Multicast Delivery of File Download Services in 3G Mobile Networks with MBMS

David Gómez-Barquero, Ana Fernández Aguilella, and Narcís Cardona
Mobile Communications Group, iTEAM Research Institute
Polytechnic University of Valencia (UPV), Spain
Email: {dagobar, anferag, ncardona}@iteam.upv.es

Abstract— **This article investigates the efficient transmission of file download services to several users simultaneously in 3G mobile networks with HSDPA (High-Speed Downlink Packet Access) and MBMS (Multimedia Broadcast Multicast Services). HSDPA supports high speed point-to-point (p-t-p) transmissions (up to several Mb/s), whereas with MBMS the same content can be transmitted with a point-to-multipoint (p-t-m) connection to multiple users in a unidirectional fashion. Multicast delivery can be implemented through only p-t-p transmissions with HSDPA, a single p-t-m transmission with MBMS, or using both jointly in a hybrid approach by employing HSDPA for error repair of the MBMS p-t-m transmission. We investigate the optimum HSDPA and MBMS transmission configuration when they are used separately, and the trade-off between the initial MBMS file p-t-m transmission and the HSDPA error repair for the hybrid delivery. The approach of minimizing the transmission energy (product of the transmit power times the transmission time) to achieve a target file acquisition probability (percentage of users that successfully receive the file) has been adopted.**

I. Introduction

After a slow start, third-generation (3G) mobile networks are now being deployed on a broad scale all over the world, and mobile operators have started to provide multimedia services, as video clips from sports events or live TV programs. However, the capabilities of the first release of the 3G standard are considerably limited, from both a cost and a technical viewpoint. In order to offer a viable business model, and to not overload the network capacity to the point of preventing subscribers from placing voice calls (which is the main function and value of the cellular networks), only short video clips can be offered at low-resolution (e.g., 2 minutes at 128 kb/s) [1].

To meet the increasing demands for high-speed data access, the 3G standard has been enhanced with the introduction of HSDPA (High-Speed Downlink Packet Access), which supports higher peak data rates (up to several Mb/s), increasing considerably the network capacity [2].

Another important bottleneck is the fact that 3G cellular systems have been optimized for unicast services delivered through dedicated point-to-point (p-t-p) connections for each individual user (including HSDPA), even if the same content should be delivered to many users. This limits the maximum number of active users the system can handle, since both radio and transport network resources are physically limited. Multicast and broadcast are more appropriate transport technologies to cope with high numbers of users consuming simultaneously the same service when compared to unicast, as there is no limit to how many users can receive the content. Multicast/broadcast wireless transmissions employ a common point-to-multipoint (p-t-m) radio bearer for all users, which allows delivering the same content to an unlimited number of users within the coverage area [3].

In order to transmit efficiently the same content to several users simultaneously, the 3G standard has been enhanced with MBMS (Mutlimedia Broadcast Multicast Services) [4]. As MBMS p-t-m transmissions are intended for multiple users, it is not possible to dynamically adapt the transmission parameters according to the user reception conditions, and hence a constant transmit power and bearer data rate are employed. The transmission should be configured statistically to serve the worst-case user contemplated. To increase the robustness of the p-t-m transmissions, MBMS introduces two diversity techniques to cope against fast fading and to combine transmissions from multiple cells [2], and an additional Forward Error Correction (FEC) mechanism at the application layer based on Raptor coding [5].

In MBMS, multimedia content is delivered either as a streaming service or as a file download service to the end user [6]. For streaming services a continuous data flow of audio, video and subtitling is transmitted to the terminals which is directly consumed by the users. For file download services, a finite amount of data is delivered and stored into the terminals as a file. In this paper we focus on these services. Applications that fall within this category are: video clips, digital newspapers, software download, etc. Common to all these services is the requirement of an error-free transmission of the files, as even a single bit error can corrupt the whole file and make it useless for the receiver. As it cannot be guaranteed that each and every user will be able to recover the file after the MBMS p-t-m transmission, as some users might have experienced too bad reception conditions, a post-delivery repair phase can be performed to complete the file download. The repair phase employs by default p-t-p transmissions, although it is also possible to employ a p-t-m transmission in case too many users fail to receive the file [7].

