INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. 2011; **24**:607–627
Published online 28 August 2010 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/dac.1178

A study of forward error correction for mobile multicast

Antonios Alexiou[1], Christos Bouras[1,2,*,†] and Andreas Papazois[1,2]

[1]*Computer Engineering and Informatics Department, University of Patras, GR-26504 Patras, Greece*
[2]*Research Academic Computer Technology Institute, N. Kazantzaki, GR-26504 Patras, Greece*

SUMMARY

3rd Generation Partnership Project (3GPP) has standardized the use of forward error correction (FEC) for the provision of reliable data transmission in the mobile multicast framework. This error control method inevitably adds a constant overhead in the transmitted data. However, it is so simple as to meet a prime objective for mobile multicast services; that is scalability to applications with thousands of receivers. In this paper, we present a study on the impact of application layer FEC on mobile multicast transmissions. We examine whether it is beneficial or not, how the optimal code dimension varies based on network conditions, which parameters affect the optimal code selection, and how this can be done. Additionally, we focus on one of the most critical aspects in mobile multicast transmission, which is power control. The evaluation is performed with the aid of a novel scheme that incorporates the properties of an evolved mobile network, as they are specified by the 3GPP. Copyright © 2010 John Wiley & Sons, Ltd.

Received 29 December 2009; Revised 6 May 2010; Accepted 6 July 2010

KEY WORDS: mobile networks; multicast; forward error correction; power control

1. INTRODUCTION

There are many ways to provide reliability in multicast transmission. The best-known method that works 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 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 additional

*Correspondence to: Christos Bouras, Research Academic Computer Technology Institute, N. Kazantzaki, GR-26504 Patras, Greece.
†E-mail: bouras@cti.gr

data allow the receiver to reconstruct the source information. 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 motivation. The encoding eliminates the effect of independent losses at different receivers. Additionally, the dramatic reduction in the packet loss rate reduces the need to send feedback to the sender. Therefore, a feedback channel may not be necessary or whenever feedback is required, the feedback implosion is avoided. 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. This is the reason why 3rd Generation Partnership Project (3GPP) recommends the use of application layer FEC for Multimedia Broadcast/Multicast Service (MBMS) and, more specifically, adopts the use of Raptor FEC code [1].

In this paper, we study the applicability of FEC over the multicast data transmission in mobile networks. Our investigation is performed with the aid of a scheme that uses a probabilistic method for modeling the multicast user distribution in the network and estimates the telecommunication cost of multicast data delivery. By using this model, we investigate the impact of FEC use in MBMS. We try to determine the efficient working point in the trade-off between the FEC code overhead and the retransmission cost. We also examine whether FEC use is beneficial or not, how the optimal FEC code dimensioning varies based on the network conditions, which parameters affect the optimal FEC code selection and how this can be done. Additionally, we focus on one of the most critical aspects in mobile multicast transmission, which is the power control in the Radio Access Network (RAN). Our scheme incorporates the properties of an evolved mobile network that uses High-Speed Downlink Packet Access (HSDPA) technology for high speed data delivery to mobile terminals. Our assessment is not only from power consumption point of view but also from energy consumption and time perspective. It is important to mention that our analysis is in accordance with the 3GPP specifications and considers all the possible transport channels deployments in the RAN (point-to-point channels (p-t-p), the point-to-multipoint channels (p-t-m), and combinations of p-t-p and p-t-m transport channels). The outcome of our work is an extensive insight into all the aspects of the FEC application during mobile multicast transmission, some of which have not been considered so far.

This paper is structured as follows: in Section 2 we present the work related to this scientific domain. In Section 3 we provide an overview of MBMS and describe the key concepts that our study deals with; namely, the power control in RAN and the FEC process in MBMS. Section 4 gives an insight into the probabilistic method through which we model the multicast user distribution in the mobile network. Section 5 provides a detailed description of our simulation scheme. In Section 6 our simulation experiments and their results are thoroughly presented. Finally, some concluding remarks and possible next steps are stated in Sections 7 and 8 respectively.

2. RELATED WORK

The initial research on the use of FEC for multicasting was conducted in the domain of fixed networks. The deployment of IP multicast in the Internet Multicast Backbone made the implementation of error control functions more challenging for multicast than for unicast. As a result, a lot of studies have been published since then. A very representative study over this domain is described in [2], where the authors propose a layered FEC scheme for video multicast over fixed networks. This scheme dictates that receivers can obtain different levels of protection that are commensurate with their respective channel conditions. This is achieved through the organization of FEC into multiple layers. The effects of bursty losses are amortized by staggering the FEC streams in time, giving rise to a trade-off between delay and quality.

The standardization of MBMS by 3GPP triggered the research on the use of FEC for multicasting in the domain of mobile networks. Although this research area is relatively new, a lot of solutions have been proposed so far. In [3], an introduction in the Raptor code structure is presented. The Raptor codes are described through simple linear algebra notation. Several guidelines for the

DOI: 10.1002/dac

practical implementation of the relevant encoders and decoders are presented and the good performance of file broadcasting with Raptor codes is verified. The same study includes an investigation over the efficient implementation of Raptor codes in traditional broadcast systems like Digital Video Broadcast (DVB).

The study presented in [4] focuses on the determination of the MBMS Systematic FEC features and characteristics in order to deploy an optimum service from the operator's point of view. The performance of Systematic Raptor FEC is evaluated through simulation experiments and detailed results are presented. The experimental results are analyzed and the amount of additional FEC repair data is estimated for various packet error rates. The final conclusion is that although Raptor coding adds redundant packets, it significantly improves the MBMS performance by recovering the lost packets during the transmission. Therefore, the deployment of Raptor codes would enable the operator to reduce the allocated base station transmission power for MBMS service, and as a result to improve the MBMS quality and extend the MBMS coverage.

The authors of [5] investigate the application of Raptor codes to MBMS in a realistic simulation environment. This work focuses on the download delivery method of MBMS and uses an overall system model that represents accurately not only the application layer but also the physical channel and the user mobility in a mobile network. In this realistic simulation environment, optimal system parameters are proposed for both application and physical layers under different mobility models, with different bearer parameters. The achieved cross-layer optimization uses low transmission power and a modest amount of Turbo FEC coding in the physical layer, which results in relatively large radio packet loss rates and that is compensated for with a substantial amount of Raptor coding. Finally, it is concluded that these optimal operating points use far less transmission energy for download delivery of files than possible operating points without Raptor.

The study presented in [6] focuses on the MBMS download delivery method and deal with the trade-off between the FEC protection and the successive file repair procedure. The authors propose a novel file repair scheme that combines a p-t-m file repair transmission and a p-t-p file repair procedure in a way that the UMTS resource usage is optimized. The proposed scheme aims at balancing the FEC transmission overhead with the file repair procedures after the MBMS transmission. It is concluded that using only a p-t-m file repair scheme is not efficient, since the sender does not know the amount of needed repair data. Additionally, the simulation results and their analysis show that the new scheme achieves better performance than a p-t-p-only file repair procedure.

The adoption of FEC is examined from another aspect in [7]. 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.

Despite the high quality and the scientific vigor of the published studies, none of these presents a complete evaluation study of the use of FEC in mobile multicast. It is also important to mention that all the existing studies have focused on the legacy UMTS system and the application of FEC has not been presented in a framework that incorporates the evolution of UMTS beyond its 3rd generation. The goal achieved by our work is threefold. At a first level, we present an extensive analysis of FEC use in MBMS. In particular, the trade-off between the FEC overhead and the retransmission cost is examined under various user distributions and error rates. At a second level, our analysis covers the impact of FEC on base stations' transmission power. Power control is one of the most important aspects in MBMS because Node B's transmission power is a limited resource and must be shared among all MBMS users in a cell. This in turn means that FEC power efficiency is something that needs to be taken into account by the Radio Resource Management (RRM) mechanisms of next generation mobile networks. To our knowledge this aspect is not presented so far by other research groups. At a third level, the advantages and drawbacks of FEC

DOI: 10.1002/dac

use in HSDPA are highlighted. To that end, we believe that our work covers the issue of FEC use in MBMS transmissions with a comprehensive way and this is actually the motivation behind our study.

3. MBMS

3.1. Overview

MBMS is a p-t-m service in which data are transmitted from a single source entity to multiple recipients. It provides the end user with two MBMS User Services; streaming delivery for real-time multimedia streams and download delivery for reliable multicasting of files. 3GPP has specified that these MBMS delivery methods make use of MBMS bearers for content delivery but may also use the associated delivery procedures for quality reporting and file repair. Streaming data such as video streams, audio programs, or timed text being encapsulated in RTP are transported over the streaming delivery network. On the other hand, during download delivery, discrete objects such as still images, text, multimedia data encapsulated in 3GPP file formats, or other binary data are transported using the File Delivery over Unidirectional Transport (FLUTE) protocol when delivering content over MBMS bearers [1]. Figure 1 gives an overview of the mobile network entities and architecture as defined for MBMS by 3GPP [1].

