A File Repair Scheme for UMTS MBMS Service

Yen-Cheng Lai, *Student Member, IEEE*, Phone Lin, *Senior Member, IEEE*,
Yi-Bing Lin, *Fellow, IEEE*, and Lu-Tsung Chang

***Abstract*—The 3rd Generation Partnership Project (3GPP) Technical Specification 23.246 proposed the Multimedia Broadcast Multicast Service (MBMS) that efficiently multicasts multimedia content. During MBMS content transmission, data may be lost. Three file repair schemes were proposed to retransmit the corrupted MBMS data. However, these schemes may introduce extra data traffic or signaling overheads. This paper proposes the Reuse Bearer Service (RBS) file repair scheme to resolve this issue. We analyze the four file repair schemes by analytical models and simulation experiments. This paper shows that the proposed RBS scheme may significantly outperform the previously proposed schemes.**

***Index Terms*—File repair, mobile core network, Multimedia Broadcast Multicast Service (MBMS), retransmission scoping, Universal Mobile Telecommunications System (UMTS).**

NOMENCLATURE

MBMS	Multimedia Broadcast Multicast Service.
UMTS	Universal Mobile Telecommunications System.
GGSN	Gateway GPRS Support Node.
SGSN	Serving GPRS Support Node.
RNC	Radio Network Controller.
UE	User Equipment.
BM-SC	Broadcast Multicast-Service Center.
RA	Routing Area.
UFR	Unicast File Repair scheme.
RMFR	Re-Multicast File Repair scheme.
NBS	New Bearer Service file repair scheme.
RBS	Reuse Bearer Service file repair scheme.
CFB	Corrupted File Block.
C-UE	Corrupted UE.
CRT	CFB Routing Table.

Manuscript received August 13, 2007; revised November 24, 2007, December 29, 2007, and February 2, 2008. First published March 3, 2008; current version published November 12, 2008. The work of Y.-C. Lai was supported in part by the National Science Council (NSC), R.O.C., under Contract NSC-97-2218-E-002-026. The work of P. Lin was supported in part by the NSC, R.O.C., under Contract NSC-96-2627-E-002-001, Contract NSC-96-2811-E-002-010, Contract NSC-96-2628-E-002-002-MY2, and Contract NSC-95-2221-E-002-091-MY3; by the Ministry of Economic Affairs (MOEA), R.O.C., under Contract 93-EC-17-A-05-S1-0017; by Telcordia Applied Research Center; by the Taiwan Network Information Center (TWNIC); by the Excellent Research Projects of National Taiwan University under Contract 95R0062-AE00-07; and by Chunghwa Telecom M-Taiwan Program M-Taoyuan Project. The work of Y.-B. Lin was supported in part by the NSC, R.O.C., under Contract NSC-96N079, Contract NSC-96N576, Contract NSC-96N230, and Contract NSC-97-2221-E-009-143-MY3; by Chung-Hwa Telecom; by the ITRI and National Chiao Tung University (NCTU) Joint Research Center; and by the MoE ATU plan. The review of this paper was coordinated by Prof. J. Li.

Y.-C. Lai is with the Department of Computer Science and Information Engineering, National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: yclai@csie.ntu.edu.tw).

P. Lin is with the Department of Computer Science and Information Engineering and the Graduate Institute of Networking and Multimedia, National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: plin@csie.ntu.edu.tw).

Y.-B. Lin is with the Department of Computer Science and Information Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C., and also with the Institute of Information Science, Academia Sinica, Nankang, Taipei 11523, Taiwan, R.O.C. (e-mail: liny@csie.nctu.edu.tw).

L.-T. Chang is with the WiMAX Development Division, MediaTek Inc., Hsinchu 300, Taiwan, R.O.C. (e-mail: lt.chang@mediatek.com).

Digital Object Identifier 10.1109/TVT.2008.919612

I. INTRODUCTION

MULTICASTING (one source, many destinations) is widely utilized for multimedia content delivery over the Internet. In recent years, mobile telecommunication networks have been integrated with the Internet, and the Multimedia Broadcast Multicast Service (MBMS) was proposed to multicast multimedia content over the Universal Mobile Telecommunications System (UMTS) [4]. Fig. 1 illustrates the UMTS-based MBMS system architecture, including Gateway GPRS Support Node (GGSN), Serving GPRS Support Node (SGSN), Radio Network Controller (RNC), User Equipment (UE), and Broadcast Multicast-Service Center (BM-SC) [Fig. 1(a)–(e)]. Details of these network nodes can be found in [10] and [11]. The MBMS file blocks are delivered through a *delivery tree*, where the root (the source) is the BM-SC, and the leaves (the destinations) are the UEs. The delivery path is BM-SC→GGSN→SGSN→RNC→UE. In the delivery tree, *downstream* is the direction of the MBMS data flow from BM-SC to UE, and *upstream* is the direction of the MBMS signaling flow from UE to BM-SC.

