Chapter Number

Forward Error Correction for Reliable e-MBMS Transmissions in LTE Networks

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1. Introduction

The Long Term Evolution (LTE) project focuses on enhancing the Universal Terrestrial Radio Access (UTRA) and optimizing 3rd Generation Partnership Project (3GPP) radio access architecture. A key new feature of LTE is the possibility to exploit the Orthogonal Frequency-Division Multiplexing (OFDM) radio interface to transmit multicast or broadcast data as a multicell transmission over a synchronized Single Frequency Network (SFN): this is known as Multimedia Broadcast and Multicast Service (MBMS) over Single Frequency Network (MBSFN) operation. MBSFN transmission enables a more efficient operation of the MBMS (3GPP, 2008a), allowing over-the-air combining of multi-cell transmissions towards the User Equipments (UEs). This fact makes the MBSFN transmission appear to the UE as a transmission from a single larger cell. Transmission on a dedicated carrier for MBSFN with the possibility to use a longer Cyclic Prefix (CP) with a sub-carrier bandwidth of 7.5 kHz is supported as well as transmission of MBSFN on a carrier with both MBMS transmissions and point-to-point (PTP) transmissions using time division multiplexing. MBMS service defines two delivery methods: the download and the streaming delivery.

There are many ways to provide reliability in multicast transmission. The best-known method that operates efficiently for unicast transmission is the Automatic Repeat re-Quest (ARQ). When ARQ is applied in a multicast session, receivers send requests for retransmission of lost packets over a back channel towards the sender. Although ARQ is an effective and reliable tool for point-to-multipoint (PTM) transmission, when the number of receivers increases, it reveals its limitations. One major limitation is the feedback implosion problem which occurs when too many receivers are transmitting back to the sender. A second problem of ARQ is that for a given packet loss rate and a set of receivers experiencing losses, the probability that every single data packet needs to be retransmitted quickly approaches unity as the number of receivers increases. In other words, a high average number of transmissions are needed per packet. In wireless environments, ARQ has another major disadvantage. On most wired networks the feedback channel comes for free, but on wireless networks the transmission of feedback from the receiver can be expensive, either in terms of power consumption, or due to limitations of the communication infrastructure. Thus, due to its requirement for a bidirectional communication link, the application of ARQ over wireless networks may be too costly or, in some cases, not possible. Forward Error Correction (FEC) is an error control method that can be used to augment or replace other methods for reliable data transmission. The main attribute of FEC schemes is that the sender adds redundant information in the messages transmitted to the receiver. This information allows the receiver to reconstruct the source data. Such schemes inevitably add a constant overhead in the transmitted data and are computationally expensive. In multicast protocols however, the use of FEC techniques has very strong motivations. The encoding eliminates the effect of independent losses at different receivers. This makes these schemes able to scale irrespectively of the actual loss pattern at each receiver. Additionally, the dramatic reduction in the packet loss rate largely reduces the need to send feedback to the sender. FEC schemes are therefore so simple as to meet a prime objective for mobile multicast services, which is scalability to applications with thousands of receivers. MBMS service for multicast transmission uses MBSFN. This is the reason why 3GPP recommends the use of FEC for MBMS and, more specifically, adopts the use of systematic Raptor FEC code (3GPP, 2008b). The Raptor codes belong to the class of fountain codes and are very popular due to their high probability for error recovery and their efficiency during encoding and decoding. In this chapter, we study the application of FEC for MBSFN transmissions over LTE cellular networks. First, we make a cost analysis and define a model for the calculation of the total telecommunication cost that is required for the transmission of the MBSFN data to end users. Then, we propose an innovative error recovery scheme for the transmission of the FEC redundant information during MBMS download delivery. This scheme takes advantage of the MBSFN properties and performs an adaptive generation of redundant symbols for efficient error recovery. The redundant encoding symbols are produced continuously until all the multicast receivers have acknowledged the complete file recovery. Then, we investigate the performance of the proposed scheme against the existing approaches under different MBSFN deployments, user populations and error rates. In this framework, we evaluate the performance of our scheme and we examine whether the use of FEC is beneficial, how the optimal FEC code dimension varies based on the network conditions, which parameters affect the optimal FEC code selection and how they do it.

This work is structured as follows: in Section 2 we present the study related to this scientific domain. In Section 3 we provide an overview of MBMS architecture and we describe the key concepts that our study deals with. The telecommunication cost analysis of the MBSFN delivery scheme is described in Section 4. In Section 5 we describe some approaches for transmission as well as our proposed scheme and in Section 6 the evaluation results of the conducted experiments. Finally, in Section 7 the conclusions are briefly described and in Section 8 all the planned next steps of this work are listed. For the reader’s convenience, Appendix A presents an alphabetical list of the acronyms used in the chapter.

2. Related work

The research over FEC for broadcast and multicast transmission has recently moved from the domain of fixed networks to the wireless communication field. The standardization of MBMS by 3GPP triggered the research on the use of FEC for multicasting in the domain of mobile networks. Even though this research area is relatively new, a lot of solutions have been proposed so far.

In (Luby et al., 2006) an introduction in the Raptor code structure is presented. The Raptor codes are described through simple linear algebra notation. Several guidelines for the practical implementation of the relevant encoders and decoders are presented and the good performance of file broadcasting with Raptor codes is verified. The simulation results verify the efficient performance of the whole process. The same authors in (Luby et al., 2007) present an investigation on MBMS download delivery services in Universal Mobile Telecommunications System (UMTS) considering a comprehensive analysis by applying a detailed and complex channel model and simulation setup. It is concluded that the optimal operating point in this trade-off uses low transmission power and a modest amount of Turbo FEC coding that results in relatively large radio packet loss rates.

The study presented in (Alexiou et al., 2010a) investigates the impact of FEC use for MBMS and examines whether it is beneficial or not and how the optimal FEC code dimensioning varies based on the network conditions, elaborating the parameters which affect the optimal FEC code selection. The simulation results show the behaviour of the standardized FEC scheme evaluated against parameters such as multicast user density and multicast user population. In (Alexiou et al., 2010b), the applicability of FEC via Raptor code in the multicast data transmission is studied while focusing on power control in the Radio Access Network (RAN). The evaluation considers the properties of PTP, PTM as well as hybrid transmission mode that combine both PTP and PTM bearers in RAN. The main assertion that came out is the fact that increasing the power in order to succeed a better Block Error Rate (BLER) is cheaper from power perspective than increasing the power to send the redundant symbols added by FEC decoder.

The study in (Lohmar et al., 2006) focuses particularly on the file repair procedure. The trade-off between FEC protection and successive file repair is discussed extensively. The authors propose a novel file repair scheme that combines PTM filer repair transmission with a PTP file repair procedure. After the analysis, it is proved that the new scheme can achieve better performance than a PTP-only file repair procedure. The overall goal is the optimization of 3G resource usage by balancing the FEC transmission overhead with file repair procedures after the MBMS transmission.

The adoption of FEC is examined from another aspect in (Wang & Zhang, 2008). A potential bottleneck of the radio network is taken into consideration and the authors investigate which are the optimal operation points in order to save radio resources and use the available spectrum more efficiently. The conducted simulation experiments and the corresponding numerical results demonstrate the performance gain that Raptor code FEC offers in MBMS coverage. In more detail, the spectrum efficiency is significantly improved and resource savings are achieved in the radio network.