Some basic mobile network nomenclature that is used in this paper is listed in Table I. Since this is not the purposes of this paper, the functionality of each element is not described. However, for more information on this, the reader is referred to the relevant bibliography, e.g. [8].

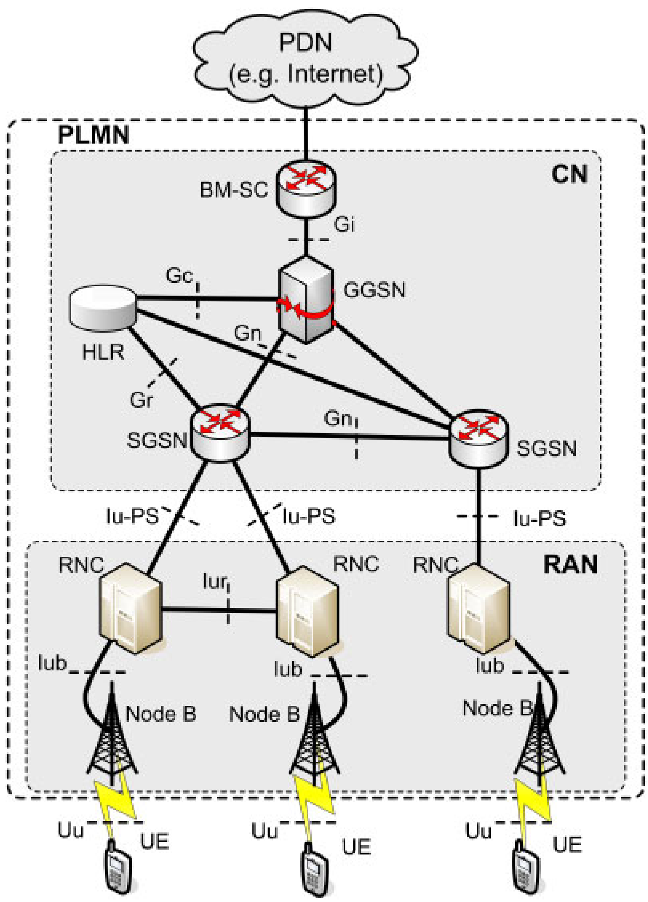

Figure 1. MBMS network architecture.

Table I. Basic mobile networks nomenclature.

Acronym	Expanded meaning
BM-SC	Broadcast Multicast-Service Center
CN	Core Network
GGSN	Gateway GPRS Support Node
PDN	Packet Data Network
PLMN	Public Land Mobile Network
RA	Routing Area
RNC	Radio Network Controller
SGSN	Serving GPRS Support Node
UE	User Equipment
RRA	RAN Registration Area
RAN	Radio Access Network

Power control in the RAN is one of the most critical aspects in MBMS. The downlink transmission power in mobile networks is the scarcest resource and, thus, it should be optimally utilized. The main purpose of power control is to minimize the transmitted power, thus avoiding unnecessary high power levels and eliminating inter-cell interference. 3GPP specifies that MBMS data delivery can be provided by either multiple p-t-p channels or by a single p-t-m channel. The most important types of downlink transport channels are the High Speed-Downlink Shared Channel (HS-DSCH) and the Forward Access Channel (FACH). The HS-DSCH has been introduced for HSDPA operation and is a p-t-p transport channel shared by several UEs. The FACH is a p-t-m channel and, consequently, a single FACH can carry information for more than one UE in a cell due to its broadcast nature [9].

During the p-t-p downlink transmissions through HS-DSCH, Link Adaptation functionality is used to maintain the quality of the link and thus to provide a reliable connection for the receiver to obtain the data with an acceptable error rate. Transmitting with just enough power to maintain the required quality for the link also ensures that there is minimum interference affecting the neighboring cells. However, when a user consumes a high portion of power, more than actually is required, the remaining power, allocated for the rest of the users, is dramatically decreased, thus leading to a significant capacity loss in the system [8, 10].

During p-t-m downlink transmissions through FACH, base station transmits at a power level that is high enough to support the connection to the receiver with the highest power requirement among all receivers in the multicast group. This would still be efficient because the receiver with the highest power requirement would still need the same amount of power in a unicast link, and by satisfying that particular receiver's requirement, the transmission power will be enough for all the other receivers in the multicast group. Consequently, the transmitted power is kept at a relatively high level in most of the time, which in turn, increases the signal quality at each receiver in the multicast group. On the other hand, a significant amount of power is wasted and moreover inter-cell interference is increased [8, 10].

As a consequence, downlink transmission power has a key role in MBMS planning and optimization. The coexistence of transport channels of different nature (both p-t-p and p-tm) in the same service and the capability of switching between these different types are some of the most important features of MBMS. Their importance is based on that these features allow high flexibility and a very efficient use of the scarce radio resources while the service constraints are preserved [8–10]. The following paragraphs provide an analytical description of the HS-DSCH and FACH power profiles and their power consumption characteristics during MBMS transmissions.

3.2. HS-DSCH power profile

HS-DSCH is a rate controlled rather than a power controlled transport channel. In HSDPA, the fast power control characterizing Release '99 channels is replaced by the Link Adaptation functionality, including techniques such as dynamic Adaptive Modulation and Coding (AMC),

DOI: 10.1002/dac

multi-code operation, fast scheduling, Hybrid ARQ (HARQ), and short Transmission Time Interval (TTI) of 2 ms [8, 11].

The HS-DSCH Signal-to-Interference-plus-Noise Ratio (SINR) constitutes a new evaluation metric that slightly differentiates HSDPA from that traditionally used in Release '99 bearers. Release '99 typically uses E_b/N_0 (received-energy-per-bit-to-noise ratio) that corresponds uniquely to a certain Block Error Rate (BLER) for a given data rate. E_b/N_0 metric is not an attractive measure for HSDPA because the bit rate on the HS-DSCH is varied every TTI using different modulation schemes, effective code rates, and a number of High Speed-Physical Downlink Shared Channel (HS-PDSCH) codes. SINR for a single-antenna Rake receiver is calculated as in Equation (1) [8]:

$$\mathrm{SINR} = \mathrm{SF}_{16} \frac{P_{\text{HS-DSCH}}}{(1-\mathrm{OF}) \cdot P_{\text{own}} + P_{\text{other}} + P_{\text{noise}}} \tag{1}$$

$P_{\text{HS-DSCH}}$ is the HS-DSCH transmission power, P_{own} is the own cell interference experienced by the mobile user, P_{other} the interference from neighboring cells, and P_{noise} the Additive White Gaussian Noise. Parameter OF is the downlink orthogonality factor. HSDPA modulation scheme employs orthogonal codes in the downlink to separate users, and without any multipath propagation the orthogonality remains when the base station signal is received by the mobile. However, if there is sufficient delay spread in the radio channel, the mobile will see part of the base station signal as multiple access interference. The orthogonality of 1 corresponds to perfectly orthogonal users. Typically, the orthogonality is between 0.4 and 0.9 in multipath channels. On the other hand, SF_{16} is the spreading factor of 16. The spreading factor or processing gain is the ratio of the chip rate divided by the symbol rate. For more information on the concepts of OF and SF_{16}, the reader is referred to [8].

Moreover, there is a strong relationship between the HS-DSCH allocated power and the obtained MBMS cell throughput. This relationship can be disclosed in the following three steps. Initially, we have to define the target MBMS cell throughput. For instance, if a 64 kbps MBMS service should be delivered to a multicast group of 10 users, then the target throughput will be equal to 640 kbps. Once the target cell throughput is set, the next step is to define the way that this throughput relates to the SINR. Finally, we can describe how the required HS-DSCH transmission power ($P_{\text{HS-DSCH}}$) can be expressed as a function of the SINR value and the user location, in terms of Geometry factor (G), as in Equation (2) [8]:

$$P_{\text{HS-DSCH}} \geqslant \mathrm{SINR}[1 - \mathrm{OF} + G^{-1}] \frac{P_{\text{own}}}{\mathrm{SF}_{16}} \tag{2}$$

The G is given by the relationship between P_{own}, P_{other}, and P_{noise} and is defined from Equation (3) [8]:

$$G = \frac{P_{\text{own}}}{P_{\text{other}} + P_{\text{noise}}} \tag{3}$$

The G is another major measure that indicates the users' position in a cell (distance from the base station). A lower G is expected when a user is located at the cell edge (where interference received from the neighboring cell is higher than the interference experienced in its own cell). Moreover, in micro-cells MBMS, users experience a better (higher) G due to the better environment isolation that leads, in turn, to lower inter-cell interference (P_{other}).

3.3. FACH power profile

FACH is a p-t-m channel that is received by all users throughout the service area of the cell (i.e. broadcast transmission). A FACH essentially transmits at a fixed power level since fast power control is not supported. FACH transport channel is multiplexed to a Secondary-Common Control Physical Channel (S-CCPCH) and specific levels of data rates are achieved depending on the used S-CCPCH slot format. The FACH fixed power should be high enough to ensure the requested QoS

Table II. Required FACH Tx power levels vs cell coverage in macro-cell environment for different BLER targets (64 kbps).