Two kinds of contexts are maintained for MBMS Bearer Service, i.e., MBMS UE Context and MBMS Bearer Context. The MBMS UE Context stores the UE-specific information, which is created through the MBMS Multicast Service Activation procedure [1]. This context is stored in all nodes of the delivery tree [see Fig. 1(f)–(j)]. The MBMS Bearer Context stores MBMS Bearer-Service-specific information and a list of the downstream nodes. The MBMS Bearer Contexts [Fig. 1(k)–(n)] specify the connectivity of the delivery tree. If this context does not exist when a network node creates the MBMS UE Context, the network node will also create the MBMS Bearer Context and notify its upstream node that it has joined the delivery tree. The upstream node then inserts the ID of this network node into the downstream node list of its MBMS Bearer Context.

During MBMS content transmission, MBMS data may be lost or corrupted. The 3rd Generation Partnership Project (3GPP) 26.346 proposed three file repair schemes to retransmit the corrupted MBMS data [2], i.e., the *Unicast File Repair* (UFR) scheme, the *Re-Multicast File Repair* (RMFR) scheme, and the *New Bearer Service* (NBS) file repair scheme. These schemes introduce extra data traffic and/or signaling overheads to the UMTS network. To resolve this issue, we propose a

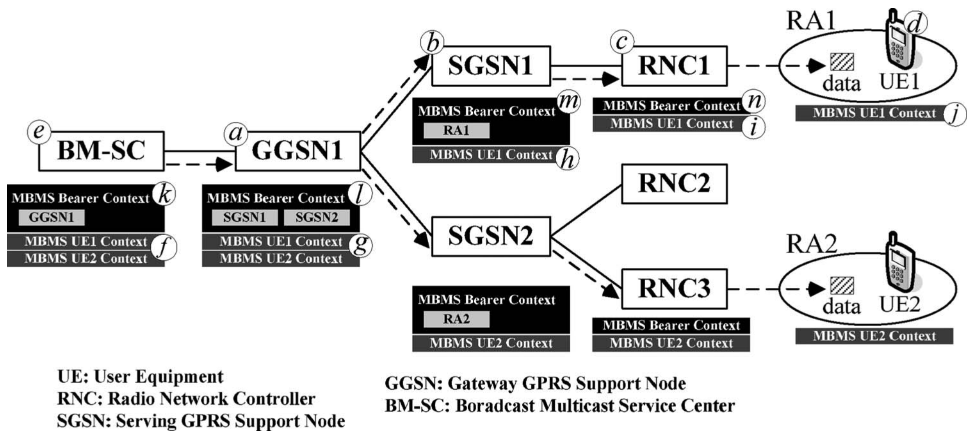


Fig. 1. MBMS delivery tree example.

new scheme called the *Reuse Bearer Service* (RBS) file repair scheme.

This paper is organized as follows. Section II describes UFR, RMFR, and NBS. Section III proposes the RBS scheme. Section IV elaborates on analytic models for the three 3GPP schemes and the RBS scheme. Section V investigates the performance of the four schemes.

II. Existing File Repair Schemes

An MBMS file is divided into several file blocks. A block is identified by the Source Block Number and Encoding Symbol ID pair. After an MBMS file download, a UE determines whether the received file blocks are corrupted by cyclic redundancy check.

A UE that receives Corrupted File Blocks (CFBs) is called a Corrupted UE (C-UE). When a CFB is detected, a C-UE sends the file repair request message to the BM-SC to indicate the Source Block Number and the Encoding Symbol ID of the CFB.

Upon receipt of the repair request message, BM-SC retransmits the CFBs by executing one of the following three repair schemes proposed by 3GPP 26.346 [2].