The reliability and efficiency in download delivery with Raptor codes are examined in (Gasiba et al., 2007). The authors propose two algorithms; one allowing to find a minimum set of source symbols to be requested in the post delivery and one allowing to find a sufficient number of consecutive repair symbols. Both algorithms guarantee successful recovery. These post-repair methods are combined with the regular Raptor decoding process and fully exploit the properties of these codes. Selected simulations verify the efficient performance of file distribution with Raptor codes as well as the algorithms for file repair in case of file distribution to more than one user. Despite the extraordinary performance of Raptor codes, reliable delivery cannot be guaranteed, especially in heterogeneous receiver environments.

Generally, it should be noted that all the existing related work covers research either on the application layer FEC for prior to LTE cellular networks or FEC for the LTE physical layer. It is important to mention that the use of FEC for the multicast transmission over LTE networks has not been studied yet. Any related work, as the works presented above, is dedicated to the previous generations of mobile networks. Therefore, it is our belief and the motivation behind our work that the impact of FEC in MBSFN transmissions should constitute a new domain where the LTE research community should focus on. The contribution of this work includes the review of the current error recovery methods, an extensive cost analysis of the data delivery during MBSFN transmissions in LTE cellular networks and the proposal of a new error recovery scheme which the simulation experiments prove to be more cost effective than the existing ones.

3. Overview of MBMS

3.1 LTE Architecture for MBMS

The LTE architecture for MBMS, or as it is commonly referred to, evolved MBMS (e-MBMS) architecture is illustrated in Fig. 1.

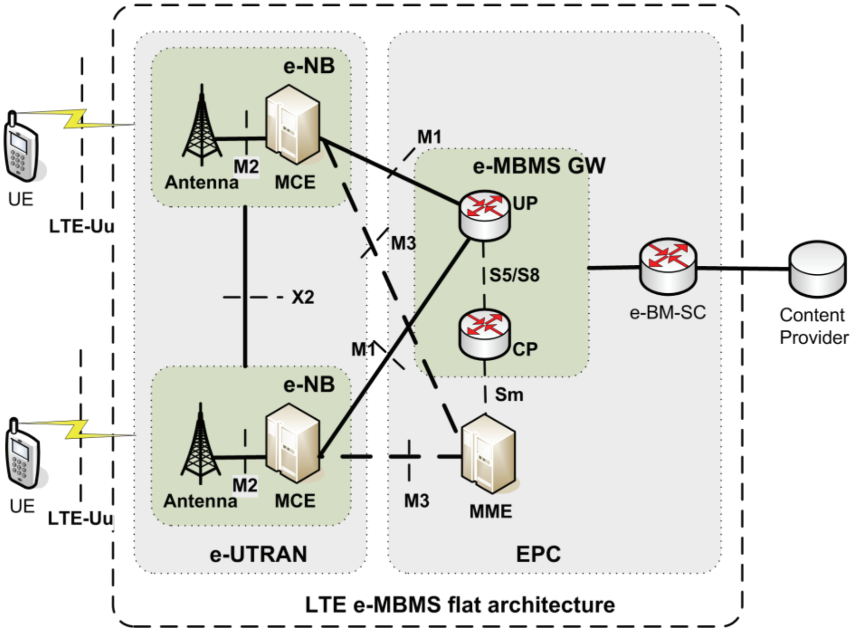


Fig. 1. e-MBMS flat architecture

Within evolved UTRA Network (e-UTRAN) the evolved Node Bs (e-NBs) or base stations are the collectors of the information that has to be transmitted to users over the air-interface. The Multicell/multicast Coordination Entity (MCE) coordinates the transmission of synchronized signals from different cells (e-NBs). MCE is responsible for the allocation of the same radio resources, used by all e-NBs in the MBSFN area for multi-cell MBMS transmissions. Besides allocation of the time / frequency radio resources, MCE is also responsible for the radio configuration, e.g., the selection of modulation and coding scheme. The e-MBMS Gateway (e-MBMS GW) is physically located between the evolved Broadcast Multicast Service Centre (e-BM-SC) and e-NBs and its principal functionality is to forward the e-MBMS packets to each e-NB transmitting the service. Furthermore, e-MBMS GW performs MBMS Session Control Signalling (Session start/stop) towards the e-UTRAN via the Mobility Management Entity (MME). The e-MBMS GW is logically split into two domains. The first one is related to control plane, while the other one is related to user plane. Likewise, two distinct interfaces have been defined between e-MBMS GW and e-UTRAN namely M1 for user plane and M3 for control plane. M1 interface makes use of IP multicast protocol for the delivery of packets to e-NBs. M3 interface supports the e-MBMS session control signalling, e.g., for session initiation and termination (3GPP, 2009; Holma & Toskala, 2009).

The e-BM-SC is the entity in charge of introducing multimedia content into the LTE network. For this purpose, the e-BM-SC serves as an entry point for content providers or any other broadcast/multicast source which is external to the network. An e-BM-SC serves all the e-MBMS GWs in a network.

3.2 Application layer FEC

3GPP has standardized Turbo codes as the physical layer FEC codes and Raptor codes as the application layer FEC codes for MBMS aiming to improve service reliability (3GPP, 2008a). The use of Raptor codes in the application layer of MBMS has been introduced to 3GPP by Digital Fountain (3GPP, 2005). Generally in the literature, FEC refers to the ability to overcome both erasures (losses) and bit-level corruption. However, in the case of an IP multicast protocol, the network layers will detect corrupted packets and discard them or the transport layers can use packet authentication to discard corrupted packets. Therefore the primary use of application layer FEC to IP multicast protocols is as an erasure code. The payloads are generated and processed using a FEC erasure encoder and objects are reassembled from reception of packets containing the generated encoding using the corresponding FEC erasure decoder.

Raptor codes belong to the class of the fountain codes. Fountain codes are record-breaking, sparse-graph codes for channels with erasures, where files are transmitted in multiple small packets, each of which is either received without error or not received. The conventional file transfer protocols usually split a file up into k packet sized pieces and then repeatedly transmit each packet until it is successfully received. A back channel is required for the transmitter to find out which packets need retransmitting. In contrast, fountain codes make packets that are random functions of the whole file. The transmitter sprays packets at the receiver without any knowledge of which packets are received. Once the receiver has received any m packets - where m is just slightly greater than the original file size k - the whole file can be recovered. The computational costs of the best fountain codes are astonishingly small, scaling linearly with the file size.

The Raptor decoder is therefore able to recover the whole source block from any set of FEC encoding symbols only slightly more in number than the number of source symbols. The Raptor code specified for MBMS is a systematic fountain code producing n encoding symbols E from $k < n$ source symbols C. This code can be viewed as the concatenation of several codes. The most-inner code is a non-systematic Luby-Transform (LT) code with l input symbols F, which provides the fountain property of the Raptor codes. This non-systematic Raptor code does not use the source symbols as input, but it encodes a set F of intermediate symbols generated by some outer high-rate block code. This means that the outer high-rate block code generates the F intermediate symbols using k input symbols D.

Finally, a systematic realization of the code is obtained by applying some pre-processing to the k source symbols C such that the input symbols D to the non-systematic Raptor code are obtained. The description of each step and the details on specific parameters can be found in (3GPP, 2008a).