Cell coverage (%)	Tx Power for 1% BLER (W)	Tx Power for 5% BLER (W)	Tx Power for 10% BLER (W)	Tx Power for 20% BLER (W)
70	3.6	2.8	2.3	1.8
90	6.4	5	3.9	3.2
100	10.2	7.8	5.4	4.1

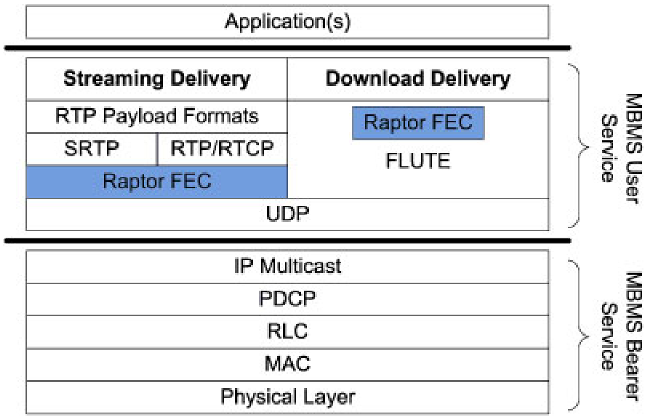

Figure 2. MBMS protocol stack.

in the desired area of the cell and serve the user with the worst path loss, i.e. the user with the higher distance from the base station.

Table II presents some indicative FACH downlink transmission power levels obtained for various cell coverage areas and for different BLER targets. These FACH transmission power levels correspond to a macro-cell environment (site-to-site distance 1 km), when a 64 kbps MBMS service is delivered. TTI is set to 80 ms and no Space Time Transmit Diversity (STTD) is assumed [8, 12].

3.4. *Raptor codes for MBMS FEC*

3GPP standardized Raptor codes as the application layer FEC codes for MBMS aiming to improve service reliability. Both the streaming delivery and the download delivery methods in MBMS mandate that the UE supports Raptor codes [13]. During streaming delivery, application layer Raptor codes are applied on UDP flows, either individually or on bundles of streams. On the other hand, during download delivery method FLUTE protocol provides reliability using Raptor FEC. Figure 2 illustrates how the Raptor FEC encoding is incorporated in the MBMS protocol stack for both streaming and download delivery service.

Apart from the provision of improved system reliability, Raptor codes also offer a large degree of freedom in parameter choice. Files are mapped to so-called source symbols and the FEC encoder uses the set of source symbols as input in order to produce the encoding symbols. Raptor codes are fountain codes, meaning that as many encoding symbols as desired can be generated by the encoder on-the-fly from the source symbols of a source block of data. The decoder is able to recover the source block from any set of encoding symbols only slightly more in number than the number of source symbols. Hence, the Raptor codes operate very closely to an ideal erasure code, which would require only exactly the number of source symbols for recovery.

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 is not

DOI: 10.1002/dac

constructed by encoding the source symbols with the LT code, but by encoding the intermediate symbols generated by some outer high-rate block code. This means that F is itself code symbols generated by some code with 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 can be found in [6], whereas details on specific parameters are listed in [13].

The simulation results presented in [6] show that Raptor codes have a performance very close to ideal. This means that only slightly more than k symbols are sufficient for the code to recover the initial source block. In fact, for $k>200$ the small inefficiency of the Raptor code can quite well be modeled by the following equation:

$$p_f(m,k)=\begin{cases}1 & \text{if } m<k\\ 0.85\times 0.567^{m-k} & \text{if } m\geqslant k\end{cases} \tag{4}$$

In the above equation, $p_f(m,k)$ 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 with increasing number of received symbols.

4. COST ANALYSIS OF DATA DELIVERY

4.1. Multicast user distribution

For the purpose of the cost analysis, we consider a typical mobile network consisting of a single GGSN as that depicted in Figure 1. For the sake of simplicity, during our analysis we consider that the functionality of the BM-SC is incorporated in the GGSN. The cost analysis is based on a probabilistic method that models the multicast user distribution in the network. This method calculates the number of multicast users in the network, the number of SGSNs that serve multicast users, the number of RNCs that serve multicast users, and the number of Node Bs that serve multicast users.

During the cost analysis of data delivery we use several parameters. The terms that are used during this analysis as well as their description are listed in Table III. It should be clarified that all the listed parameters that represent cost correspond to the cost for a single packet delivery.

The probabilistic method considers the classification of the network RAs into L_{RA} categories. If we consider that for $1\leqslant i\leqslant L_{\mathrm{RA}}$, there are $N_{(\mathrm{RA})i}$ RAs of class i, then the total number of RAs within the mobile network is:

$$N_{\mathrm{RA}}=\sum_{i=1}^{L_{\mathrm{RA}}} N_{(\mathrm{RA})i}$$

Let that the distribution of the multicast users among the classes of RAs follows a Poisson distribution with $\lambda=\theta_{(\mathrm{RA})i}$ where $1\leqslant i\leqslant L_{\mathrm{RA}}$. Then, the probability that k multicast users reside in the RAs of class i is:

$$p(k,\theta_{(\mathrm{RA})i})=\frac{\mathrm{e}^{-\theta_{(\mathrm{RA})i}}\cdot(\theta_{(\mathrm{RA})i})^k}{k!}$$

Therefore, the probability that at least one multicast user is served by the RAs of class i is:

$$p=1-p(0,\theta_{(\mathrm{RA})i})=1-\mathrm{e}^{-\theta_{(\mathrm{RA})i}}$$

Since every class i consists of $N_{(\mathrm{RA})i}$ RAs then, if $\theta_{(\mathrm{RA})i}$ denotes the number of multicast users for the $N_{(\mathrm{RA})i}$ RAs of class i, then the total number of the RAs that have multicast users is:

$$n_{\mathrm{RA}}=\sum_{i=1}^{L_{\mathrm{RA}}} N_{(\mathrm{RA})i}(1-\mathrm{e}^{-\theta_{(\mathrm{RA})i}}) \tag{5}$$

DOI: 10.1002/dac

Table III. Cost analysis terms.

Term	Description
D_{gs}	Tx cost for delivery from GGSN to SGSN
D_{sr}	Tx cost for delivery from SGSN to RNC
D_{rb}	Tx cost for delivery from RNC to Node B
D_{FACH}	Radio Tx cost for delivery over FACH
$D_{\mathrm{HS\text{-}DSCH}}$	Radio Tx cost for delivery over HS-DSCH
P_g	Processing cost for unicast delivery in GGSN
P_{gM}	Processing cost for multicast delivery in GGSN
P_s	Processing cost for unicast delivery in SGSN
P_{sM}	Processing cost for multicast delivery in SGSN
P_r	Processing cost for unicast delivery in RNC
P_{rM}	Processing cost for multicast delivery in RNC
P_b	Processing cost of delivery Node B
n_{UE}	Number of multicast users in the PLMN
n_{SGSN}	Number of SGSNs serving multicast users
n_{RA}	Number of RAs having multicast users
n_{RNC}	Number of RNCs serving multicast users
n_{NODEB}	Number of Node Bs serving multicast users
N_{RA}	Total number of RAs in the PLMN
N_{ra}	Number of RAs served by the same SGSN
N_{rnc}	Number of RNCs belonging to the same RA
N_{rra}	Number of RRAs managed by the same RNC
N_{nodeb}	Number of Node Bs belonging to the same RRA

If θ_i denotes the number of multicast users in the RAs of class i, then the total number of multicast users in the network is represented from the following equation:

$$n_{\mathrm{UE}} = \sum_{i=1}^{L_{\mathrm{RA}}} N_{(\mathrm{RA})i} \cdot \theta_i \tag{6}$$

If N_{RA} is the total number of RAs in the PLMN and if each SGSN serves a number of N_{ra} RAs, then the probability that an SGSN does not control any RA serving multicast users is:

$$p_{\mathrm{SGSN}} = \begin{cases} \dfrac{\dbinom{N_{\mathrm{RA}} - N_{\mathrm{ra}}}{n_{\mathrm{RA}}}}{\dbinom{N_{\mathrm{RA}}}{n_{\mathrm{RA}}}} & \text{if } n_{\mathrm{RA}} \leqslant N_{\mathrm{RA}} - N_{\mathrm{ra}} \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Since the total number of SGSNs that serve multicast users is $n_{\mathrm{SGSN}} = N_{\mathrm{SGSN}}(1 - p_{\mathrm{SGSN}})$ it can be calculated based on Equation (7).

Assuming that all RNCs within an RA of class i have the same multicast population distribution density as in the RA case, then the multicast user population for an RNC within the service area of a class i RA is $\theta_{(\mathrm{RNC})i} = \theta_{(\mathrm{RA})i}/N_{\mathrm{rnc}}$ and the total number of RNCs of class i is $N_{(\mathrm{RNC})i} = N_{(\mathrm{RA})i} \cdot N_{\mathrm{rnc}}$, where N_{rnc} is the number of RNCs belonging to the same RA.