- UFR: For each C-UE, BM-SC retransmits the requested CFBs. If two or more C-UEs request the same CFBs, then multiple copies of the CFBs are individually unicasted to these C-UEs. This scheme does not take the advantage of multicast, and an extra unicast traffic is required.
- RMFR: When BM-SC receives the repair request message from a C-UE, it informs UE that the requested CFBs will be multicasted through the original delivery tree. Then, BM-SC multicasts all CFBs to all UEs. In this scheme, a UE may receive file blocks that have previously been correctly received. This phenomenon is known as the *retransmission scoping* problem [5], which is defined as "Each receiver receives all of the retransmissions of a packet, even after correctly receiving the packet." Therefore, RMFR imposes unnecessary CFB transmission.
- NBS File Repair: Upon receipt of the repair request message from C-UE, BM-SC informs C-UE that a new multicast group (i.e., the new MBMS Bearer Service) will be created to deliver the CFBs. Then, all C-UEs join the new multicast group and await to receive the CFBs. BM-SC then multicasts all CFBs to all C-UEs in the new multicast group. Although the UEs successfully receiving all blocks are not involved in NBS retransmission, the C-UEs do incur the retransmission scoping problem. Furthermore, a C-UE needs to join the new multicast group, which introduces extra signaling overhead for constructing the delivery tree.

Clearly, the suggested 3GPP file repair schemes incur extra traffic and signaling overheads for CFB retransmission, which can be avoided in the scheme proposed in the next section.

III. RBS

In the RBS file repair scheme, the concept of CFB Routing Table (CRT) is introduced, and a CFB list parameter is added in the MBMS UE Context. With these minor modifications, we show that a CFB is multicasted only to the C-UEs requesting it, and the retransmission scoping problem is resolved.

For every CFB, a CRT is maintained in each of the BM-SC (denoted as CRT_B), GGSN (denoted as CRT_G), SGSN (denoted as CRT_S), and RNC (denoted as CRT_R). For each CFB, $\mathrm{CRT}_S/\mathrm{CRT}_G/\mathrm{CRT}_B$ store the IDs of Routing Areas (RAs)/ SGSNs/GGSNs and the number of C-UEs (that request this CFB) in each of these RAs/SGSNs/GGSNs, and CRT_R stores the IDs of C-UEs connected to this RNC. The CRT is created and updated when a network node receives the repair request messages from C-UEs and is deleted when the CFB has been transmitted to the C-UEs requesting the CFB. BM-SC can determine whether all repair request messages have been received by using a timer. When the file repair message is received by the BM-SC, the timer is reset. After the timer expires, BM-SC

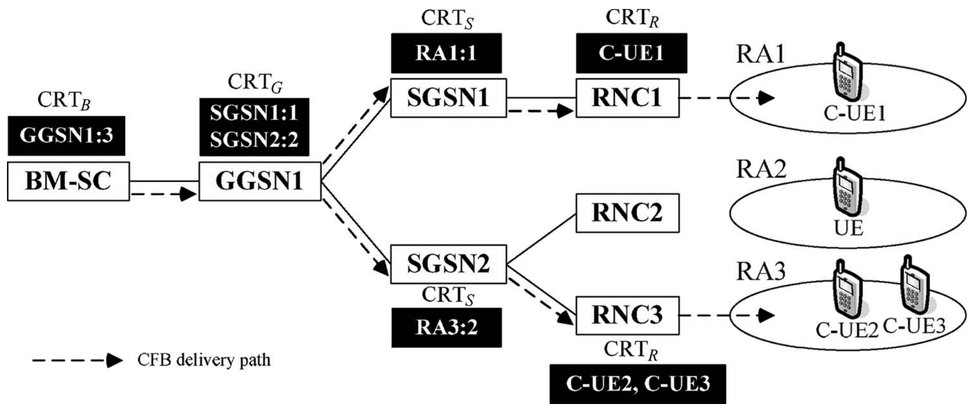


Fig. 2. CFB delivery example in RBS.

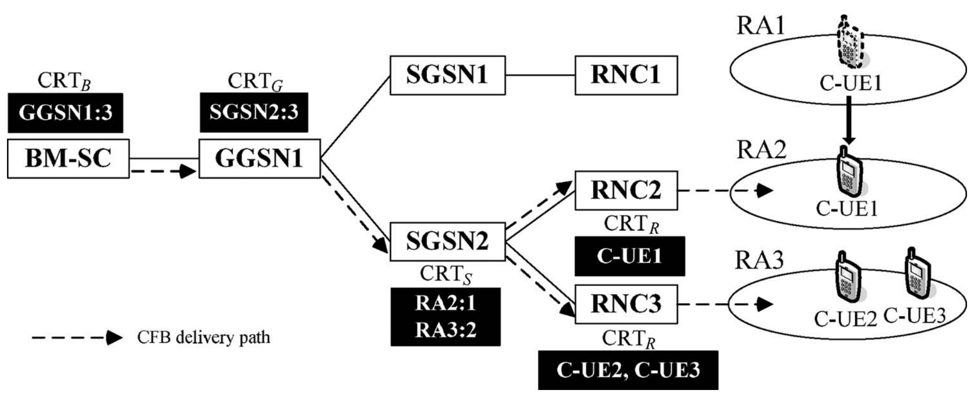


Fig. 3. Updated CRTs.