In this article we specifically focus on the efficient multicast delivery of file download services to several users simultaneously in evolved 3G mobile networks with HSDPA and MBMS. Multicast delivery can be implemented through only p-t-p transmissions with HSDPA, a single p-t-m transmission with MBMS, or using both jointly in a hybrid approach by employing HSDPA for error repair of the MBMS p-t-m transmission. The hybrid delivery is potentially the most efficient configuration, as in a realistic scenario there will always be some users that experience significantly worse reception conditions than the majority, and it may be more efficient to serve them through p-t-p connections with HSDPA. It can be shown that the optimum configuration does not imply a p-t-m repair phase, as in this case it is more efficient increase the duration of the initial p-t-m transmission instead. For this reason, we only consider p-t-p repair with HSDPA.

To determine the optimum configurations, the criteria of minimizing the transmission energy to achieve a certain file probability acquisition target (percentage of users that successfully receive the file) has been adopted. The transmission energy is defined as the product of the transmit power and the transmission time, and by minimizing the energy, the system capacity is maximized. For p-t-m MBMS transmissions the energy is constant and independent of the number of users, whereas for p-t-p HSDPA transmissions it is directly proportional to the number of users. In our investigations we have considered a background service without any time constraint to deliver the file, but we have also studied the effect of reducing the time to deliver the file.

The rest of the paper is organized as follows. First we provide an overview of MBMS in Section II. Then in Section III we explain how file download services are transmitted in MBMS, describing the main parameters that influence the overall system performance. In Section IV we describe the system models adopted in our radio network simulations. In Section V we provide some illustrative results of multicast file delivery with MBMS and HSDPA when used separately, and also when they are used jointly (hybrid approach). Finally, we give some concluding remarks in Section VI.

II. Multimedia Broadcast Multicast Services

MBMS provides a seamless integration of multicast and broadcast transport technologies into the existing 3G networks and service architectures, reusing much of the existing 3G functionalities[1]. It introduces only small changes into the existing radio and core network protocols, as well as into most of the functional entities of the architecture, and adds a new entity called Broadcast/Multicast-Service Center (BM-SC) [4]. The BM-SC acts as an MBMS server, and it serves as an entry point for the content delivered with MBMS.

MBMS p-t-m transmissions use the Forward Access Channel (FACH), QPSK modulation and turbo codes at the physical layer, and a constant transmission power and bearer data rate during the complete transmission of the service. As MBMS services are intended for multiple users, it is not possible to adapt the transmission parameters dynamically according to the user reception conditions as in a p-t-p connection like in HSDPA. Moreover, during the MBMS transmission the uplink is not utilized, and there is no communication between the terminals and the server. Terminals identify and discard erroneously received transport blocks each Transmission Time Interval (TTI) and do not request any retransmission. For this reason MBMS introduces two diversity techniques that do no require any feedback from the users.

In particular MBMS supports the use of long TTI, up to 80 ms, to provide time diversity against fast fading, and the combination of transmissions from multiple cells (sectors) to obtain a macro diversity gain. The use of long TTI increases the network latency, however the unidirectional nature of MBMS hides it from the user perception. On the other hand, macro diversity techniques achieve a significant reduction in transmit power compared to the single cell reception case. However these techniques increase the complexity and cost of the terminals. Two combining strategies are supported: selection combining and soft combining. With selection combining, signals received from different cells are decoded individually, such that terminals select each TTI the correct data (if any). With soft combining, the soft bits received from the different radio links prior to decoding are combined. Soft combining results in higher improvements, as it provides also a power gain as the received power from several cells is added coherently. However, it is more difficult to implement, as it requires to synchronize the transmissions between cells.

MBMS has also adopted an additional FEC mechanism at the application layer based on Raptor codes in order to cope with the radio transmission errors experienced by mobile users due to the fact of employing a constant transmit power and bearer data rate during the transmission [5].

FEC mechanisms rely on the transmission of additional parity data that allows recovering the original information when transmission errors occur without a need for feedback, as it is possible to recover the original content even if some packets are lost (it des not matter which packets are received but that enough packets are correctly received). Obviously, if all source packets are correctly received, no parity data is needed at all. Otherwise, as Raptor codes achieve close to ideal performance, only a slightly greater number of packets than the number of source packets are needed (i.e., 1-5% reception overhead, in average). In this way it is possible to benefit from the spatial diversity introduced by users' mobility, and thus it can be also seen as another diversity technique.

