12}\Delta U(s_{12}) \\ \Delta U_{a_2} = P_{21}\Delta U(s_{21}) + P_{22}\Delta U(s_{22}) \end{cases} \tag{7}$$

Finally, the action performed is the one that satisfies

$$\bar{a} = \arg\max_{a_i \in A} \sum_{s_{ij} \in S} P_{ij} \Delta U(s_{ij}). \tag{8}$$

V. Handoff Procedure

At the initial state, the mobile handset is moving and receiving content from the source: a file download is active in the web browser and suddenly, the device enters in an area covered by an IEEE 802.11n AP. The decision algorithm chooses action a_1 and the system goes to state s_{11}. An important assumption is that UE sojourn time in WLAN network is long enough to justify the utility of the handoff procedure to avoid ping-pong effect. Next, MH is moving from WLAN when it is going out from the coverage of the AP, and action a_1 is performed to go into state s_{12}. All the handovers performed are hard, especially, when system state is s_{11}, a hard backward handover is performed. Moreover, the VHO is lossless in the sense that acknowledge is used to guarantee the correct reception of the files.

Handover delay is analytically modelled as

$$T_{VHO} = T_{wireless} + T_{wire} \tag{9}$$

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 to the target radio technology chosen, $T_{wireless}$ is equal to either T_{WLAN} or T_{LTE}. On the other hand, T_{wire} is defined as

$$T_{wire} = \sum_{i=1}^{N} (T_i^{proc} + T_i^{trans}) \tag{10}$$

where T_i^{proc} and T_i^{trans} are respectively the delays to process and to transmit at each node *i* of the wired network. Figure 1 depicts the scenario considered, in which T_1, T_2, T_3 are the delays due to transmissions. 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 $T_i^{proc} = 10ms$ for $i = 1, .., 3$ and for AP node $T_4^{proc} = 5ms$ is considered. Finally, according to (10) the delay of wired network becomes $T_{wire} \simeq 40ms$.

Packet loss during hard VHO is due to packets sent to the previous IP address [14]. Then, this loss is

$$p_{loss} = \left\lceil \frac{rT_{VHO}}{p_{size}} \right\rceil \tag{11}$$

where *r* is the DL rate of UE/MH in the old network and 1500B is the IP packet size. Given the delays obtained above,

$$p_{loss}^{LTE \to WLAN} = \left\lceil \frac{r(T_{meas} + T_{WLAN} + T_{wire})}{1500B} \right\rceil = 348 \tag{12}$$

and

$$p_{loss}^{WLAN \to LTE} = \left\lceil \frac{r(T_{LTE} + T_{wire})}{1500B} \right\rceil = 3446. \tag{13}$$

Figure 2 shows how losses for hard handovers are represented in this work: VHOs are erasure channels and a feedback element represents the acknowledgment processes.

VI. Batched Sparse Codes for Hard VHOs

BATS codes are network codes that can be deployed instead of classical link layer erasure codes to correct errors due to erasures. This family of network codes has been demonstrated to be efficient in case of file transmission. 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. At each intermediate node, there are two separated queues that sequentially transmit network coded packets. The characteristics and the optimization of processes at intermediate nodes are out of the scope of the initial analysis. Once mobile user has received all the packets in a batch, it starts decoding them. The complexity of BATS coding [6] is $\mathcal{O}(tk), 2\mathcal{O}(tk), \mathcal{O}(k^2 + tk)$, respectively at source node, intermediate node and destination node. The parameters of BATS codes are chosen according to the results in [5], [7]. The number of packets,