recognizes that all request messages (from C-UEs) have been received. Then, each network node routes a CFB to its downstream node according to the CRT. Consider the example in Fig. 2, where C-UE1 (in RA1), C-UE2, and C-UE3 (in RA3) request a CFB. RA1 and RA3 are connected to RNC1 and RNC3, respectively. RNC1 (RNC3) is served by SGSN1 (SGSN2). Both SGSN1 and SGSN2 are served by GGSN1. Thus

$$\begin{aligned} \text{CRT}_B[\text{BM}-\text{SC}] &= \{\text{GGSN1}:3\} \\ \text{CRT}_G[\text{GGSN1}] &= \{\text{SGSN1}:1, \text{SGSN2}:2\} \\ \text{CRT}_S[\text{SGSN1}] &= \{\text{RA1}:1\} \\ \text{CRT}_S[\text{SGSN2}] &= \{\text{RA3}:2\} \\ \text{CRT}_R[\text{RNC1}] &= \{\text{C}-\text{UE1}\} \\ \text{CRT}_R[\text{RNC3}] &= \{\text{C}-\text{UE2}, \text{C}-\text{UE3}\} \end{aligned}$$

where the notation "$\{X : k\}$" (X = GGSN, SGSN, or RA) means that there are k C-UEs within the service area of the X node. BM-SC, GGSN, and SGSN deliver the CFB to their downstream nodes specified in CRT$_B$, CRT$_G$, and CRT$_S$, respectively. RNC transmits the CFB to the C-UEs specified in its CRT$_R$. Therefore, a CFB is multicasted only to the C-UEs requesting it. The UEs (that correctly receive the file block) will not receive the CFB, and the retransmission scoping problem can be resolved.

A CFB *list* is maintained in a C-UE's MBMS UE Context to store the IDs of the CFBs requested by this C-UE. The CFB list is created when a network node receives the repair request message from C-UE and is deleted when all CFBs requested by this C-UE have been transmitted. When a C-UE moves from the old RA to a new RA, the CRTs should be updated for correct CFB delivery, and the CFB list for this C-UE is referenced to determine all CRTs that should be updated. Consider the example in Fig. 2 again. Suppose that C-UE1 moves from RA1 (served by RNC1) to RA2 (served by RNC2). The RBS scheme updates the CRTs of the CFBs requested by C-UE1 as follows (see Fig. 3).

1) CRT$_S$[SGSN1].RA1 is decremented by 1. RA1 is removed from CRT$_S$ if CRT$_S$[SGSN1].RA1 $= 0$.
2) If RA2 is not found in CRT$_S$[SGSN2], RA2's ID is inserted into CRT$_S$[SGSN2]. Then, CRT$_S$[SGSN2].RA2 is incremented by 1.
3) CRT$_G$[GGSN1].SGSN1 is decremented by 1. SGSN1 is removed from CRT$_G$ if CRT$_G$[GGSN1].SGSN1 $= 0$. If SGSN2 is not found in CRT$_G$[GGSN1], SGSN2's ID is inserted into CRT$_G$[GGSN1]. Then, CRT$_G$[GGSN1]. SGSN2 is incremented by 1.
4) The ID of C-UE1 is removed from CRT$_R$[RNC1] and inserted into CRT$_R$[RNC2].

The above tree update procedure can be conducted through standard location and Packet Data Protocol (PDP) context modification procedures [9], and, therefore, does not incur any extra signaling traffic.

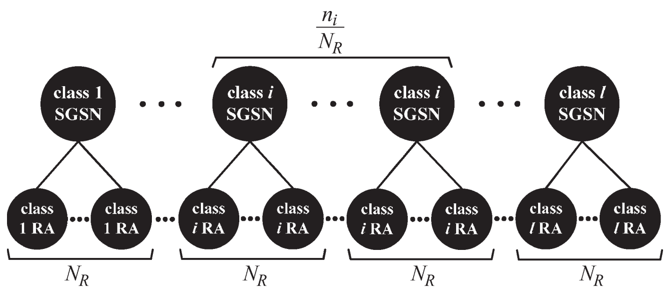


Fig. 4. RA distribution.