The study presented in (Luby et al., 2006) shows that Raptor codes have a performance very close to ideal, i.e., the failure probability of the code is such that in case that only slightly more than k encoding symbols are received, the code can recover the source block. In fact, for $k > 200$ the small inefficiency of the Raptor code can accurately be modelled by the following equation (Luby et al., 2007):

$$p_f(m,k) = \begin{cases} 1 & \text{if} \quad m < k, \\ 0.85 \times 0.567^{m-k} & \text{if} \quad m \geq k. \end{cases} \tag{1}$$

In (1), $p_f(m,k)$ denotes the failure probability of the code with k source symbols if m symbols have been received. It has been observed that for different k, the equation almost perfectly emulates the code performance. While an ideal fountain code would decode with zero failure probability when $m = k$, the failure for Raptor code is still about 85%. However, the failure probability decreases exponentially when number of received encoding symbols increases.

3.3 File repair procedure

The purpose of file repair procedure is to repair lost or corrupted file segments that appeared during the MBMS download data transmission (3GPP, 2008b). At the end of the MBMS download data transmission each multicast user identifies the missing segments of the transmitted file and sends a file repair request message to the file repair server. This message determines which exactly the missing data are. Then, the file repair server responds with a repair response message. The repair response message may contain the requested data, redirect the client to an MBMS download session or to another server, or alternatively, describe an error case.

The file repair procedure has significant disadvantages since it may lead to feedback implosion in the file repair server due to a potential large number of MBMS clients requesting simultaneous file repairs. Another possible problem is that downlink network channel congestion may be occurred due to the simultaneous transmission of the repair data towards multiple MBMS clients. Last but not least, the file repair server overload, caused by bursty incoming and outgoing traffic, should be avoided. The principle to protect network resources is to spread the file repair request load in time and across multiple servers. The resulting random distribution of repair request messages in time enhances system scalability.

4. Cost analysis of MBSFN

4.1 Introduction

In this section, we present a performance evaluation of MBSFN delivery scheme. As performance metric for the evaluation, we consider the total telecommunication cost for both packet delivery and control signals transmission (Ho & Akyildiz, 1996). In our analysis, the cost for MBSFN polling is differentiated from the cost for packet deliveries. Furthermore, in accordance with (Ho & Akyildiz, 1996), we make a further distinction between the processing costs at nodes and the transmission costs on links. For the analysis, we apply the notations presented in Table 1:

Symbol	Explanation
D_{Uu}	Transmission cost of single packet over Uu interface
C_{Uu}	Total transmission cost over Uu (air) interface
D_{M1}	Transmission cost of single packet over M1 interface
C_{M1}	Total transmission cost over M1 interface
$C_{polling}$	Total transmission cost for polling
C_{SYNC}	Total processing cost for synchronization at eBM-SC
D_{p_eNB}	Cost of polling procedure at each e-NB
D_{M2}	Transmission cost of single packet over M2 interface
N_p	Total number of packets of the MBSFN session
N_{eNB}	Number of e-NBs that participate in MBSFN
N_{cell}	Total number of e-NBs in the topology
N_{p_burst}	Mean number of packets in each packet burst
C_{MBSFN}	Total telecommunication cost of the MBSFN delivery

Table 1. Notations

Before presenting in detail the parameters introduced in Table 1, some general assumptions of our analysis and the topology under examination are presented.

4.2 General assumptions and topology

We assume that the topology is scalable and has the possibility to consist of an infinite number of cells according to Fig. 2. Moreover, in order to calculate the total cost, we assume that the users can be located in a constantly increasing area of cells in the topology, called “UE drop location cells”. Therefore, in the case when UE drop location cells are equal to 1, all users are located in the centre cell (see Fig. 2). The six cells around the centre cell constitute the inner 1 ring. Likewise, the inner 2 ring consists of the 12 cells around the first ring. Following this reasoning, we can define the “inner 3 ring”, the “inner 4 ring” etc.

In this chapter the following user distributions are examined:

- All MBSFN users reside in the centre cell (UE drop location cells = 1).
- All MBSFN users reside in the area included by the inner 1 ring (UE drop location cells = 7).
- All MBSFN users reside in the area included by the inner 2 ring (UE drop location cells = 19).
- And so forth…
- All the infinite cells of the topology contain MBSFN users (UE drop location cells = infinite, i.e., number of cells >> 721 or number of cell rings >> 15).

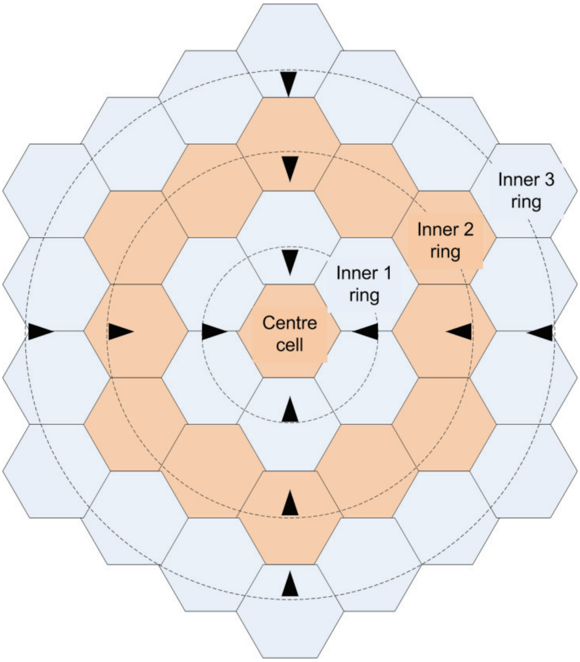


Fig. 2. Topology under examination

The performance of the MBSFN increases rapidly when rings of neighbouring cells outside the "UE drop location cells" area assist the MBSFN service and transmit the same MBSFN data. More specifically according to (3GPP, 2008a; Rong et al., 2008), even the presence of one assisting ring can significantly increase the overall spectral efficiency. Moreover, we assume that a maximum of 3 neighbouring rings outside the "UE drop location cells" can transmit in the same frequency and broadcast the same MBSFN data (assisting rings), since additional rings do not offer any significant additional gain in the MBSFN transmission (3GPP, 2008a; Rong et al., 2008). Our goal is to examine the number of neighbouring rings that should be transmitting simultaneously to the UE drop location cells in order to achieve the highest possible gain, in terms of overall packet delivery cost. For this purpose, we define the following three MBSFN deployments (where "A" stands for an Assisting ring and "I" for an Interference ring, i.e.: a ring that does not participate in the MBSFN transmission):

- AII: The first ring around the UE drop location cells, contributes to the MBSFN transmission, the second and third rings act as interference.
- AAI: The first and the second ring around the UE drop location cells assist in the MBSFN transmission, the third ring acts as interference.
- AAA: indicates that each of the 3 surrounding rings of the UE drop location cells assists in the MBSFN transmission

The system simulation parameters that were taken into account for our simulations are presented in Table 2. The typical evaluation scenario used for LTE is macro Case 1 with 10 MHz bandwidth and low UE mobility. The propagation models for macro cell scenario are based on the Okamura-Hata model (3GPP, 2008a; Holma & Toskala, 2009).