III. File Delivery in MBMS

Generally speaking, a file download service in MBMS consists in three phases:

1) Service advertisement phase; in which the service is announced and set-up by the network and the users discover the service.
2) MBMS initial file transmission phase; in which both source data file and a fixed pre-configured amount of parity data are initially transmitted through MBMS.

[1] MBMS is split into the MBMS bearer service and the MBMS user service, in such a way that it is possible to integrate p-t-p and p-t-m radio bearers in a transparent way to the MBMS service layer. Thus, it is possible to delivery an MBMS service with p-t-p transmissions. For the sake of clarity, in the rest of the paper we associate MBMS only to p-t-m transmissions, and HSDPA to p-t-p transmissions.

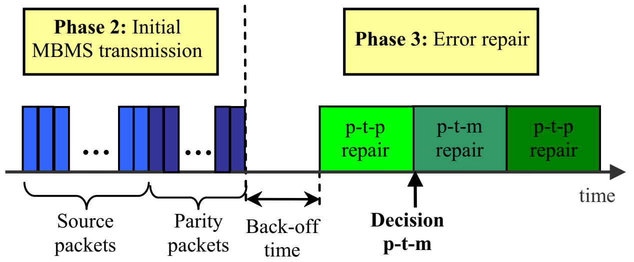

Fig. 1. MBMS file download service. Initial p-t-m MBMS transmission phase and error repair phase.

3) Post-delivery repair phase; in which users not able to decode the file after the initial MBMS transmission are served by default via HSDPA to complete the reception of the file, although it is also possible to employ MBMS in case too many users fail to receive the file.

Fig. 1 shows a temporal diagram of both phases.

A. MBMS Initial File Transmission Phase

In this phase the MBMS server must ensure that the file is successfully received by most of the users to avoid congestion problems in the error repair phase. The configuration of the MBMS transmission parameters should be done statistically, in order to serve the worst-case user contemplated, such that the desired file acquisition probability for this phase is reached (percentage of users that receive the file).

The robustness of the MBMS transmission is given by the coverage level and the amount of parity data transmitted. The coverage level depends on many factors: scenario, macro diversity technique implemented in the terminals, interference conditions, etc. The only parameters that the network operator can control are the transmit power, the bearer data rate, and the amount of parity data transmitted (or alternatively the transmission time, which can be limited by a maximum time to complete the transmission of the service). The transmit power and the bearer data rate yield the area coverage. Obviously, the higher the transmit power, the larger the coverage level (keeping the bearer data rate constant), and thus the amount of required parity data will be smaller, and the service transmission time will be reduced. However, maximizing the transmit power does not necessarily need to be the optimum configuration, as 3G systems are interference-limited, and the interference level is directly proportional to the transmission powers. On the other side, when increasing the bearer data rate the file should be in theory received faster by the users. However, it should be taken into account that an increase in the bearer data rate results in a reduction of the area coverage (keeping the transmit power constant), what implies an increase in the transmission time. The optimum configuration will be the one that delivers the file in due time and minimizes the transmission energy, defined as the product of the transmit power and the transmission time:

$$E = P_{tx} \cdot T_{tx}. \tag{1}$$

By minimizing the energy, the system capacity is maximized, as the number of services that can be provided with the same amount of power and during the same time period is maximized.

B. Post-Delivery Repair Phase

The purpose of this phase is to repair erroneous received files in the previous phase. To avoid congestion issues, error reporting messages from terminals can be distributed over time within a back-off window and across multiple repair servers. The time period should be large enough to prevent congestion, but should not unnecessarily increase the duration of the repair phase.

As mentioned before, terminals start the repair phase using dedicated p-t-p connections with HSDPA. However if the number of active users in this phase is high enough, it is possible to employ a p-t-m connection with MBMS. One important benefit of Raptor coding is that it can generate additional parity packets on-demand that can be used by all users.