IV. Analytic Models

This section proposes analytic models for MBMS file repair schemes. Based on the population distribution of the UEs in the RAs, the RAs of the UMTS network are classified into l classes. Let n_i $(1 \leq i \leq l)$ be the number of class i RAs in the UMTS network, N_R be the number of RAs served by an SGSN, and N_s be the number of SGSNs in the system. All SGSNs are connected to a GGSN. That is, $N_sN_R = \sum_{I=1} n_i^l$. This paper assumes that all RAs served by an SGSN are of the same class, and an SGSN containing class i RA is called a class i SGSN (see Fig. 4). Therefore, the total number of class i SGSNs is n_i/N_R. We also consider other scenarios such as uniform RA distribution (i.e., the class i RAs are uniformly distributed among N_s SGSNs, and every SGSN has n_i/N_s class i RAs), the performance trends are similar, and the results will not be presented.

Assume that the file size is F times the signaling message size, and each block is b times the signaling message size. Let p_i be the error probability that the transmission of a block from a class i RA to a UE is corrupted. If a CFB is erroneously transmitted in the rth retransmission run, it is retransmitted in the $r+1$st retransmission run. BM-SC and C-UEs should exchange the file repair request and response signaling messages before retransmission. By convention, $r = 0$ represents the initial multicasting of the MBMS file to all joined UEs.

We derive the CFB transmission and the signaling costs between BM-SC, GGSNs, SGSNs, and RAs for the MBMS file repair schemes. All costs are normalized by the signaling message size. In the radio access network, the radio transmission cost for CFBs depends on the radio bearer, which is out of the scope of this paper and has been treated in our previous study. The output measures derived in this paper are introduced as follows:

1) M_g: expected number of CFBs delivered from BM-SC to GGSN;
2) M_s: expected number of CFBs delivered from GGSN to SGSNs;
3) M_R: expected number of CFBs delivered from SGSNs to RAs;
4) S_R: expected number of file repair request messages and file repair response messages delivered;
5) S_d: expected number of signaling messages required to establish and delete the delivery tree for CFB delivery;
6) C_t: net cost of CFB transmissions, where

$$C_t = b(M_g + M_s + M_R) \tag{1}$$

7) $C_s = S_R + S_d$: cost for signaling message transmissions;
8) C_n: net repair cost, where

$$C_n = C_t + C_s. \tag{2}$$

In the remainder of this paper, we use the notations $M_{g,\mathrm{X}}$, $M_{s,\mathrm{X}}$, $M_{R,\mathrm{X}}$, $C_{t,\mathrm{X}}$, $C_{s,\mathrm{X}}$, $C_{n,\mathrm{X}}$, $S_{R,\mathrm{X}}$, and $S_{d,\mathrm{X}}$ to represent the costs for schemes X = UFR, RMFR, NBS, or RBS.

A. Analysis for UFR

Suppose that the arrivals of UEs to a class i RA are a Poisson process with arrival rate λ_i, and the RA residence time for a UE in a class i RA has a general distribution with mean $1/\mu_i$. These two assumptions model the user mobility behavior in the UMTS network. In other words, we consider the effects of user mobility on the performance of file repair schemes. Then, from the M/G/∞ model and Little's law [9], the expected number of UEs in a class i RA is $\rho_i = \lambda_i/\mu_i$. Consider an arbitrary MBMS file block. Let p_i be the probability that this block is erroneously transmitted to a UE in a class i RA. Then, the probability that C-UE erroneously receives this block at the end of the rth retransmission run is p_i^{r+1}.

Since there are F/b blocks in an MBMS file, the expected number of CFBs after the rth retransmission run in a class i RA is $\rho_i p_i^{r+1}(F/b)$. Therefore, $M_{R,\mathrm{UFR}}$ is expressed as

$$M_{R,\mathrm{UFR}} = \sum_{r=0}^{\infty}\sum_{I=1}^{l} n_i\rho_i p_i^{r+1}\left(\frac{F}{b}\right) = \sum_{i=1}^{l}\frac{n_i\rho_i p_i F}{(1-p_i)b}.$$

In UFR, BM-SC individually unicasts CFBs to each requesting C-UE. Therefore, $M_{g,\mathrm{UFR}} = M_{s,\mathrm{UFR}} = M_{R,\mathrm{UFR}}$, and

$$\begin{aligned} C_{t,\mathrm{UFR}} &= b(M_{g,\mathrm{UFR}} + M_{s,\mathrm{UFR}} + M_{R,\mathrm{UFR}}) \\ &= \sum_{i=1}^{l}\frac{3n_i\rho_i p_i F}{1-p_i}. \end{aligned} \tag{3}$$