Parameter	Units	Case 1
Inter Site Distance (ISD)	m	500
Carrier Frequency	MHz	2000
Bandwidth	MHz	10
Penetration Loss (PL)	dB	20
Path Loss	dB	Okumura-Hata
Cell Layout		Hexagonal grid, 3 sectors per site, infinite rings
Channel Model		3GPP Typical Urban (TU)
# UE Rx Antennas		2
UE speed	Km/h	3
BS transmit power	dBm	46
BS # Antennas		1
BS Ant. Gain	dBi	14

Table 2. Simulation parameters

4.3 Air interface cost

In this section the transmission cost over the air interface is defined for different network topologies, user distributions and MBSFN deployments. Fig. 3 depicts the resource efficiency of SFN transmission mode (i.e., the spectral efficiency of the SFN transmission normalized by the fraction of cells in the SFN area containing UEs) as the number of UE drop location cells increases, for the 3 different MBSFN deployments (AII, AAI, AAA) presented in the previous paragraph. More specifically, Fig. 3 presents the way the resource efficiency changes with the number of UE drop location cells for a macrocellular Case 1 environment (3GPP, 2008a).

In Fig. 3, we observe that when all users are distributed in the centre cell, the resource efficiency for AAA is 0.06, for AAI 0.12 and for AII 0.19. As a result, when all the MBSFN users reside in the centre cell, AII is the best deployment in terms of resource efficiency. However, we have to mention that in the specific example; the best deployment was selected based only on the air interface performance. Next in our analysis, we will present an alternative/improved approach that selects the best MBSFN deployment based on the overall cost.

To define the telecommunication cost over the air interface, we define as resource efficiency percentage (*RE_percentage*) the fraction of current deployment resource efficiency to the maximum SFN resource efficiency. This percentage indicates the quality of the resource efficiency our current deployment achieves for the macrocellular Case 1, compared to the maximum resource efficiency that can be achieved in Case 1. Then, we define the cost of packet delivery over the air interface (D_{Uu}) as the inverse of *RE_percentage*. This means that as the resource efficiency of a cell increases, the *RE_percentage* increases too, which in turn means that the cost of packet delivery over the air interface decreases.

Finally, the total telecommunication cost for the transmission of the data packets over Uu interface is derived from (2), where N_{eNB} represents the number of e-NBs that participate in MBSFN transmission, N_p the total number of packets of the MBSFN session, and D_{Uu} is the cost of the delivery of a single packet over the Uu interface.

$$C_{Uu} = D_{Uu} \cdot N_p \cdot N_{eNB} \tag{2}$$

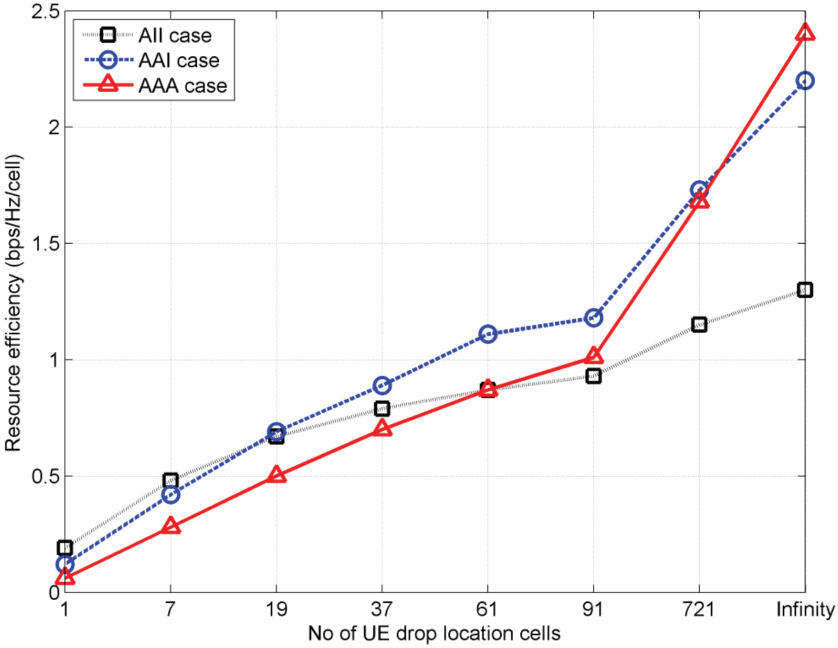


Fig. 3. Resource efficiency vs. number of UE drop location cells for ISD = 500m

4.4 Cost over M1 interface

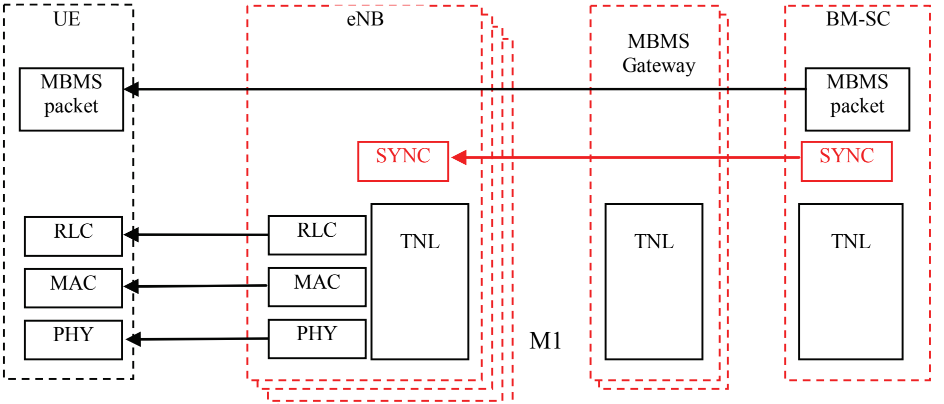
M1 interface uses IP multicast protocol for the delivery of packets to e-NBs. In multicast, the e-MBMS GW forwards a single copy of each multicast packet to those e-NBs that participate in MBSFN transmission. After the correct multicast packet reception at the e-NBs that serve multicast users, the e-NBs transmit the multicast packets to the multicast users via Multicast Traffic Channel (MTCH) transport channels. The total telecommunication cost for the transmission of the data packets over M1 interface is derived from (3), where D_{M1} is the cost of the delivery of a single packet over the M1 interface.

$$C_{M1} = D_{M1} \cdot N_P \cdot N_{eNB} \tag{3}$$

More specifically, D_{M1} depends on the number of hops between the nodes connected by M1 interface and the profile of the M1 interface in terms of link capacity (Alexiou et al., 2007). In general, a high link capacity corresponds to a low packet delivery cost over M1 and a small number of hops, corresponds to a low packet delivery cost.

4.5 Synchronization cost

In order to implement a SFN, each of the transmitting cells should be tightly time-synchronized and use the same time-frequency resources for transmitting the bit-identical content. The overall user plane architecture for content synchronization is depicted in Fig. 4.



SYNC: Protocol to synchronise data used to generate a certain radio frame

Fig. 4. Content synchronization in MBSFN

The SYNC protocol layer is defined on transport network layer to support content synchronization. It carries additional information that enables e-NBs to identify the timing for radio frame transmission and detect packet loss. Every e-MBMS service uses its own SYNC entity. The SYNC protocol operates between e-BM-SC and e-NB. As a result of synchronization, it is ensured that the same content is sent over the air to all UEs (3GPP, 2009). The e-BM-SC should indicate the timestamp (*T*) of the transmission of the first packet of a burst of data (block of packets) by all e-NBs and the interval between the radio transmissions of the subsequent packets of the burst as well. Since the synchronization protocol has not yet been standardized and many alternative protocols have been proposed (3GPP, 2007a), we assume that the transmission timestamp of the first packet of a burst of data is sent before the actual burst in a separate Packet Data Unit (PDU). When time *T* is reached, the e-NB buffer receives another value of *T* and new packet data which correspond to the next burst. All in all, in this case the transmission timing for subsequent bursts is implicitly determined by the size and the number of previous packets (3GPP, 2007a). This in turn means that the synchronization cost depends on the total numbers of multicast bursts/packets per MBSFN session. The total telecommunication cost for the transmission of the synchronization packets is derived from the following equation where D_{M1} is the cost of the delivery of a single packet over the M1 interface and N_{p_burst} is the mean value of the number of packets transmitted each time in the sequential bursts of the MBSFN session.

$$C_{SYNC} = \frac{N_P}{N_{p\_burst}} \cdot D_{M1} \cdot N_{eNB} \tag{4}$$

4.6 Polling cost

To determine which cells contain users interested in receiving a MBSFN service, we assume that a polling procedure is taking place. In contrast to counting procedure used in UMTS MBMS, where the exact number of MBMS users was determined, with polling we just determine if the cell contain at least one user interested for the given service.