Without the loss of generality, we consider that the number of RA categories is equal to the number of RNC categories ($L_{\mathrm{RNC}} = L_{\mathrm{RA}}$) and then the total number of RNCs serving multicast users is:

$$n_{\mathrm{RNC}} = \sum_{i=1}^{L_{\mathrm{RNC}}} N_{(\mathrm{RNC})i} \cdot (1 - \mathrm{e}^{-\theta_{(\mathrm{RNC})i}}) \tag{8}$$

DOI: 10.1002/dac

A similar analysis leads to the below representation of the total number of Node Bs serving multicast users:

$$n_{\text{NODEB}} = \sum_{i=1}^{L_{\text{NODEB}}} N_{(\text{NODEB})i} \cdot (1 - e^{-\theta_{(\text{NODEB})i}}) \tag{9}$$

In Equation (9) the multicast user population for a Node B within a cell of a class i RA is $\theta_{(\text{NODEB})i} = \theta_{(\text{RNC})i} / (N_{\text{rra}} \cdot N_{\text{nodeb}})$ and the total number of Node Bs of class i is $N_{(\text{NODEB})i} = N_{(\text{RNC})i} \cdot N_{\text{rra}} \cdot N_{\text{nodeb}}$, where N_{rra} is the number of RRAs administered by the same RNC and N_{nodeb} is the number of cells belonging to the same RRA.

4.2. *Cost aspects*

We perform the cost evaluation in terms of telecommunication cost. It should be noted that although other studies like [14] consider the cost of multicast group management as part of the total telecommunication cost, this study does not follow the same approach. The reason is that this study focuses only on the actual data transmission along with its cost. On the other hand, the multicast group management cost should not be added since it precedes the data delivery. Therefore, the cost of paging is not taken into account in our analysis.

In unicast data delivery, each packet is forwarded separately from the BM-SC and the intermediate GGSN, SGSN, and RNC (Figure 1). Finally, it is transmitted to the mobile terminal through the selected RAN transport channel. Naturally, p-t-p data delivery through HS-DSCH is used for the unicast transmission and thus the cost of a single packet transmission to n_{UE} receivers is given by the number of receivers times the cost of a single packet delivery over the data delivery path. Therefore, the total cost for unicast data delivery to multiple receivers is given by the following equation:

$$U = n_{\text{UE}} \cdot (P_g + D_{\text{gs}} + P_s + D_{\text{sr}} + P_r + D_{\text{rb}} + P_b + D_{\text{HS-DSCH}}) \tag{10}$$

In multicast data delivery, the SGSNs and RNCs forward a single copy of each packet to the RNCs or Node Bs, respectively, that are serving multicast users. As soon as the packets are received at the Node Bs serving multicast users, they are transmitted to the appropriate UEs via common or shared transport channels. The total cost for the multicast data delivery is derived from Equation (11) below:

$$M = P_{gM} + n_{\text{SGSN}} \cdot (D_{gs} + P_{sM}) + n_{\text{RNC}} \cdot (D_{sr} + P_{rM}) + C_{\text{RAN}} \tag{11}$$

C_{RAN} represents the cost of data delivery over the RAN. Both FACH and HS-DSCH can be used as RAN transport channel and therefore the C_{RAN} calculation varies depending on the channel used. The following equation gives this cost:

$$C_{\text{RAN}} = \begin{cases} n_{\text{NODEB}} \cdot (D_{\text{FACH}} + D_{\text{rb}} + P_b) & \text{if channel is FACH} \\ n_{\text{UE}} \cdot (D_{\text{HS-DSCH}} + D_{\text{rb}} + P_b) & \text{if channel is HS-DSCH} \end{cases} \tag{12}$$

$D_{\text{HS-DSCH}}$ and D_{FACH} represent the cost over the Uu interface. In more detail, D_{FACH} represents the cost of using a FACH to serve all the multicast users residing in a specific cell, whereas $D_{\text{HS-DSCH}}$ represents the cost of using a single HS-DSCH to transmit the data to a single multicast user of the network.

Regarding the cost over the Iub interface, if FACH is used as transport channel each multicast packet is sent once over the Iub interface and then it is transmitted to the multicast receivers by the corresponding Node B. The use of HS-DSCH for the transmission of the multicast packets means that a separate timeslot must be used to transport the multicast data to each multicast receiver per Node B.

DOI: 10.1002/dac

5. SIMULATION SCHEME

The simulation scheme that we have developed is in accordance with the 3GPP specifications and it is important to mention that both techniques of FEC with Raptor codes and selective retransmission may be employed by the BM-SC in order to provide a reliable data delivery [13]. Moreover, 3GPP recommends in [13] that the retransmission should be performed over a selective unicast context, since the setup of a new multicast bearer for packet retransmission is rather costly. Therefore, the scheme that we have designed and have implemented combines both the fundamental repair processes:

- Multicast bearers and application layer FEC with Raptor codes.
- Unicast bearers for selective retransmission of lost packets.

As we have already mentioned, we have developed our simulation scheme towards two directions. The first direction covers the cost analysis of the use of application layer FEC in MBMS and the relevant part of our simulation scheme is described in Section 5.1. The other direction covers the impact of FEC in MBMS power control. This simulation scheme aspect is described in Sections 5.2 and 5.3.

5.1. Simulation environment

Our scheme component for cost analysis incorporates all the properties of a typical Raptor code defined for data delivery over MBMS as they are described by 3GPP in [13]. It is worth mentioning 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, equals to the fraction $(n-k)/k$. Given that the packet size is fixed, the FEC overhead that is needed for the transmission of a given amount of data is also equal to the same fraction and, thus, the overhead of additional packets that are needed for the delivery of a given amount of data is $(n-k)/k$.

During the decoding procedure in each UE, there is a decoding failure probability represented by Equation (4). When a packet loss rate $p_{\text{loss}}>0$ is applied over the MBMS bearer, the number of the received symbols m may become less than the n symbols initially transmitted. As a result of the packet losses, the failure probability $p_f(m,k)$ increases. If the recovery of the k source symbols through decoding procedure fails in a UE, then the UE requests selective retransmission of the lost packets from the BM-SC. The selective retransmission is performed over a unicast context.

For the definition of our simulation environment we assume a typical PLMN topology with $N_{\text{SGSN}}=10$, $N_{\text{ra}}=10$, $N_{\text{rnc}}=10$, $N_{\text{rra}}=5$ and $N_{\text{nodeb}}=5$. Moreover, we assume that we have two classes of RAs: RAs of class $i=1$ have multicast user population of $\theta_1=1/\delta$ and RAs of class $i=2$ have multicast user population $\theta_2=\delta$. If α denotes the proportion of the class $i=1$ and $(1-\alpha)$ be the proportion of the class $i=2$. Thus, the number of RAs of class $i=1$ is $N_{(\text{RA})1}=\alpha\cdot N_{\text{RA}}$ and the number of RAs of class $i=2$ is $N_{(\text{RA})2}=(1-\alpha)\cdot N_{\text{RA}}$. Similarly, each RA of class $i\in\{1,2\}$ is divided into N_{rnc} RNCs of the same class i, and each RNC of class $i\in\{1,2\}$ is subdivided into $N_{\text{rra}}\cdot N_{\text{nodeb}}$ Node Bs of the same class.

The estimated value of the packet transmission cost (D_{xx}) in any segment of the network depends on two parameters:

- The number of hops between the edge nodes of this network segment, and
- The capacity of the link of the network segment.

The typical values of the above parameters that are used for the purpose of our experimental evaluation are presented in Table IV.

It is obvious from Equations (10) and (11) that the costs of the schemes depend on several other parameters. The work presented in [15] has been used as input for the determination of the parameters values, which are listed in Table V.

DOI: 10.1002/dac

Table IV. Calculation of the transmission cost.

Link	Link capacity factor (k)	Number of hops (l)	Tx cost (D)
GGSN-SGSN	$k_{gs}=0.5$	$l_{gs}=6$	$D_{gs}=12$
SGSN-RNC	$k_{sr}=0.5$	$l_{sr}=3$	$D_{sr}=6$
RNC-Node B	$k_{rb}=0.2$	$l_{rb}=1$	$D_{rb}=5$

Table V. Values of the simulation parameters.

D_{rb}	P_g	P_s	P_r	P_{gM}	P_{sM}	P_{rM}	P_b	D_{FACH}	$D_{HS\text{-}DSCH}$
5	1	1	1	2	2	2	1	16	12

Table VI. Simulation environment parameters.

Parameter	Value
Cellular layout	Hexagonal grid
Number of cells	18
Site-to-site distance	1 km
Maximum BS Tx power	20 W
Other BS Tx power	5 W
Common pilot channel power	2 W
Common channel power	1 W
Propagation model	Okumura Hata
Multipath channel	Vehicular A (3 km/h)
Orthogonality factor	0.5

5.2. Power control for streaming delivery method

The main difficulty in the assessment of MBMS power control is the existence of a large number of parameters in the system and the complexity of the involved components. Our intention is to make a parameter selection as generic as possible so as to have a simulation environment that is reasonably representative of an actual system. Therefore, for the purpose of the simulation experiments a typical macro-cell environment is considered. The simulation environment parameters are presented in Table VI. It should be noted that no STTD is employed in our simulation.