$S_{R,\mathrm{UFR}}$ and $S_{d,\mathrm{UFR}}$ are derived as follows. The probability that a UE correctly receives all blocks after the rth retransmission run is $(1-p_i^{r+1})^{F/b}$, and the probability that a UE receives one or more error blocks after the rth retransmission run is $1-(1-p_i^{r+1})^{F/b}$. Let $N^{(r)}$ be the expected number of C-UEs in the system at the end of the rth retransmission run. Then

$$N^{(r)} = \sum_{i=1}^{l} n_i\rho_i\left[1-\left(1-p_i^{r+1}\right)^{F/b}\right]. \tag{4}$$

As specified in the standard [1], the number of signaling messages (including file repair request messages and the file repair response messages) exchanged between BM-SC, GGSN, SGSNs, and RAs is 6. From (4), $S_{R,\mathrm{UFR}}$ is expressed as

$$\begin{aligned} S_{R,\mathrm{UFR}} &= \sum_{r=0}^{\infty} 6N^{(r)} \\ &= \sum_{r=0}^{\infty}\sum_{i=1}^{l} 6n_i\rho_i\left[1-\left(1-p_i^{r+1}\right)^{F/b}\right]. \end{aligned} \tag{5}$$

In UFR, the signaling messages to establish and delete the delivery tree for CFB delivery are not required. Therefore, $S_{d,\mathrm{UFR}} = 0$, and $C_{s,\mathrm{UFR}} = S_{R,\mathrm{UFR}}$. Substituting (3) and (5) into (2), $C_{n,\mathrm{UFR}}$ can be expressed as

$$\begin{aligned} C_{n,\mathrm{UFR}} &= 3\sum_{i=1}^{l}\left\{n_i\rho_i\left\{\frac{p_iF}{1-p_i}+2\sum_{r=0}^{\infty}\left[1-\left(1-p_i^{r+1}\right)^{F/b}\right]\right\}\right\} \\ &= 3\sum_{i=1}^{l}\left\{n_i\rho_i\left[\frac{p_iF}{1-p_i}-2\sum_{j=1}^{F/b}\binom{F/b}{j}\frac{(-p_i)^j}{1-p_i^j}\right]\right\}. \end{aligned}$$

B. Analysis for RMFR

Let $\pi_i(j)$ be the probability that there are j MBMS UEs in a class i RA. From the M/G/∞ model, we have

$$\pi_i(j) = \left(\frac{\rho_i^j}{j!}\right)e^{-\rho_i}. \quad (6)$$

Consider an arbitrary MBMS file block. Let $P_i^{(r)}$ be the probability that there is at least one UE in a class i RA, and all joined UEs in this RA correctly receive this block after the rth retransmission run. From (6), we have

$$P_i^{(r)} = \sum_{j=1}^{\infty}\left(1-p_i^{r+1}\right)^j\pi_i(j) = e^{-\rho_i p_i^{r+1}} - e^{-\rho_i} \quad (7)$$

where $(1-p_i^{r+1})^j$ is the probability that there are j joined UEs in a class i RA, and all of these UEs correctly receive the block after the rth retransmission run. Let $P_{c,i}^{(r)}$ be the probability that this file block will not be transmitted to a class i RA in the $r+1$st retransmission run. By using (6) and (7), we compute $P_{c,i}^{(r)}$ as

$$\begin{aligned} P_{c,i}^{(r)} &= \pi_i(0) + P_i^{(r)}\left(P_i^{(r)}+\pi_i(0)\right)^{n_i-1} \\ &\quad\times\left[\prod_{1\le j\le l, j\ne i}\left(P_j^{(r)}+\pi_j(0)\right)^{n_j}\right] \quad (8) \\ &= e^{-\rho_i} + \left[1-e^{-\rho_i\left(1-p_i^{r+1}\right)}\right]\left(\prod_{j=1}^{l}e^{-\rho_j p_j^{r+1}n_j}\right) \quad (9) \end{aligned}$$

where the first term of the right-hand side of (8) is the probability that there is no joined UE in this class i RA. The second term is the probability that, after the rth retransmission run, this file block is correctly received by all UEs in class i RA, this file block is not transmitted in the other class i RAs, and this file block is not transmitted in class j RAs (where $j \ne i$).