The e-NBs initiate the detection procedure by sending a UE feedback request message on Multicast Control Channel (MCCH). The cost of sending this request message corresponds to the cost of polling procedure at e-NB (D_{p_eNB}). The message includes the MBMS service ID that requires the user feedback and a "dedicated access information" (in the form of a particular signature sequence) that is to be used for the user feedback by the UEs. After receiving the feedback request message, the UEs which are interested in receiving the particular e-MBMS service, respond to the request by sending a feedback message using the allocated "dedicated access resources" over non-synchronous Random Access Channel (RACH).

The e-NB receives the feedback from the UEs in the form of signature sequence. If energy is detected corresponding to the known signature sequence, this indicates that at least one user in the coverage area of the e-NB is interested in or activated the particular e-MBMS service. This information (packet) is sent to the MCE over M2 interface which in turn estimates which cells contain multicast users interested for the given e-MBMS service (3GPP, 2006).

The total cost associated to the polling procedure is derived from (5), where N_{eNB} represents the number of e-NBs that participate in MBSFN transmission, N_{cell} is the total number of e-NBs in the topology and D_{M2} is the cost of the delivery of a single packet over the M2 interface.

$$C_{Polling} = D_{p\_eNB} \cdot N_{cell} + D_{M2} \cdot N_{eNB} \tag{5}$$

4.7 Total telecommunication cost

Based on the analysis presented in the previous paragraphs, the total telecommunication cost of the MBSFN delivery scheme is derived from (6)

$$\begin{aligned} &C_{MBSFN} = C_{Uu} + C_{M1} + C_{SYNC} + C_{Polling} = \\ &\left(D_{Uu} + D_{M1} + \frac{D_{M1}}{N_{p\_burst}} \right) \cdot N_p \cdot N_{eNB} + \left(D_{p\_eNB} \cdot N_{cell} + D_{M2} \cdot N_{eNB} \right) \end{aligned} \tag{6}$$

5. Proposed scheme

The scheme that we propose introduces the exclusive sending of redundant encoding symbols instead of using the file repair procedure for the complete recovery of a transmitted file. It is important to clarify that the transmission of all the encoding symbols is performed over the MBSFN infrastructure. The scheme takes advantage of the fact that the Raptor FEC decoder, based on a fountain code, is able to recover the source blocks from any set of encoding symbols only slightly more in number than the number of source symbols. Therefore, it is proposed that the Raptor FEC encoder in the sender generates redundant symbols until it takes an acknowledgement from all the receivers that all the initial source symbols have been recovered. Our work investigates the application of FEC over the download delivery method, so the rest of our analysis focuses only on this MBMS delivery method.

In the rest of this section, we describe our proposed scheme in more detail and we present it against existing error recovery approaches specified by 3GPP for the MBMS download delivery method (3GPP, 2008b). In general, depending on the error recovery scheme used, the following three different approaches can be distinguished:

- Approach A1: Retransmission of the lost file's segments with MBSFN.

- Approach A2: Prefixed FEC overhead during the e-MBMS service transmission combined with retransmission of lost file's segments.
- Approach A3: Exclusive transmission of redundant symbols for file recovery (proposed scheme).

Assuming that an MBMS download delivery of a file is performed using MBSFN operation, then based on the error recovery approach used (A1, A2 or A3), the transmission process proceeds as illustrated in Fig. 5.

Initially, we examine the case where no FEC is used (Fig. 5, A1). In this case, the single error recovery scheme used is the file repair procedure and thus the receivers request the retransmission of the lost file's segments at the end of the process. Since MBSFN operation is used, the lost segments are transmitted to all the users in the area irrespectively of whether they have requested them or not. On the other hand, in case FEC is used (Fig. 5, A2 and A3), then the file to be downloaded is partitioned into one or several so-called source blocks. As mentioned above, for each source block, additional repair symbols can be generated by applying Raptor FEC encoding.

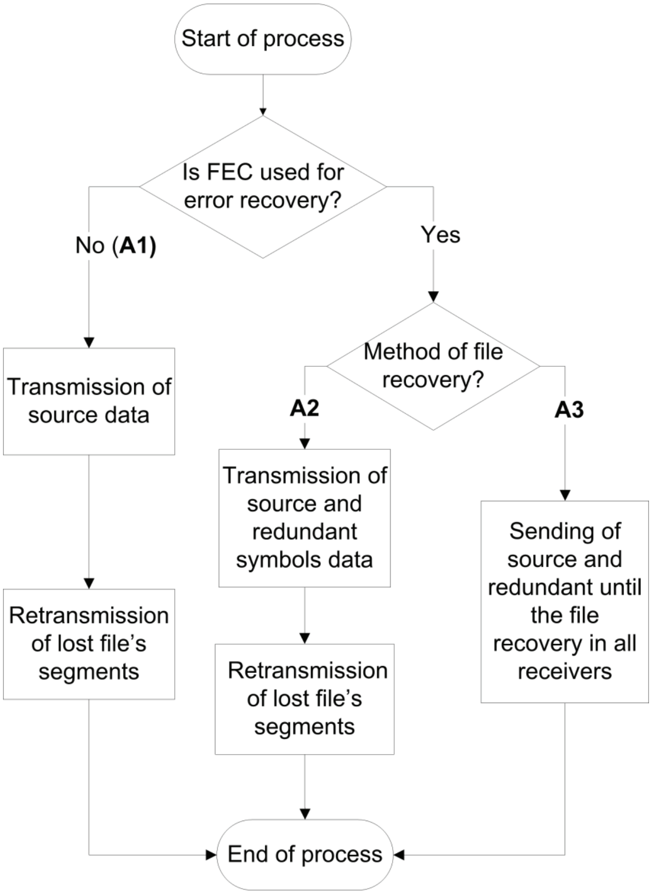


Fig. 5. Flowchart of error recovery approaches

The ideal situation in an MBMS session is that all the multicast receivers have collected the source blocks from the file and therefore the complete file recovery is possible. Nevertheless, the above occasion rarely happens. In most of cases, due to miscellaneous network conditions, receivers cannot recover all the source blocks since some of the received blocks are corrupted and they are rejected. In order to solve this situation and repair lost or corrupted file segments, we can use the standardized method defined by 3GPP in (3GPP, 2008b) (Fig. 5, A2). According to this approach, the complete error recovery may be achieved through the retransmission of source and redundant data through the file repair procedure, i.e., the selective retransmission of lost file's segments that takes place at the end of the transmission. On the other hand, the scheme that we propose introduces the exclusive use of FEC for efficient error recovery during MBMS transmission over MBSFN. In more detail, redundant symbols are produced continuously by the sender until the sender has received acknowledgment messages from all the receivers participating in the multicast group (Fig. 5, A3). On the MBMS receiver's side, each receiver sends back to the sender an acknowledgment message upon collection of the encoding symbols that are sufficient for the complete file recovery. The sender keeps track of which receivers have acknowledged and continues to send redundant encoding symbols until all receivers have acknowledged the complete file reception.