As during the initial file transmission there is no communication between the terminals and the server, once the MBMS transmission is finished the server does not have any information about the number of users that have not received the file and the amount of repair data needed by each of them. This information can be estimated in the beginning of the p-t-p repair session. The decision of performing a p-t-m repair transmission should be taken as soon as possible once a representative number of error reporting messages have been collected. Usually it is recommended to take this decision once the 10% of the back-off window has elapsed [7]. The amount of repair data transmitted through the p-t-m connection can be for example the maximum amount of repair data requested by the users at that time. Once the p-t-m repair session is completed, a new p-t-p repair session can be initiated if needed. It should be pointed out that the repair server should immediately proceed to initiate a p-t-m repair session as soon as a congestion issue is detected.

Besides the duration of the back-off window, the main parameter that the network operator should configure in the p-t-p repair session is the HSDPA transmit power devoted to repair the file. Higher power levels will imply that the users receive the file faster, although it may not be the most efficient resource allocation as we have explained before. It should be noted that the performance of the p-t-p repair phase with HSDPA depends on the actual number of users that fail to receive the file after the initial MBMS transmission and their positions. Nevertheless, in this case it is also possible to employ the approach of minimizing the transmission energy required to achieve a certain total file acquisition probability between both phases for a given number of users per cell. The energy employed with HSDPA is computed in the same way than for MBMS, but taking into account that the transmission time is the sum of all active transmission intervals in which data is transmitted to the users.

IV. SYSTEM MODELS

A. Deployment Scenario

Radio network simulations have been performed in a typical urban scenario. The deployment scenario consists of 19 cells, with the cell under study in the center. No cell sectorization is considered and omnidirectional antennas have been assumed. The cell radius is 866 m and the inter-site distance is 1.5 km.

All users are assumed to be located outdoors moving according to a pedestrian mobility model. Users are initially uniformly distributed over the cell under study, and they do not leave the cell but bounce at the edges.

B. Link Budget

Link budget values corresponding to an urban scenario at a frequency of 2000 MHz have been considered. We assume lognormal shadowing with a standard deviation of 8 dB and a correlation distance of 50 m (correlation factor between cells is 0.5). Fast fading (Rayleigh distributed) is also considered. The distance dependent path loss has been modeled with an Okumura-Hata propagation model.

The maximum total transmission power per cell is 20 W, and it has been considered that control channels use 20% out of the maximum 20 W (i.e., 4 W). All simulated cells transmit with the same power. The thermal noise power at the terminals is -103 dBm, which are modeled with an omnidirectional antenna of -0 dBi gain.

C. Interference Model

In the simulations, both intra and inter-cell interferences are considered. A constant orthogonality factor is used to characterize the interference between channels of the same cell in the downlink (the value employed in the simulations is 0.6). No other services than the file download service under study have been simulated.

D. Radio Link Performance Model

For the shake of simplicity, the radio link performance model is based on a shifted version of the Shannon limit, as proposed in [8]. The maximum Modulation and Coding Rate (MCR), in bps/Hz, that can be achieved for a given SINR can be computed as:

$$MCR = \log_2\{1 + \gamma \cdot SINR\}. \quad (2)$$

Where $0 < \gamma \leq 1$ is a degradation term, which shifts the link performance away from the Shannon limit. The effective data rate is obtained from multiplying the MCR with the amount of spectrum utilized for the transmission (5 MHz in our case). In our simulations we have chosen a value of $\gamma = 0.4$ (4 dB degradation from Shannon limit and assumption of BER 10^{-4}), which resembles quite accurately the performance of HSDPA terminals of category 6 (up to 2 Mbps).

E. MBMS and HSDPA Performance Models

In the simulations, we upgrade the propagation losses including shadowing every 80 ms (MBMS TTI period), and the fast fading every 2 ms (HSDPA TTI period). For MBMS we have employed the ECM method (Equivalent SNR Method based on Convex Metrix) to obtain an effective SINR value in the TTI [5]. We compare the effective SINR to the threshold given by (2) for the bearer data rate employed to decide whether the TTI is correctly received or not.

For HSDPA we assume that the effective data rate given by (2) is always correctly received (i.e., ideal link adaptation without retransmissions of lost packets). Moreover, we have considered a minimum data rate equal to 68.5 kbps and a maximum data rate equal to 2 Mbps.

F. Raptor Code Model

To account for a practical implementation of a Raptor code, a constant 5% reception overhead has been assumed, as this will generally allow recovery of the file in most cases [5].