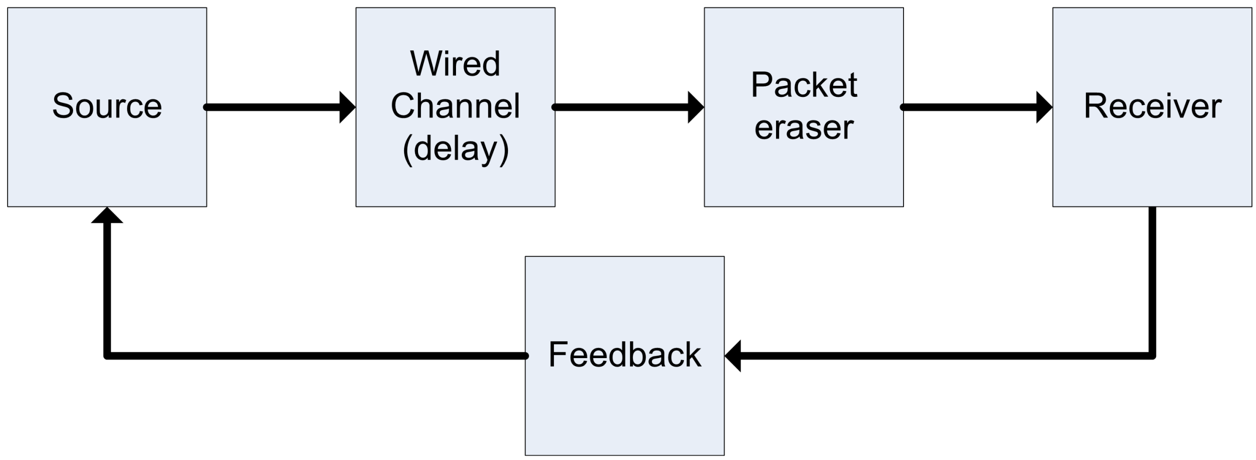

Fig. 2. The transmission during the hard VHOs are interpreted as packets sent through a packet erasure channel (PEC). The wired network is a delay element that does not produce any loss. A feedback element represents the acknowledgement process when the mobile user receives packets.

TABLE II

RATES ACHIEVED BY IEEE 802.11N AND LTE WITH BATS CODES USED IN THIS WORK. THE INITIAL RATES WERE $r_{WLAN} = 250Mb/s$ AND $r_{LTE} = 50Mb/s$.

Finite field	r_{WLAN} $[Mb/s]$	r_{LTE} $[Mb/s]$
$\mathbb{F}_2$	156.5	31.3
$\mathbb{F}_4$	166.4	33.3
$\mathbb{F}_8$	169	33.8
$\mathbb{F}_{16}$	170.5	34.1

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 hypotheses, BATS code can recover all the packets lost during hard VHOs.

Let consider a BATS code with $K = 32$ batches. In order to calculate the performances of BATS codes in terms of energy consumption, we use the average rates the codes can achieve, when a file of $96MB$ is transmitted. These rates are: $C = 0.6259$ over a binary field, $C = 0.6655$ over a finite field $\mathbb{F}_4$, $C = 0.6762$ over $\mathbb{F}_8$ and $C = 0.6818$ over $\mathbb{F}_{16}$. Then, once these BATS codes are used in the system, data rates becomes the ones in Table II.

$^*\eta$ is a value arbitrarily small. Example of values are $\eta = 0.01$ and $\eta = 0.08$ [5].

TABLE III

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

IEEE 802.11n		LTE	
MAC state	Energy Consumption $[mJ]$	UE model	Energy Consumption $[mJ]$
Off	0	Off	0
Sleep	100	Idle	594
Listen	1130	Connected	1680
Receive	1270	Receiving	420
Transmit	1990	Transmitting	550
		Rx + Tx	160
		Two codewords	70

VII. ENERGY ANALYSIS

The energy consumption of UE which transmits two files of $96MB$ is calculated, during two hard VHOs. Table III shows the energy consumption of IEEE 802.11n and LTE during of the different states of the system, based on measurements in [11] and [15], [16]. Figure 3 depicts the sequence of events, which occur during the handover.