6. Performance evaluation

6.1 Simulation model

During our simulation experiments, we compare the proposed approach (A3) with the existing error recovery approaches (A1 and A2) presented above. The performances of the above approaches are evaluated through a realistic simulation model that incorporates all the network parameters and is consistent with the corresponding 3GPP specifications. In this framework, we consider the performance of our approach under different error rates, user populations and FEC configurations.

As already mentioned, the evaluation of the above approaches is performed from telecommunication cost perspective. The estimation of each factor of the cost is based on the telecommunication cost for MBSFN transmission given by equation (6). It should be noted that the above recovery processes are provided via MBSFN transmissions. Our simulation model incorporates all the properties of a typical Raptor code defined for data delivery over e-MBMS as they are defined by 3GPP in (3GPP, 2009). The total telecommunication cost for a complete file reception is the sum of the cost for the initial file transmission, the cost for the transmission of the additional packets due to FEC encoding and the cost for the selective retransmission of lost packets. The estimation of each of the above three terms is based on the telecommunication cost for MBSFN transmission given by (6).

It is worth clarifying that since n encoding symbols are produced from $k < n$ source symbols, then the overhead added due to the Raptor encoding, i.e., the number of repair symbols divided by the number of source symbols, is equal to the fraction $(n-k)/k$. Given that the packet size is fixed, the FEC overhead that is needed for the transmission of a file of given size is also equal to the same fraction. Thus, it is obvious that, in terms of percentage over the initial file size, the overhead of the additional packets that are needed for the download delivery of a given file is $(n-k)/k$. This packet overhead creates additional cost which is taken into account by our scheme. During the decoding procedure in each UE, there is a decoding failure probability represented by (1). When a packet loss rate $p_{loss} > 0$ is applied over the e-MBMS bearer, the number of the received symbols m may become less than the n symbols initially transmitted. As a result of the packet loss, the failure probability $p_f(m,k)$ increases. If the recovery of the k source symbols through decoding procedure fails in a UE and selective retransmission is invoked by the UE for the recovery of the lost packets, then this procedure creates an additional cost which is also taken into account by our scheme.

The system simulation parameters that were taken into account for our simulations are presented in Table 2. The typical evaluation scenario used for LTE is macro Case 1 with 1.4 MHz bandwidth and low UE mobility. The propagation models for macro cell scenario are based on the Okamura-Hata model (3GPP, 2007b).

6.2 Cost vs. MBSFN deployment

Having analyzed the distinct costs of the MBSFN delivery scheme, we evaluate the total cost of each of the MBSFN deployments (AAA, AAI, AII) for different user distributions for the distinguished error recovery approaches (A1, A2, A3). The topology we use is the one described in Section 4.2. Through this experiment, our goal is to evaluate each MBSFN deployment for different user distribution and not to examine whether FEC use is beneficial or not.

Fig. 6 depicts the total cost of the SFN transmission without FEC, with a prefixed FEC overhead and using redundant symbols for the 3 different deployments (AII, AAI, AAA) as the number of UE drop location cells increases. We observe that for the first 3 user distributions (cases of 1, 7, 19 UE drop location cells), the AII deployment ensures the lowest cost for the delivery of the MBSFN data and therefore is the most efficient deployment for

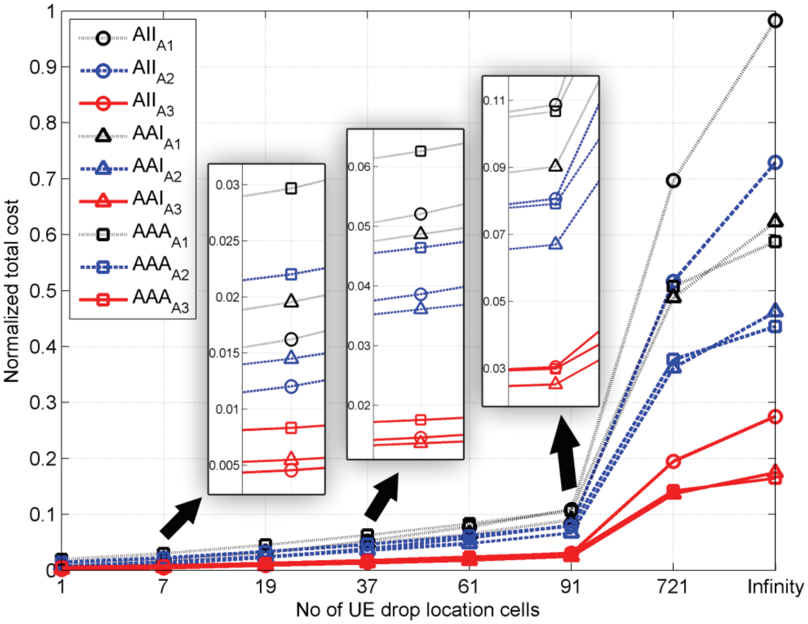


Fig. 6. Cost vs. MBSFN Deployment (Packet loss rate=5%, FEC overhead =5%, UE population=100)

the delivery of the MBSFN data. On the other hand, for UE drop location cells 37, 61, 91 and 721 cells, AAI is the most cost efficient deployment. Finally, for the case of the MBSFN transmission where the users are residing in infinite cells, the AAA deployment is more efficient than the other two deployments since it results in a lower overall cost.

Generally, it is necessary to switch between the 3 MBSFN deployments, when the number of UE drop location cells increases, so as to achieve the lowest possible transmission cost. As the number of UE drop location cells increases, the most efficient deployment for the delivery of the MBSFN data, switches from AII, to AAI and finally to AAA when the number of cells that have users interested in the MBSFN service approaches infinity (number of cells >> 721). This switching can save resources both in the core network and the air interface. For example, in the case of 721 UE drop location cells, we observe that the normalized total cost without FEC application is 0.6967 when AII is used. However, when AAI is used the total cost is 0.4879. Therefore, the deployment of AAI instead of AII can decrease the total telecommunication cost by (0.6967-0.4879) / 0.6967 = 29.96%.

At this point, it is important to clarify that for the rest of our analysis the number of the UE drop location cells is 7 so the deployment that we choose for the carried experiments is AII that results in the lowest telecommunication cost for the specific case. Table 3 lists all the additional simulation settings for the rest of our experiments.

Parameters	Units	Value
Cellular layout		Hexagonal grid, 19 cell sites
UE drop location cells		7
System bandwidth	MHz	1.4
UE # Rx Antennas		2

Table 3. Additional simulation settings for the experiment

6.3 Cost vs. packet loss

This section evaluates the total costs for different packet loss rates assuming: for the examined approaches. In the first instance of the experiment (Fig. 7), the fixed overhead used by the FEC encoding in approach A2 has been set to 5%. In Fig. 7, the normalized total telecommunication cost is plotted against the packet loss probability. As Fig. 7 presents, the conventional retransmission of lost segments (approach A1) is the most inefficient approach compared to the two other approaches that use FEC, irrespectively of the packet loss rate. Furthermore, in this figure, we observe that approach A2 has nearly the same total telecommunication cost with the proposed approach A3 until the packet loss rate reaches 3%. However, as the packet loss rate increases, the cost of approach A2 increases exponentially. On the other hand, an increase in the packet loss rate causes a linear increase in the cost of approach A3.