V. RESULTS AND DISCUSSIONS

In this section we present simulation results obtained for a download service of a 512 KB file. For MBMS we consider the reference case without any macro diversity combining technique. The implications of considering different acquisition probability targets, smaller and larger file sizes, and employing selective combining in MBMS with 2 radio links (as the gain obtained by using 3 links is not significant), are also discussed.

For MBMS we investigate the optimum bearer data rate and transmit power. This approach is different to the one proposed in [5], where it is optimized the coding rate of the turbo-code at the physical layer for a fixed bearer. For HSDPA we only investigate the optimum transmit power, as we assume a MaxCIR scheduling algorithm, and for the hybrid delivery we also investigate the optimum balance between the initial MBMS transmission and the HSDPA error repair phase by computing the optimum file acquisition probability after the MBMS transmission. In this paper we focus on the optimum transmission configurations without time constraints, and the study of the effect of reducing the time to deliver the files is left for future work. Feasible MBMS bearer data rates employed in the simulations are: 64, 96, 128, 192, and 256 kbps, and useful transmit power values range from 0.5 up to 16 W for both MBMS and HSDPA.

A. File Delivery Results with MBMS

Fig. 2 shows the energy required to achieve a 95% acquisition probability of a 512 KB file with MBMS as a function of the transmit power for different bearer data rates. We can see how the energy is proportional to the transmit power, and that the minimum energy point regardless the bearer data rate is the minimum transmit power considered, 0.5 W. Thus, it is more efficient to reduce the transmission power, which implies a reduction of the coverage level but also of the interferences, and increase the amount of Raptor parity data transmitted.

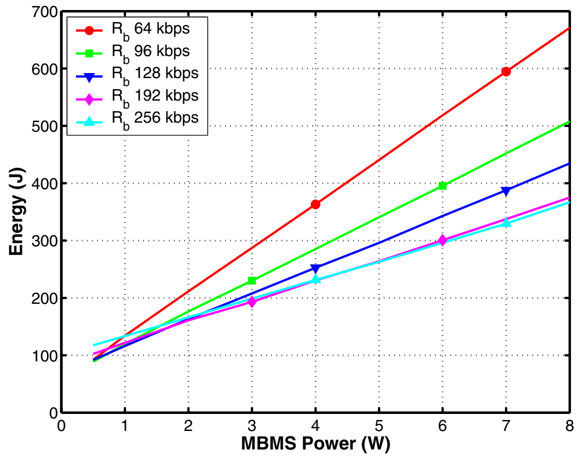

Fig. 2. MBMS energy vs. MBMS transmit power. File 512 KB. Acquisition probability 95%. No selective combining.

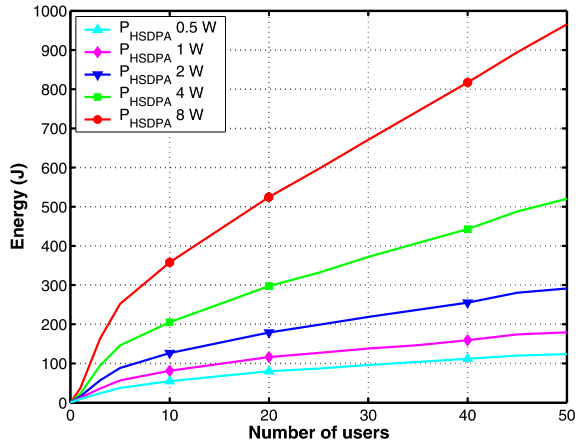

Fig. 3. HSDPA energy vs. Number of users. File 512 KB. Acquisition probability 95%.

As discussed previously, smaller powers imply larger transmission times. Therefore there is a clear trade-off between minimizing the resource consumption and the transmission time of the files.

In Fig. 2 we can note that for low transmit power values the energy provided by the different bearer data rates is rather small, whereas for large powers, the differences are evident, being thus more important to choose the optimum bearer. In the figure we can see that the optimum bearer for large power values is the maximum considered, 256 kbps. The reason is that the coverage level is high enough so most users can benefit of transmitting more data per TTI. When the transmit power (and coverage level) decreases, the optimum bearer data rate decreases. For a similar reason the optimum bearer data rate increases as a function of the file acquisition probability target, as the coverage level perceived by the worst-case user served (which gives the final energy value) is reduced.

When implementing selective combining we observed a significant performance improvement in both energy and transmission time (the minimum transmission energy was approximately reduced down to a third and the minimum transmission time by half). Selective combining also implies higher optimum bearer data rates, as the coverage level is higher.