The simulation scheme takes into account the properties of the RAN transport channels and their power consumption characteristics during MBMS transmissions as they are described by 3GPP [9]. Therefore, it is possible to examine the various effects of data delivery over mobile networks in a realistic way under various network configurations and channel conditions. Our intention is to conduct simulation experiments that cover both MBMS User Services (streaming delivery and download delivery services). Details for each of the above two methods are presented in the remaining of this section as well as in the following section.

For the investigation of streaming delivery method, transmissions over both HS-DSCH and FACH channels are simulated. In the case of HS-DSCH, our simulation scheme calculates the required transmission power for the delivery of streaming data over MBMS. The power depends on the number of users and, therefore, an average of up to 20 users per cell is examined. It should be noted that the use of HS-DSCH for the MBMS data delivery towards more than 20 users per cell is meaningless since it causes a large waste of power in comparison with the use of FACH [16]. During the simulation of the streaming delivery over HS-DSCH channel, the BLER caused by the channel is set by the scheme to a certain level. By setting a required BLER target at the receiver, an appropriate amount of FEC redundant symbols are added by the sender in order for the receiver to retrieve the streaming data with the required BLER after the FEC decoding.

FACH transport channel is multiplexed to an S-CCPCH; therefore, there are specific data rates that are achieved depending on the S-CCPCH slot format. In our simulation S-CCPCH with slot

DOI: 10.1002/dac

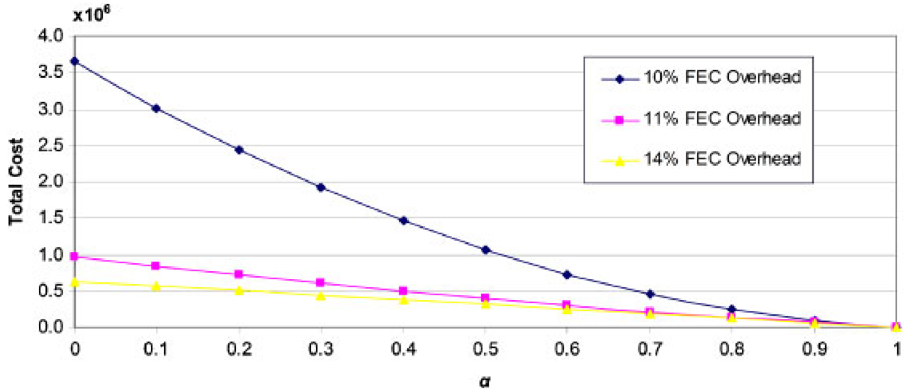

Figure 3. Total cost against α when $p_{\text{loss}}=5\%$ and $\delta=500$.

format 10 is used to achieve a 64 kbps data rate [12]. During our experiments, we choose to simulate a media data stream of 64 kbps bit rate and, since FEC encoding adds redundant symbols to the source data, it is not possible to use FEC encoding without transmitting through a higher level of S-CCPCH data rate. This means that 128 kbps, corresponding to slot format 12, would be necessary to deliver both the 64 kbps media streams and the FEC redundant information. Obviously, the use of slot format 12 for the transmission of a 64 kbps media stream causes a large waste of power resources. Thus, we have chosen not to use FEC encoding for the streaming data delivery over FACH. The BLER target for the FACH data delivery is set to 1% and therefore, the required transmission power for the various cell coverage levels is given by Table II.

5.3. Power control download delivery method

For the purpose of the investigation of download delivery method, the transmission of data files over both HS-DSCH and FACH channels is simulated. Contrary to the streaming delivery, application layer FEC with Raptor codes is applied over both types of transport channels. Our scheme for download delivery method follows the 3GPP recommendation presented in [1]. More specifically, both techniques of FEC with Raptor codes and selective retransmission are applied to provide a reliable data download delivery and therefore our scheme has a hybrid functionality regarding error control. Moreover, 3GPP recommends that the retransmission may be performed over a selective unicast context, since in some cases the setup of a new multicast bearer for packet retransmission is rather costly [13].

The scheme that we have designed and implemented combines both the fundamental repair processes and therefore combines the MBMS multicast and unicast bearers. It is worth to explain that when a certain BLER is applied over the MBMS bearer, the number of the received symbols m may become less than the n symbols that were initially transmitted. As a result of the packet losses, the failure probability $p_{\text{f}}(m,k)$ increases. If the recovery of the k source symbols through decoding procedure fails in a UE, then selective retransmission is initiated by the BM-SC over a unicast context.

6. EXPERIMENTAL EVALUATION

6.1. Cost vs multicast user density

Figure 3 depicts the cost in function of α when p_{loss} is 5% and δ equals to 500 for various amounts of recovery symbols. Before proceeding to the analysis of Figure 3 it should be clarified what parameter α qualitatively represents. The value of α denotes the proportion of the RAs belonging in the class $i=1$ and therefore the properties of the RAs belonging in either class $i=1$ or $i=2$ prevail as the value of α approaches zero or one respectively. The properties of each class of RAs are determined by the value of δ. If $\delta\gg 1$, the RAs of class $i=1$ have a small multicast user

DOI: 10.1002/dac

population and the RAs of class $i=2$ have a large multicast user population. Consequently, the parameter α qualitatively represents the multicast user density in the sense that as the value of α increases, the number of RAs with small multicast user population also increases and vice versa.

We estimate the total telecommunication cost for various values of FEC overhead. In Figure 3, we indicatively present the simulation results for three different values of the FEC overhead that are close to the optimal value for the given simulation setting (i.e. around 13.5%). We observe that the total cost decreases as α increases. This occurs because as α increases, the number of RAs with no multicast users also increases and hence the multicast user population resides in a restricted number of RAs. For small FEC overheads, the cost decreases exponentially with α whereas for large FEC overheads, the cost decreases linearly.

For a given value of α, the total cost decreases as the FEC overhead increases but down to a lower bound. When the FEC overhead exceeds the value that corresponds to this bound, the total cost starts to increase. This is reasonable, since the addition of new recovery symbols increases linearly the total cost whereas it has minor contribution to the source symbol recovery. The FEC overhead that achieves the optimal cost depends on the given parameters. For the scenario depicted in Figure 3, the optimal FEC overhead is around 13.5%. Similar behavior is observed when different packet loss rates are applied.

6.2. Cost vs multicast user population

Another aspect we examine in our simulation experiments is the total cost vs the multicast user population. The magnitude of the multicast user population in the defined classes of RAs is determined by the value of δ. As δ increases, the probability that there are no multicast members in a RA of class $i=1$ increases whereas the multicast user population in the RAs of class $i=2$ increases. In the figures below, the total cost is plotted against δ for 5% packet loss rates and two different values of α. Again, we estimate the total telecommunication cost for various values of FEC overhead. In the following figures, we indicatively present the simulation results for three different values of the FEC overhead that are close to the optimal value for the given simulation setting.

When $\alpha=0.1$, the total cost constantly increases as the value of δ increases. This is reasonable since the value of α is low and therefore there is a large number of RAs with a lot of multicast users residing in them. As δ increases, the number of the multicast users in those RAs increases and so does the total cost. There is also an optimal FEC overhead that creates a minimal total cost for a given δ.

For the scenario depicted in Figure 4, this optimal FEC overhead is 14%. For a given packet loss rate this optimal FEC overhead increases as the value of δ increases. A qualitative explanation of this is that as the multicast user population increases the number of the receivers that cannot recover a transmitted packet increases and so does the cost due to packet retransmissions.

When $\alpha=0.9$ a lot of RAs exist with a few or no residing receivers. For small values of δ the cost is too high independently of whether FEC is used or not. This is because the multicast transmission

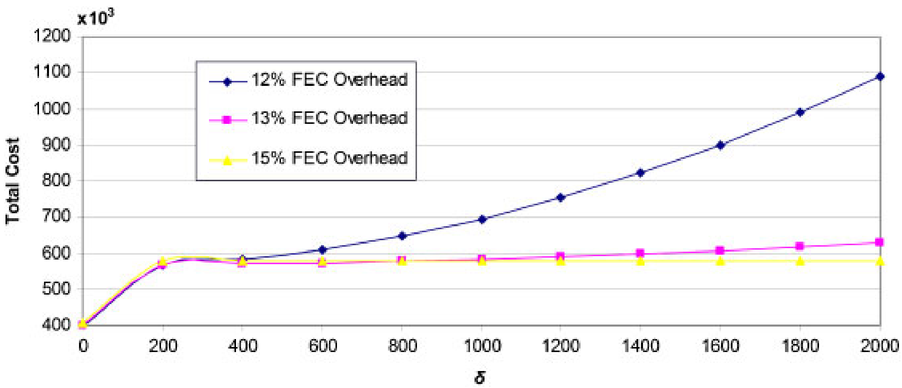

Figure 4. Total cost against δ when $p_{\text{loss}}=5\%$ and $\alpha=0.1$.