The first observation from Fig. 8 is that for higher fixed FEC overhead (15%) for approach A2, the approach A1 presents again the highest total telecommunication cost among the three approaches. Fig. 8 also reveals that approaches A2 and A3 show very close behaviour until packet loss approaches 10%. In approach A2, however, higher values of packet loss rate increase the total telecommunication cost drastically. Therefore, it is worth mentioning that a further increase in FEC overhead of A2 will just increase the total cost without actually improving the overall performance of the FEC scheme. To sum up, it has been shown that the proposed approach A3 ensures the lowest total cost irrespectively of the network conditions in terms of packet loss rate.

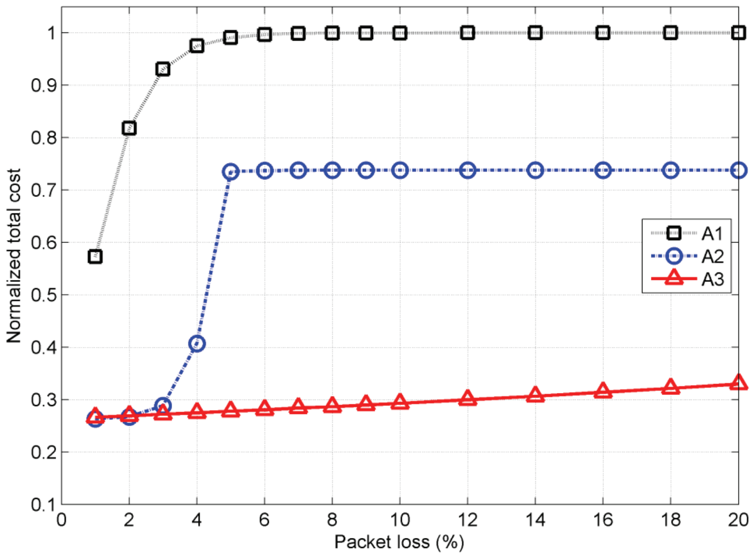


Fig. 7. Cost vs. packet loss rate (UE population = 100, fixed FEC overhead = 5%)

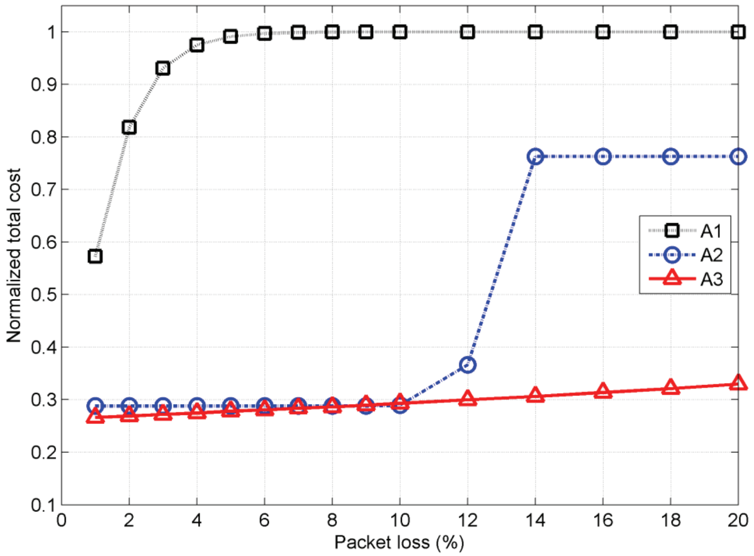


Fig. 8. Cost vs. packet loss rate (UE population = 100, fixed FEC overhead=15%)

6.4 Cost vs. FEC overhead

This paragraph presents the impact of the prefixed FEC overhead used on the approach A2 on the comparison of the three approaches under investigation. More specifically, Fig. 9 presents the normalized total cost of the three approaches as a function of the applied FEC overhead percentage, when the packet loss rate is equal to 5% and the total number of MBSFN users in the topology is 100. Obviously, the prefixed FEC overhead concerns only approach A2 and the total telecommunication cost for approaches A1 and A3 is constant and does not depend on this parameter (Fig. 9).

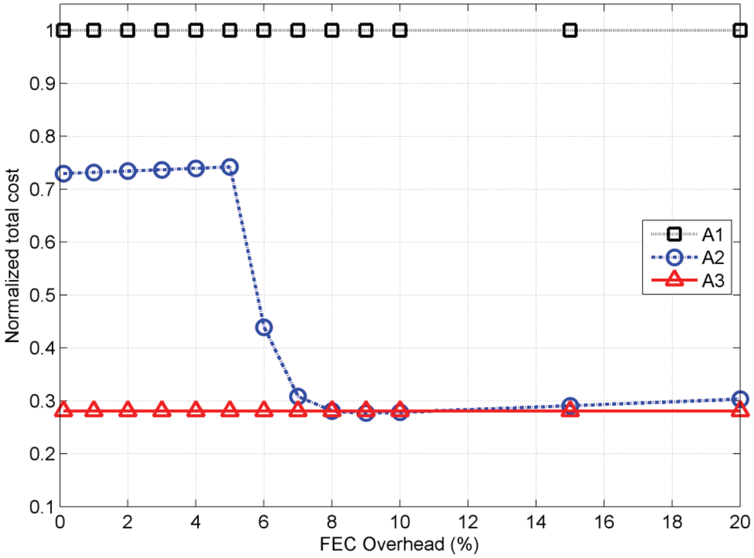


Fig. 9. Cost vs. fixed FEC overhead (packet loss rate = 5%, UE population =100)

On the other hand, the prefixed FEC overhead percentage has a direct impact on the performance of approach A2. Indeed, when approach A2 is applied and the additional information introduced by FEC remains low enough (0%-5%), the unreliable redundant retransmissions keep the total cost in unacceptable high levels. On the other hand, if the percentage of the applied FEC overhead is high enough (in the specific scenario higher than 10%) the total cost increases without actually improving the system's performance. The lowest values of total cost are achieved when the percentage of redundant information introduced by approach A2 is around 8%.

It is worth mentioning that the amount of the prefixed FEC overhead is a matter of argument in FEC schemes. Sometimes a small amount does not have any effect to the transmission and, consequently, the need for packets' retransmission and the total telecommunication cost increase. On the other hand, a large amount of a fixed FEC overhead may cause the same results. In any case, as depicted in Fig. 9, the proposed scheme (A3) ensures the lowest cost and proves a stable behaviour when network condition changes are often.

In order to further prove the efficiency and the stability of the proposed approach, we present an overview of how the value of the total telecommunication cost varies based on the FEC overhead used for approach A2 and the packet loss rate. The same experiment is conducted for the different MBSFN deployments (AAA, AII, AAI) with similar results and therefore we only present the results for the most efficient deployment (i.e., AII). It is should be mentioned that the term FEC overhead is only used for comparison purposes since the FEC overhead only affects the performance of approach A2 where this term actually represents the prefixed FEC overhead that is selected.

Fig. 10 summarizes the simulation results. It confirms the previous observations and reveals the efficiency of the proposed approach. More specifically, it can be noticed that the total cost introduced by the proposed approach (A3) increases linearly as the packet loss rate increases, ensuring in this way the system's stability. On the other hand, the increase in the packet loss rate causes an abrupt increment in the total cost of A1 and A2. However, the most important observation from Fig. 10 is that the proposed method ensures the lowest telecommunication cost irrespectively of the packet loss and the FEC overhead rate. This fact can relax the network in heavy load conditions.