When comparing the delivery of files of different sizes (128 KB, 512 KB and 2 MB), it was found that it is more efficient transmit larger files in the reference case without macro diversity (the minimum energy values of the different files were scaled by a factor of about 2.7 times, instead of 4 times as the relationship of the file sizes considered). This is because the spatial diversity gain due to users' mobility obtained with Raptor coding is higher for larger files (for the same proportion of parity data transmitted), enhancing the coding efficiency. For this reason the optimum bearer data rates are also higher for larger files. On the other hand, there is no much difference when implementing selective combining, as the coverage level is considerably higher and the amount of parity data required is small.

B. File Delivery Results with HSDPA

Fig. 3 shows the energy required to achieve a 95% acquisition probability of a 512 KB file with HSDPA as a function of the number of users for different transmit powers. As expected the energy grows linearly with an increasing number of users, but we can note that the optimum transmission configuration is the minimum transmit power considered as in MBMS, which is the configuration that provides the largest service time. Therefore, there is again a trade-off between resource consumption and file delivery time. In case there is a maximum time to deliver the service, the optimum transmit power is the minimum value that transmits the file in due time.

If we compare the minimum energy that can be achieved with HSDPA as a function of the number of users per cell with the minimum energy provided with MBMS, it is more efficient to employ HSDPA if there are up to 29 users in the cell. In case selective combining is implemented the threshold goes down to only 4 users. The threshold depends on the file size and the acquisition probability target. In particular, for larger files the threshold decreases for the MBMS reference case without macro diversity, as in this case MBMS performs more efficiently (HSDPA also benefits of larger files, but in a lower extent than MBMS). On the other side, the threshold increases for larger acquisition probabilities targets. This is because it becomes increasingly more costly to serve the final percentage of users using only MBMS compared to HSDPA. These users are the ones located in bad reception locations that move at low speeds, and they cannot be served efficiently with MBMS. The key with HSDPA is that resources are only consumed when one user is actively using the service (i.e., there is at least one user in coverage), whereas with MBMS the transmission is active during the complete session. Finally, it should be pointed out that the number of users threshold when implementing selective combining is practically constant. This is because the efficiency improvement obtained when considering larger files with HSDPA is similar to the one obtained for MBMS with selective combining.

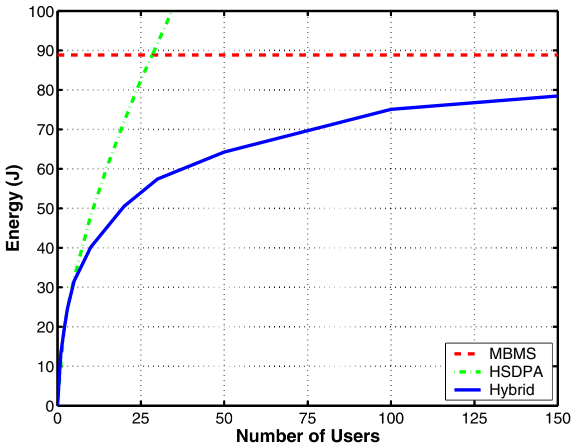

Fig. 4. Minimum energy vs. Number of users. File 512 KB. Acquisition probability 95%.

C. File Delivery Results with MBMS and HSPDA

Finally we investigate the potential efficiency gain that can be achieved by using HSDPA for error repair of the MBMS transmission to serve the final percentage of users. We have assumed that the back-off window is set to zero, in order to make a fair comparison with the results obtained when using only MBMS. This implies that there are no congestion problems in the network during the error repair phase, and the radio link is the bottleneck. As we do not consider any time constraint to deliver the service, the transmit power values employed for both MBMS and HSDPA is 0.5 W.