DOI: 10.1002/dac

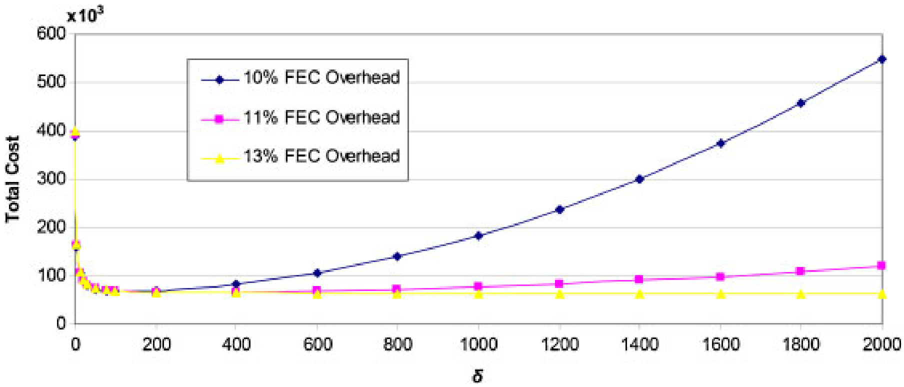

Figure 5. Total cost against δ when $p_{\text{loss}}=5\%$ and $\alpha=0.9$.

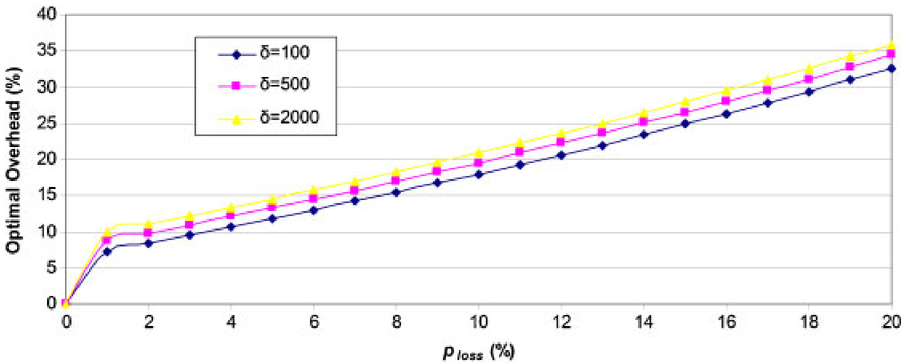

Figure 6. Optimal overhead against packet loss rate when $\alpha=0.1$.

cost does not depend on the number of the actual receivers, but it depends on the number of the cells where they reside. As δ increases, the multicast population increases and the total cost does the same. It should be noted that the optimal FEC overhead increases as δ increases (Figure 5).

6.3. Optimal overhead vs packet loss rate

Finally, experiment related to the cost analysis is the evaluation of the optimal overhead against the applied packet loss rate. In Figure 6 we observe that the optimal overhead of recovery symbols increases as the packet loss probability increases. For $p_{\text{loss}}>1\%$, the increase is linear with gradient around 1.3. For small values of p_{loss}, the optimal overhead rapidly increases as the packet loss rate increases. This is caused owing to the poor effectiveness of Raptor codes for small number of recovery symbols.

6.4. Power control for streaming delivery

For the assessment of streaming delivery method the delivery of a media data stream of 64 kbps bit rate with BLER target set to 1% over both HS-DSCH and FACH channels is simulated. It should be clarified that the BLER target is the BLER that results after the FEC decoding at the receiver and is determined by the probability $p_f(m,k)$. This means that the actual BLER at the radio channel might be larger than 1%.

In the case of transmission over HS-DSCH, four scenarios are examined:

1. Streaming delivery over HS-DSCH channel without FEC and channel BLER set to 1%.
2. Streaming delivery over HS-DSCH channel with FEC and channel BLER set to 5%.
3. Streaming delivery over HS-DSCH channel with FEC and channel BLER set to 10%.
4. Streaming delivery over HS-DSCH channel with FEC and channel BLER set to 20%.

DOI: 10.1002/dac

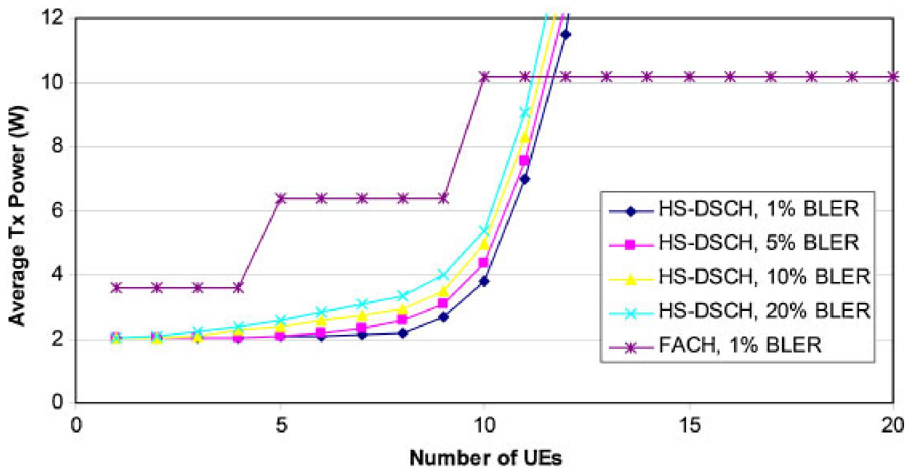

Figure 7. Average transmission power for the delivery of a 64 kbps media stream. BLER target is set to 1%.

In the three latter cases the BLER target after the FEC decoding at the receiver is set to the required one (i.e. 1%).

P-t-p transmissions over HS-DSCH are more efficient for a limited number of users. In case the number of receivers exceeds a certain threshold, the application of p-t-m transmission is recommended [16]. Therefore, in our analysis we use the power levels of p-t-m transmission over FACH as a reference for an efficient channel selection. In more detail, the delivery of the same media stream over FACH without application layer FEC has also been simulated. The BLER applied at this type of transmission is also set to the target of 1%.

The simulation results for the streaming delivery method are illustrated in Figure 7. Figure 7 shows the required transmission power to deliver the 64 kbps media stream over the examined channels as a function of the number of receivers. The three levels of FACH transmission power illustrated in Figure 7 correspond to the required power for the percentages of cell coverage (70, 90, and 100%) that are indicatively selected and are presented in Table II.

What can be easily observed in Figure 7 is that for relatively large number of receivers, the addition of FEC encoding increases the required transmission power. For instance, the delivery of the media stream to eight MBMS users over an HS-DSCH channel with 20% BLER requires 47% more power than the delivery over an HS-DSCH channel with 1% BLER. Therefore, the increment in power consumption that is caused by the redundant symbols of FEC encoding with Raptor codes is much higher in comparison with the increment needed in order to achieve a lower BLER. On the other hand, in the case of relatively small number of receivers, the required power for the transmission with FEC encoding closely matches the required power when no FEC is supported.

Finally, our experimental results show that when the number of receivers exceeds a certain threshold, the power consumption of HS-DSCH increases rapidly, thus the application of p-t-m transmission becomes more efficient. For the examined network configuration, this threshold is 10 to 11 multicast receivers depending on the BLER which is applied.

6.5. *Power control for download delivery*

The basic scenario that we simulate for the evaluation of FEC power efficiency during download delivery is that a file of a certain size with static contents is transmitted in multicast mode to a group of users which are randomly placed in each serving cell. We have chosen to simulate the distribution of a 512 kB file, which might represent a short multimedia clip, a still image, or a reasonably sized ring tone. For the finally presented results, bearers supporting 64 kbps have been chosen. Simulations are run for various numbers of MBMS receivers per cell, whereby their starting position is randomly and uniformly distributed over each cell area.

DOI: 10.1002/dac

Our scheme for download delivery method uses both HS-DSCH and FACH channels for the transmission of data files. Contrary to the streaming delivery simulation, application layer FEC with Raptor codes is applied over both types of transport channels. In the assessment of the various channel configurations for the download delivery method, basically three aspects are of major interest: the required transmission power, the consumed transmission energy, and the necessary download time.

The required transmission power is almost the same as that of streaming delivery case, which is depicted in Figure 7. Some minor differences exist and are caused by the sizes of the MBMS User Services packet headers (RTP vs FLUTE) as depicted in Figure 2. In fact, the streaming protocol headers are simpler and therefore a slightly less transmission power is needed in comparison with the protocol headers used for the download service. The results for average total transmission power during download data delivery are not depicted due to space limitations and the reader is referred to Figure 7.

The other aspect that we examine during our simulation experiments is the consumed transmission energy. The minimization of energy consumption for the transmission of a given data portion is an important goal for mobile operators and therefore the required transmission energy is a critical metric. During our assessment different BLER are applied over the channels and the energy requirements of each channel configuration is examined for various users' distributions. The BLER that are applied are 5, 10, and 20%. The required energy is estimated in terms of Joules (J) where $1\,J = 1\,W 1\,s$. The results of our simulations are presented in the following figures.