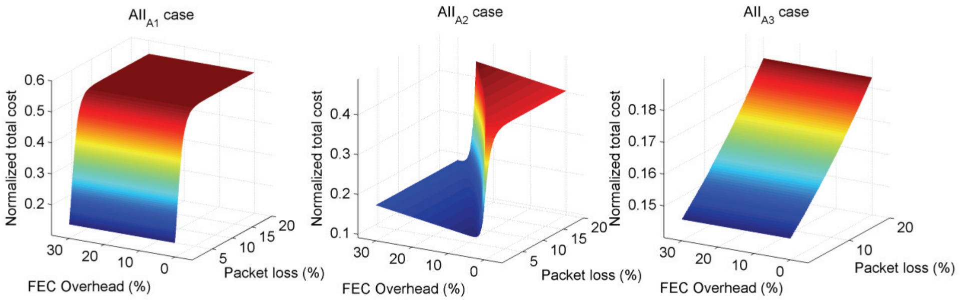


Fig. 10. Cost vs. packet loss rate vs. FEC overhead (UE population =100, deployment: AII)

6.4 Cost vs. multicast user population

One parameter that has a significant impact on the total telecommunication cost for the transmission of a multicast MBSFN service is the user population. Fig. 11 presents the normalized total cost of the three approaches as a function of the number of users in the

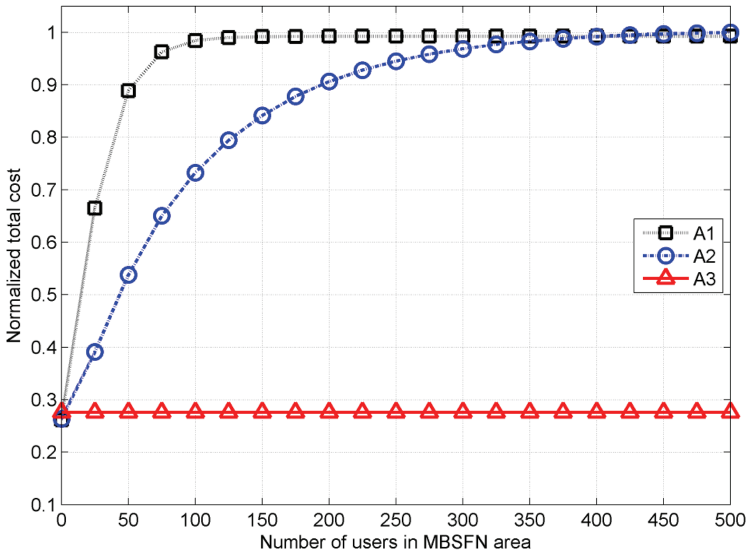


Fig. 11. Cost vs. multicast user population (packet loss rate=5%, fixed FEC overhead = 5%)

MBSFN area when the packet loss rate is equal to 5% and prefixed FEC overhead introduced by A2 is 5%. One important result is that the conventional retransmissions of lost segments (approach A1) and the application of a prefixed FEC overhead (approach A2) may keep the total cost in acceptable levels only for small number of users. As the number of users becomes large, it is evident that approaches A1 and A2 do not perform cost-efficiently. This occurs because an increase in the number of users results in an increase of failure probability. This in turn indicates that there is an extra need for retransmission of the lost segments.

On the other hand, Fig. 11 reveals that the normalized total cost of the proposed scheme is independent of the number of users and also remains in very low levels. Therefore sending redundant symbols is proven to be the most efficient way to ensure the reliable reception of MBSFN data among the three approaches.

7. Conclusion

In this chapter, we have presented a study on the application of FEC during MBSFN transmission over LTE cellular networks. We have investigated the performance of the file recovery approaches which are standardized by 3GPP for the multicast data delivery via e-MBMS and proposed an efficient new error recovery scheme for the MBSFN operation. The proposed scheme is based on the Raptor codes standardized by 3GPP for FEC use in cellular multicasting. It uses exclusively the FEC technique for the complete file recovery. The sender generates symbols, through a Raptor FEC encoder, and sends the redundant encoding symbols until it receives an acknowledgment message from all the receivers participating in the multicast group, that the file recovery has been completed. In order to evaluate our approach, we have conducted extensive simulation experiments. Also a direct comparison of our approach with the other existing approaches has been performed. Various MBSFN deployments, FEC code dimensions and error rates have been examined. Based on these parameters, we have calculated the total telecommunication cost that is required for the MBSFN transmission towards the mobile users for the various approaches. Our evaluation has been performed through a realistic simulation model that incorporates all the above parameters and is consistent with the relevant 3GPP specifications.

The simulation results have shown how the optimal FEC code dimension varies depending on the different network conditions. In more detail, we have concluded that parameters like the MBSFN deployment, the multicast user population and the packet loss rate affect the optimal FEC code dimension and we have investigated how they do it. It is important to mention that all the above results have been qualitatively assessed and explanations for the model behaviour have been provided.

The most important conclusion of our simulation experiment is that the proposed approach can offer improved performance during MBSFN operation in terms of total telecommunication cost. The main reason is that our approach can take advantage of the main property of MBSFN operation which specifies that MBMS data are broadcasted simultaneously over the air from multiple tightly time-synchronized cells. Therefore it transmits redundant information that is necessary to all receivers for the error recovery, instead of selectively retransmitting lost segments that are probably different among the receivers (due to different packet loss patterns). Based on the above procedure, the proposed approach can save resources both in the wired and more importantly in the wireless link, allowing the uses to experience more demanding applications and services.

8. Future work

The step that follows this work could be the investigation of the proposed scheme against a PTP file repair session. The reason is that, in some cases, the setup of multiple file repair procedures could be more efficient that the use of already setup MBSFN sessions. Another idea could be the modelling and the implementation of a mechanism that makes efficient Raptor code selection for LTE networks. This mechanism could monitor the network conditions, e.g., parameters like the multicast user population, the user distribution and the packet loss rate, and use them as input in order to forecast the appropriate amount of redundant symbols for FEC encoding. Finally, another possible field for future research may be the investigation of the FEC schemes from power control perspective. The work presented in this chapter could be the base for a scheme that combines FEC code selection with efficient power allocation in LTE cellular networks.

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Appendix A. Acronyms

Acronym	Explanation
3GPP	3rd Generation Partnership Project
ARQ	Automatic Repeat re-Quest
BLER	Block Error Rate
CP	Cyclic Prefix
e-BM-SC	Evolved Broadcast Multicast Service Center
e-MBMS	Evolved MBMS
e-MBMS GW	E-MBMS Gateway
e-NBs	Evolved Node B
e-UTRAN	Evolved UTRA Network
FEC	Forward Error Correction
ISD	Inter Site Distance
LT	Luby-Transform
LTE	Long Term Evolution
MBMS	Multimedia Broadcast and Multicast Service
MBSFN	MBMS over Single Frequency Network
MCE	Multicell/multicast Coordination Entity
MME	Mobility Management Entity
OFDM	Orthogonal Frequency-Division Multiplexing
PL	Penetration Loss
PTM	Point-to-Multipoint
PTP	Point-to-Point
RACH	Random Access Channel
RAN	Radio Access Network
SFN	Single Frequency Network
TU	Typical Urban
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTRA	Universal Terrestrial Radio Access