Fig. 4 shows the minimum energy that can be achieved with an hybrid delivery to achieve a 95% acquisition probability of a 512 KB file as a function of the number of users compared to using MBMS and HSDPA separately. The optimum acquisition probability after the MBMS transmission increases as a function of the number of users. This is simply because MBMS is more efficient than HSDPA for larger number of users. For few users (up to 5 users in Fig. 4), it equals to zero percent, meaning that all users are served with HSDPA and that there is no gain due to the hybrid delivery. For more users than this threshold, the optimum MBMS acquisition probability increases first rapidly (reaching 50% for 15 users and 80% for 60 users in our example). This is the area where the highest gain due to the hybrid delivery is achieved. Note that it corresponds to the crossing point of the two reference curves using HSDPA and MBMS separately. In Fig. 4 a reduction of the energy of 35.4% is achieved. After this point, the gain decreases with the number of users. The optimum MBMS acquisition probability also starts to saturate slowly when approaching the overall acquisition probability target (in our case for 100 users the optimum is 85%, and for 150 users almost 90%). For very large number of users, the optimum MBMS acquisition probability is close to the overall target, and there is very little gain using HSDPA.

It should be pointed out that the gain brought by the hybrid delivery increases for higher acquisition probabilities targets, as it becomes very costly to serve the last percentage of users, and thus a 100% error free MBMS transmission of the file is not efficient. The energy reduction achieved using MBMS and HSDPA jointly behaves in a similar way than the number of users required so MBMS is more efficient than HSDPA. That is, the reduction decreases for larger files and when implementing selective combining. The reason is that in those cases MBMS performs better, and thus the gain obtained by using HSDPA as a complement of MBMS is lower.

VI. Conclusions

In this paper we have discussed multicast delivery in evolved 3G mobile networks with HSDPA and MBMS. We have shown that if there are no time constraints to deliver the files, it is more efficient to reduce the transmit power for MBMS in order to decrease the level of interferences, and increase the amount of Raptor parity data transmitted in order to benefit from the spatial diversity gain due to users' mobility. This diversity gain is higher for larger files, enhancing the Raptor coding efficiency for the same proportion of parity data transmitted, and thus with MBMS it is more efficient to deliver larger files. However, it becomes very costly to serve the last percentage of users using only MBMS, and thus a significant gain can be achieved employing HSDPA to repair errors of the MBMS transmission.

For HSDPA it is also more efficient to reduce the transmit power at the expense of a larger file delivery time, and it outperforms MBMS to serve the last percentage of users because resources are only consumed when at least one user is actively using the service. The use of Raptor coding is key to achieve an efficient hybrid MBMS/HSDPA delivery, as all correctly received packets during the initial MBMS transmission are useful to the receivers, and it is possible to generate additional parity packets on-demand in the error repair phase that can be used by all users.

Acknowledgment

This work has been partially supported by the Spanish Ministry of Industry, Tourism and Commerce under the project FURIA (Futura Red Integrada Audiovisual).

References

[1] Y. Solomon, "The Economics of Mobile Broadcast TV," Mobile DTV Alliance Whitepaper, Jan. 2007.

[2] S. Parkvall, E. Englund, M. Lundevall, and J. Torsner, "Evolving 3G Mobile Systems: Broadband and Broadcast Services in WCDMA," *IEEE Commun. Mag.*, vol. 44, no. 2, Feb. 2006, pp. 68-74.

[3] R. Walsh, A. P. Vainio, and J. Aaltonen, "*Content Networking in the Mobile Internet: Multicast Content Delivery for Mobiles*," Wiley 2004.

[4] F. Hartung, *et al.*, "Delivery of Broadcast Services in 3G Networks," *IEEE Trans. on Broadcasting*, vol. 52., no. 1, pp. 188-199, March 2007.

[5] M. Luby, T. Gasiba, T. Stockhammer, and M. Watson, "Reliable Multimedia Download Delivery in Cellular Broadcast Networks," *IEEE Trans. on Broadcasting*, vol. 52., no. 1, pp. 235-246, March 2007.

[6] 3GPP TS 26.346 v7.1.0, "Multimedia Broadcast/Multicast Service (MBMS); Protocols and Codecs," Sept. 2006.

[7] T. Lohmar, P. Zhaoyi, and P. Mahonen, "Performance Evaluation of a File Repair Procedure based on a Combination of MBMS and Unicast Bearers," *Proc. IEEE WoWMoM*, Niagara Falls, USA, 2006.

[8] K. L. Baum, T. A. Kostas, P. J. Sartori, and B. K. Classon, "Performance characteristics of cellular systems with different link adaptation strategies," *IEEE Trans. on Vehicular Technology*, vol. 52, no. 6, pp. 1497-1507, Nov. 2003.