Let $\overline{P_{c,i}}^{(r)}$ be the probability that SGSN transmits this CFB to a class i RA in the $r+1$st retransmission run. From (9), $\overline{P_{c,i}}^{(r)}$ can be expressed as

$$\begin{aligned} \overline{P_{c,i}}^{(r)} &= 1 - P_{c,i}^{(r)} \\ &= 1-e^{-\rho_i}-\left[1-e^{-\rho_i\left(1-p_i^{r+1}\right)}\right]\left(\prod_{j=1}^{l}e^{-\rho_j p_j^{r+1}n_j}\right). \quad (10) \end{aligned}$$

Since there are F/b blocks in an MBMS file, we have

$$M_{R,\mathrm{RMFR}} = \left(\frac{F}{b}\right)\left[\sum_{r=0}^{\infty}\sum_{i=1}^{l}n_i\overline{P_{c,i}}^{(r)}\right]. \quad (11)$$

By applying (10), (11) is rewritten as

$$\begin{aligned} M_{R,\mathrm{RMFR}} = \left(\frac{F}{b}\right)\sum_{r=0}^{\infty}\sum_{i=1}^{l}n_i\Bigg\{1-e^{-\rho_i}-\left[1-e^{-\rho_i\left(1-p_i^{r+1}\right)}\right] \\ \times\left(\prod_{j=1}^{l}e^{-\rho_j p_j^{r+1}n_j}\right)\Bigg\}. \quad (12) \end{aligned}$$

Similar to the derivation for $M_{R,\mathrm{RMFR}}$, $M_{s,\mathrm{RMFR}}$ and $M_{g,\mathrm{RMFR}}$ are expressed as

$$\begin{aligned} M_{s,\mathrm{RMFR}} &= \left(\frac{F}{bN_r}\right)\sum_{r=0}^{\infty}\sum_{i=1}^{l}n_i\Bigg\{1-e^{-\rho_i N_r}-\left[1-e^{-\rho_i N_r\left(1-p_i^{r+1}\right)}\right] \\ &\quad\times\left(\prod_{j=1}^{l}e^{-\rho_j p_j^{r+1}n_j}\right)\Bigg\} \quad (13) \end{aligned}$$

$$M_{g,\mathrm{RMFR}} = \left(\frac{F}{b}\right)\sum_{r=0}^{\infty}\left(1-\prod_{i=1}^{l}e^{-\rho_i p_i^{r+1}n_i}\right). \quad (14)$$

Substituting (12)–(14) into (1), we obtain $C_{t,\mathrm{RMFR}}$. In RMFR, $S_{R,\mathrm{RMFR}}$ is the same as that in UFR and is expressed in (5). The signaling messages to establish and delete the delivery tree for CFB delivery are not required in RMFR. Therefore, we have $S_{d,\mathrm{RMFR}} = 0$ and $C_{s,\mathrm{RMFR}} = S_{R,\mathrm{RMFR}}$, and $C_{n,\mathrm{RMFR}}$ can directly be computed from (2).

C. Analysis for NBS

In NBS, a new multicast group is created to deliver all CFBs requested by C-UEs. These C-UEs join a new multicast group before CFB transmission. Then, BM-SC multicasts all the requested CFBs to the C-UEs in this new multicast group. Analytic analysis for $C_{t,\mathrm{NBS}}$ is too complicated and will not be derived in this paper. Instead, they will be investigated through simulation.

In NBS, $S_{R,\mathrm{NBS}} = S_{R,\mathrm{UFR}}$ and is expressed in (5). $S_{d,\mathrm{NBS}}$ is derived as follows. In NBS, each C-UE and the network nodes should exchange 27 signaling messages to exercise the MBMS Multicast Service Activation and the MBMS Multicast Service Deactivation procedures to establish and delete the delivery tree for CFB delivery between BM-SC, GGSN, SGSNs, and RAs [1]. From (4), $S_{d,\mathrm{NBS}}$ can be expressed as

$$S_{d,\mathrm{NBS}} = \sum_{r=0}^{\infty}\sum_{i=1}^{l} 27 n_i \rho_i \left[1 - \left(1 - p_i^{r+1}\right)^{F/b}\right]. \quad (15)$$

From (5) and (15), we have

$$\begin{aligned} C_{s,\mathrm{NBS}} &= S_{R,\mathrm{NBS}} + S_{d,\mathrm{NBS}} \\ &= \sum_{r=0}^{\infty}\sum_{i=1}^{l} 33 n_i \rho_i \left[1 - \left(1 - p_i^{r+1}\right)^{F/b}\right] \\ &= 33 \sum_{i=1}^{l}\sum_{j=1}^{F/b} \binom{F/b}{j} \left[\frac{n_i \rho_i (-p_i)^j}{p_i^j - 1}\right]. \end{aligned}$$