From the simulation results it is immediately observed that, from transmission energy point of view, the switching point where the p-t-m transmission over FACH turns to be more efficient is a number of 10–11 mobile users. In more detail, all the simulation results show that the download delivery over HS-DSCH is more expensive when the UEs are more than 10. The transmission over FACH even with 100% cell coverage is more efficient from energy perspective as the receivers become more than 10.

Another interesting observation is that the use of application layer FEC adds a minor overhead at the total transmission energy over the p-t-m channel. Although this overhead is not clear from Figure 8 where the two curves almost coincide, the simulation logs show that this overhead varies from 1.1 to 1.5%. Nevertheless, during p-t-m transmission the 64 kbps bit rate level has to be kept and, since FEC encoding adds redundant symbols to the source data, a longer transmission time is necessary for the delivery of the distributed file. The corresponding measurements are also listed in Table VII.

On the other hand, when the transmission is made over p-t-p channel (HS-DSCH) there is the flexibility to achieve a download time that corresponds to 64 kbps bit rate. Therefore, the transmission of the total amount of the encoding symbols (encoding symbols are the source symbols plus the redundant ones added due to the FEC encoding) is performed at the higher bit rate. This causes an increment in the p-t-p total transmission energy from 10 to 25% (Figure 8). From the above results it is obvious that for non time-constrained transmissions it is considerably advantageous to keep the transmission energy low.

In terms of users perception, file download is in some sense only binary, namely it is evaluated if the file is correctly received or not. On the other hand, there is an aspect that can be considered as strongly connected with user perception: that is, the experienced download time. In other words, we evaluate how long it takes to receive the file after the joining has happened. Figure 9 presents the average experienced download time for each channel configuration.

When comparing the average download times for the various channel configurations, we conclude that using a p-t-m channel can be more time consuming. This is reasonable since a fixed bit rate level of 64 kbps has to be followed. This means that any redundant symbols added by the FEC encoding or any additional packet retransmissions cause an extension of the user perceived download time.

On the other hand, the p-t-p channel offers the flexibility to regulate the transmission bit rate to any desired level. Therefore, by increasing the transmission power any additional redundant symbols or any retransmitted packets are transferred without affecting the actual bit rate of 64 kbps.

DOI: 10.1002/dac

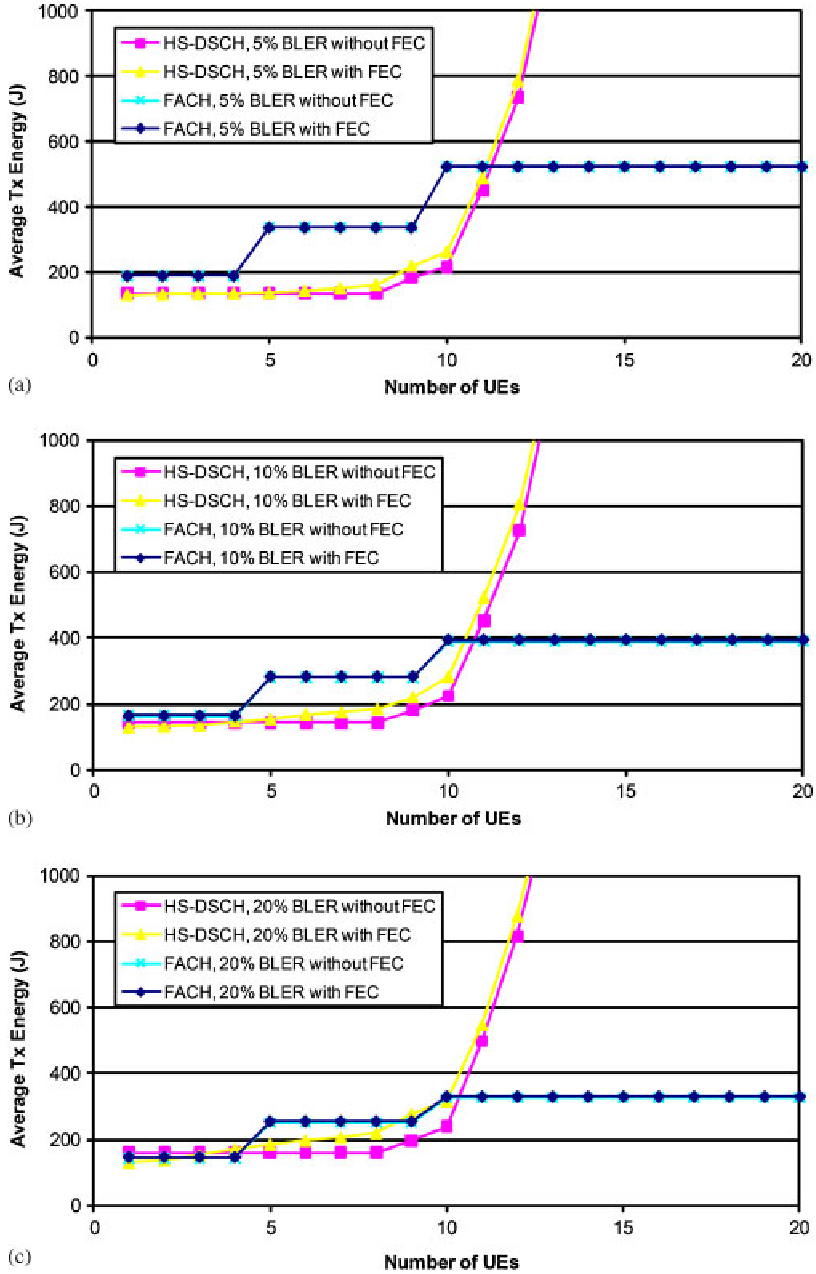

Figure 8. Average total transmission energy for the delivery of the distributed file. BLER is set to: (a) 5%; (b) 10%; and (c) 20%.

Table VII. Average total transmission energy for FACH transport channel.

Number of users	20% BLER without FEC	20% BLER with FEC
1–4	142.8 J	145.1 J
5–9	250.7 J	254.8 J
10–20	325.3 J	330.6 J

DOI: 10.1002/dac

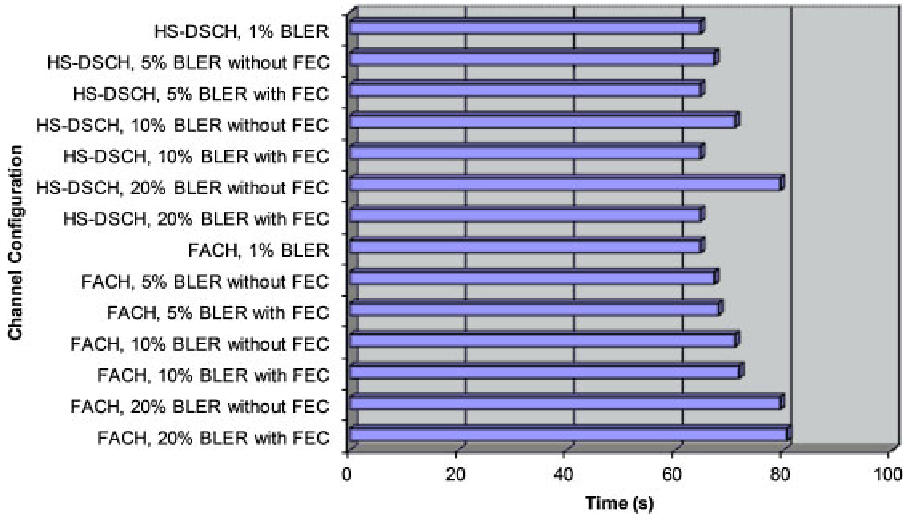

Figure 9. Average total transmission time for the delivery of the distributed 512 kB file.

7. CONCLUSIONS

In this paper, we have presented a complete study of the impact of application layer FEC use in mobile multicast transmission. First, the use of FEC is evaluated in terms of telecommunication cost under various user distributions. The evaluation is performed with the aid of a scheme that uses a probabilistic method for modeling the multicast user distribution in the network and estimates the telecommunication cost of multicast data delivery. The behavior of the standardized FEC mechanism is examined against parameters such as the multicast user density and the multicast user population. The optimal dimensioning of FEC codes, i.e. the efficient working point in the trade-off of the FEC code overhead against the retransmission cost, is estimated for different network conditions. Additionally, the power control which is an aspect of major importance during mobile multicast transmission is separately examined. Our scheme allows the simulation of both streaming delivery and download delivery methods of MBMS. It is important that it incorporates the properties of an evolved mobile network that uses HSDPA technology for high-speed data delivery to mobile terminals, as they are determined by the 3GPP specifications. The power profiles for p-t-p and p-t-m transmission are taken into account by the scheme.

Furthermore, we have presented a cost analysis scheme that considered the properties of an evolved mobile network that uses HSDPA technology for a high-speed data delivery to mobile terminals. The results of our simulation experiments are presented and analyzed. In particular, the behavior of the standardized FEC scheme is evaluated against parameters such as the multicast user density and the multicast user population. The optimal dimensioning of FEC codes, i.e. the efficient working point in the trade-off of the FEC code overhead against the retransmission cost, is estimated depending on the network conditions. Last but not least, all the above results are qualitatively assessed and explanations for the model behavior are given.