First, evaluation of energy consumption of the system without coding follows. Let consider a web browser downloading a file while UE is surfing the web. The size of the file is fixed at $96MB$ (64000 IP packets). At time t_0, UE starts receiving the first data packet in DL at r_{LTE} and, side by side, it is answering in UL with ACKs. At $t_1 = 8s$, UE has received $50MB$: 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 results in $E_{t_1}^{LTE} = 23.04J$. The respective energy consumption per bit is $E_c^{LTE} = 57.6nJ/bit$. At t_1, LTE radio interface switches off and the hard VHO is performed: $p_{loss}^{LTE \rightarrow WLAN}$ are the packets which need to be retransmitted. Once MH is authenticated to WLAN AP, at t_2 starts receiving packets at r_{WLAN} from the last one acknowledged during previous LTE communication till MH finishes the download of the file ($\Delta t_{23} = 1.4887s$). The WLAN connection consumes per second

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

After Δt_{23}, $E_{t_3}^{WLAN} = 4.853J$. The respective energy consumption per bit is $E_c^{WLAN} = 13nJ/bit$.

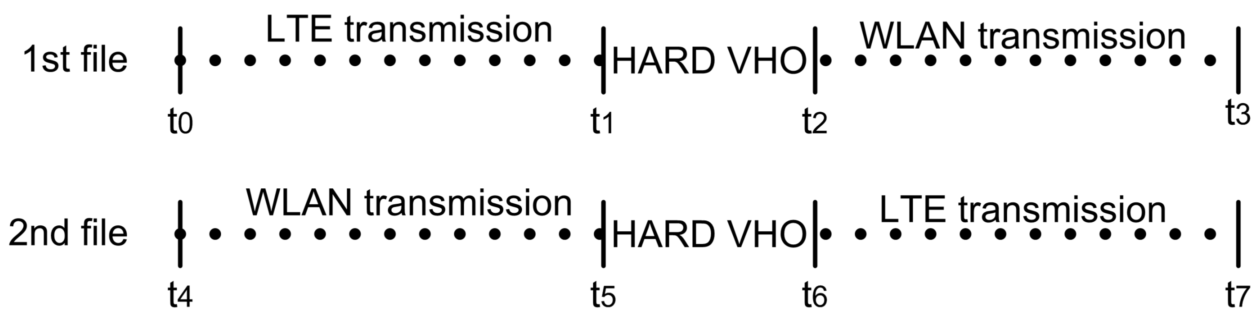

Fig. 3. Representation of the example that simulate the reception of two files of $96MB$ during two hard VHOs. This particular case helps to evaluate the energy performance of the system with and without BATS codes.

The MH enters in sleep mode. At t_4, MH initiates the download of another file of $96MB$. At $t_5 = 2s$, IEEE 802.11n interface turns off to perform hard VHO to LTE network: MH has already received $62.5MB$ by consuming $E_{t_5}^{WLAN*} = 6.52J$. The hard VHO results in $p_{loss}^{WLAN \rightarrow LTE}$ packets, which need retransmissions. Finally, at t_6, UE sends NACKs for all the packets it has not received yet and eNB retransmits the packets not acknowledged and the remaining packets to complete the download: $E_{t_7}^{LTE*} = 17.832J$ and $E_c^{LTE*} = 58nJ/bit$.

When BATS codes are applied the packet erased are recovered: then, retransmissions are avoided. Nevertheless, the price to pay is a reduction of data rate, as shown above in Table II. The same analysis above can be reproduced for the coded system by taking into account the modified transmission rates. Figure 4 represents the results of the energy consumption per bit of LTE and IEEE 802.11n, with and without network coding and the trend according to the variation of size of the finite field. It is possible to see that the fact of not having packet loss due to BATS codes is paid by increasing the energy consumption per bit. On the other hand, by augmenting the size of the finite field, the energy consumption can be reduced. However, in this case, it is important to keep monitored the complexity of the coding operations at the nodes.

VIII. Conclusion

This paper developed a theoretical model to describe and analyse the main properties and behaviours of LTE and IEEE 802.11n in hard VHOs. Next, in order to reduce packet loss due to the change of technology, network coding is applied: in particular, BATS codes are used to correct the errors given by packet erasures because of their low decoding complexity. At the best of authors' knowledge this is the first work investigating performances of network coding in hard VHOs. Finally, the energy consumption of the system with and without BATS codes is calculated. The final outcome demonstrates that the reduction

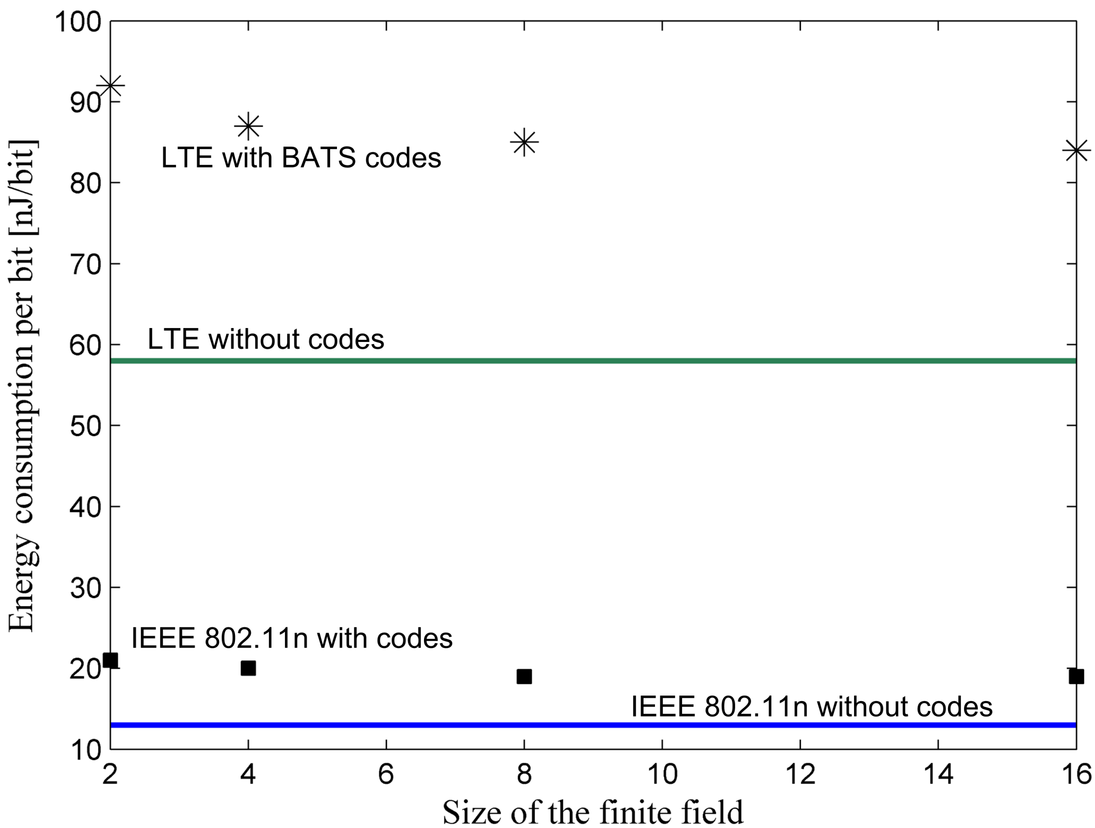

Fig. 4. Comparison of energy consumption between LTE and IEEE 802.11n in the system with and without coding. In case of BATS codes applied, the energy consumption per bit is represented according to the size of the finite field (2, 4, 8, 16).

of losses has the drawback of higher energy consumption. However, a future work is to research how to vary the size of the finite field to achieve rates which make energy consumption equal or lower than the one calculated in case of classical store-and-forward routing.

Acknowledgment

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