From power control perspective, it is generally concluded that the use of application layer FEC causes an increment at the power consumption in comparison with the traditional packet retransmission. In other words increasing the power to succeed a better BLER is cheaper from power perspective than increasing the power to send the redundant symbols added by FEC encoder. This is applicable for time constrained transmission, i.e. for transmissions that should be completed at a given bit rate (for streaming delivery) or in a given download time (for download delivery). On the other hand, it is concluded that the use of application layer FEC causes a relatively small increment at the power consumption also in comparison with the packet retransmission. Another general conclusion is that the use of HS-DSCH offers a large flexibility in the selection of the actual bit rate and the amount of redundant symbols used. Instead, FACH offers only specific bit rate levels. The use of Raptor codes FEC encoding does not therefore offer downlink power savings. Instead, the benefits of FEC are strongly connected with the uplink direction, mainly with its operability even with limited or no uplink resources and the avoidance of feedback implosion that it offers.

In the case of streaming delivery service our experimental results show that when the number of receivers exceeds the threshold of 10 to 11 users, the power consumption of HS-DSCH increases rapidly, thus the application of p-t-m transmission over FACH becomes more efficient. The evaluation of FEC encoding for download delivery service shows that in terms of power consumption the figures for download delivery closely match those of streaming delivery. From energy point of view, the switching point where the p-t-m transmission over FACH turns to be more efficient is a number of 10 to 11 mobile users. Therefore, it is clear that both from energy and power perspective the switching point for download delivery method is the same. The final aspect that we have examined is the total transmission time. Its importance stems from its association with user perception since it matches the user experienced download time. The evaluation of the total transmission time shows that the use of p-t-m channel can be more time consuming since a fixed bit rate level of 64 kbps has to be followed. This means that any redundant symbols added by the FEC encoding or any additional packet retransmissions cause an extension of the user perceived download time. This does not happen in the case of the p-t-p channel due to the flexibility that it offers to regulate the transmission bit rate to any desired level.

8. FUTURE WORK

The step that follows this work may be the modeling and implementation of a mechanism that makes efficient selection of the amount of application layer FEC encoding for mobile networks. This mechanism would monitor the network conditions and use them as input in order to select the appropriate amount of redundant symbols for FEC encoding and regulate the transmission power to an optimal level. The results presented in this study against parameters such as the BLER in the RAN, the multicast user population, and density can be used as input in order to make an efficient application of Raptor codes and choose the optimal transport channel and transmission power level in the RAN.

Another idea would be the investigation of the impact of FEC encoding over the Long Term Evolution (LTE) networks. The key feature for the provision of MBMS in LTE networks is the Multimedia Broadcast over a Single Frequency Network (MBSFN), where a time-synchronized common waveform is transmitted from multiple cells. MBSFN is an interesting domain for future research where the first steps are currently performed. The work presented in this paper may be used as a platform to examine the impact of application layer FEC in the next generation networks.

REFERENCES

1. 3GPP. *TS 23.246 V9.3.0. Technical Specification Group Services and System Aspects*; *MBMS*; *Architecture and Functional Description* (*Release 9*). December 2009.
2. Tan WT, Zakhor A. Video multicast using layered FEC and scalable compression. *IEEE Transactions on Circuits and Systems for Video Technology* 2001; **11**(3):373–386. DOI: 10.1109/76.911162.
3. Luby M, Watson M, Gasiba T, Stockhammer T, Wen W. Raptor codes for reliable download delivery in wireless broadcast systems. *Proceedings of the CCNC 2006*, Las Vegas, NV, U.S.A., vol. 1, 8–10 January 2006; 192–197.
4. Hepsaydir E, Witvoet E, Binucci N, Jadhav S. Enhanced MBMS in UMTS networks and raptor codes. *Proceedings of the PIMRC 2007*, Athens, Greece, 3–7 September 2007; 1–5. DOI: 10.1109/PIMRC.2007.4394642.
5. Luby M, Gasiba T, Stockhammer T, Watson M. Reliable multimedia download delivery in cellular broadcast networks. *IEEE Transactions on Broadcasting* 2007; **53**(1):235–246. DOI: 10.1109/TBC.2007.891703.
6. Lohmar T, Peng Z, Mahonen P. Performance evaluation of a file repair procedure based on a combination of MBMS and unicast bearers. *Proceedings of the WoWMoM 2006*, Niagara-Falls, Buffalo, NY, U.S.A., 26–29 June 2006; 349–357. DOI: 10.1109/WOWMOM.2006.86.
7. Wang N, Zhang Z. The impact of application layer Raptor FEC on the coverage of MBMS. *Proceedings of the RWS 2008*, Orlando, FL, U.S.A., 22–24 January 2008; 223–226. DOI: 10.1109/RWS.2008.4463469.
8. Holma H, Toskala A. *WCDMA for UMTS*: *HSPA Evolution and LTE* (4th edn). Wiley: New York, 2007.

9. 3GPP. *TS 25.346 V8.3.0. Technical Specification Group RAN*; *Introduction of the MBMS in the RAN*; *Stage 2* (*Release 8*). March 2009.
10. Dahlman E, Parkvall S, Sköld J, Beming P. *3G Evolution*: *HSPA and LTE for Mobile Broadband* (2nd edn). Elsevier: Amsterdam, 2008.
11. 3GPP. *TS 25.308 V9.1.0. Technical Specification Group Radio Access Network*; *High Speed Downlink Packet Access* (*HSDPA*); *Overall Description*; *Stage 2* (*Release 9*). September 2009.
12. 3GPP. *TR 25.803 V6.0.0*, *Technical Specification Group Radio Access Network*; *S-CCPCH Performance for MBMS*; (*Release 6*). September 2005.
13. 3GPP. *TS 26.346 V9.1.0 Technical Specification Group Services and System Aspects*; *MBMS*; *Protocols and codecs* (*Release 9*). December 2009.
14. Rümmler R, Chung YW, Aghvami AH. Modeling and analysis of an efficient multicast mechanism for UMTS. *IEEE Transactions on Vehicular Technology* 2005; **54**(1):350–365. DOI: 10.1109/TVT.2004.836893.
15. Alexiou Bouras C. Multicast in UMTS: evaluation and recommendations. *Wireless Communications and Mobile Computing* 2006; **8**(4):463–481. DOI: 10.1002/wcm.464.
16. Alexiou A, Bouras C, Kokkinos V, Rekkas E. An improved mechanism for multiple MBMS sessions assignment in B3G cellular networks. *Wireless Networks* 2009 (Published online). DOI: 10.1007/s11276-009-0161-6.

AUTHORS' BIOGRAPHIES

Antonios Alexiou obtained his Diploma from the Department of Electrical and Computer Engineering of the Aristotle University of Thessaloniki (Greece). Furthermore, he obtained his Masters Degree and his PhD from the Computer Engineering and Informatics Department of Patras University (Greece). His research interests include data networks, mobile telecommunications networks, multicast routing and group management, radio resource management, radio network planning and optimization, wireless networks. He has published over 40 papers in Journals, International Conferences and Book Chapters.

Christos Bouras obtained his Diploma and PhD from the Computer Science and Engineering Department of Patras University (Greece). He is currently a Professor in the above department. Also he is a scientific advisor of Research Unit 6 in the Research Academic Computer Technology Institute (CTI), Patras, Greece. His research interests include Analysis of Performance of Networking and Computer Systems, Computer Networks and Protocols, Telematics and New Services, QoS and Pricing for Networks and Services, e—learning, Networked Virtual Environments and WWW Issues. He has extended professional experience in Design and Analysis of Networks, Protocols, Telematics and New Services. He has published more than 400 papers in various well-known refereed books, conferences and journals. He is a co-author of 8 books in Greek. He has been a PC member and referee in various international journals and conferences. He has participated in R&D projects such as RACE, ESPRIT, TELEMATICS, EDUCATIONAL MULTIMEDIA, ISPO, EMPLOYMENT, ADAPT, STRIDE, EUROFORM, IST, GROWTH and others. Also he is a member of experts in the Greek Research and Technology Network (GRNET), Advisory Committee Member to the World Wide Web Consortium (W3C), IEEE—CS Technical Committee on Learning Technologies, IEEE ComSoc Radio Communications Committee, IASTED Technical Committee on Education W 6.4 Internet Applications Engineering of IFIP, ACM, IEEE, EDEN, AACE, New York Academy of Sciences and Technical Chamber of Greece.

Andreas Papazois obtained his Diploma, Master's Degree and PhD from the Computer Engineering and Informatics Department of Patras University (Greece). He has worked as Telecommunication Systems Engineer at Intracom Telecom S.A. and he is currently working as a Research Associate in the Research Unit 6 of Research Academic Computer Technology Institute. His research interests include Mobile Telecommunication Networks, Quality of Service, Forward Error Correction and Congestion Control during Multicast Transmission. He has published several research papers in well-known refereed international conferences and scientific journals and a book chapter.