D. Analysis for RBS

In RBS, CRT and CFB lists are created when a network node receives repair request messages from C-UEs. A network node only multicasts a CFB to the C-UEs listed in its CRT. Like RMFR, RBS does not need to create a new multicast group for CFB delivery. Consider an arbitrary MBMS file block. Let $\overline{P_i}^{(r)}$ be the probability that there are more than one C-UE (receiving this block erroneously) in a class i RA after the rth retransmission run. Therefore, $P_i^{(r)} + \overline{P_i}^{(r)} + \pi_i(0) = 1$. From (6) and (7), $\overline{P_i}^{(r)}$ can be expressed as

$$\overline{P_i}^{(r)} = 1 - e^{-\rho_i p_i^{r+1}}. \quad (16)$$

In RBS, if there is one or more C-UEs in class i RAs after the rth retransmission run, the block is multicasted from the SGSN to this RA in the $r+1$st retransmission run. Since there are F/b blocks in an MBMS file, from (16), we have

$$\begin{aligned} M_{R,\mathrm{RBS}} &= \left(\frac{F}{b}\right) \sum_{r=0}^{\infty}\sum_{i=1}^{l} n_i \overline{P_i}^{(r)} \\ &= \left(\frac{F}{b}\right) \sum_{r=0}^{\infty}\sum_{i=1}^{l} n_i \left(1 - e^{-\rho_i p_i^{r+1}}\right). \quad (17) \end{aligned}$$

The derivations for $M_{s,\mathrm{RBS}}$ and $M_{g,\mathrm{RBS}}$ are similar to that for $M_{R,\mathrm{RBS}}$, and we have

$$M_{s,\mathrm{RBS}} = \left(\frac{F}{bN_r}\right) \sum_{r=0}^{\infty}\sum_{I=1}^{l} n_i \left(1 - e^{-\rho_i p_i^{r+1} N_r}\right) \quad (18)$$

$$M_{g,\mathrm{RBS}} = \left(\frac{F}{b}\right) \sum_{r=0}^{\infty} \left(1 - \prod_{i=1}^{l} e^{-\rho_i p_i^{r+1} n_i}\right). \quad (19)$$

From (17)–(19), $C_{t,\mathrm{RBS}}$ can be expressed as

$$C_{t,\mathrm{RBS}} = F \sum_{r=0}^{\infty} \left[\sum_{i=1}^{l} n_i \left(1 - e^{-\rho_i p_i^{r+1}} + \frac{1 - e^{-\rho_i p_i^{r+1} N_r}}{N_r}\right) + 1 - \prod_{i=1}^{l} e^{-\rho_i p_i^{r+1} n_i}\right]. \quad (20)$$

TABLE I
VALIDATION OF C_n/F FOR UFR ($F = 5000, b = 100, \rho_1 = 50, \rho_2 = 1, p_1 = 0.05$, AND $p_2 = 0.001$)

	C_n/F (UFR)		
δ	**Analysis**	**Simulation**	**Error** (%)
0.0	0.076540477	0.076187352	0.46126
0.4	79.62164328	79.64192000	0.00844
0.8	159.1667522	159.0923340	0.04600

TABLE II
VALIDATION OF C_n/F FOR RMFR ($F = 5000, b = 100, \rho_1 = 50, \rho_2 = 1, p_1 = 0.05$, AND $p_2 = 0.001$)

	C_n/F		
δ	**Analysis**	**Simulation**	**Error** (%)
0.0	0.548645108	0.546918552	0.31469
0.4	45.88393510	45.87048348	0.02931
0.8	60.78854880	60.801319420	0.02100

TABLE III
VALIDATION OF C_n/F FOR RBS ($F = 5000, b = 100, \rho_1 = 50, \rho_2 = 1, p_1 = 0.05$, AND $p_2 = 0.001$)

	C_n/F		
δ	**Analysis**	**Simulation**	**Error** (%)
0.0	0.076155603	0.075811752	0.45151
0.4	15.85065426	15.84907827	0.00994
0.8	30.13710388	30.13351902	0.01189

TABLE IV
VALIDATION OF C_s/F FOR NBS ($F = 5000, b = 100, \rho_1 = 50, \rho_2 = 1, p_1 = 0.05$, AND $p_2 = 0.001$)

	C_S/F		
δ	**Analysis**	**Simulation**	**Error** (%)
0.0	0.008059329	0.008084604	0.31360
0.4	3.460780492	3.460828800	0.00139
0.8	6.913501656	6.913163120	0.00489

In RBS, $S_{R,\mathrm{RBS}}$ is the same as that in UFR and is expressed in (5). In RBS, the signaling messages to establish and delete the delivery tree for CFB delivery are not required. Therefore, $S_{d,\mathrm{RBS}} = 0$, and $C_{s,\mathrm{RBS}} = S_{R,\mathrm{RBS}}$. Then, $C_{n,\mathrm{RBS}}$ can be derived from (5) and (20).

V. Numerical Results

This section investigates the performance of MBMS file repair schemes based on simulation experiments. The simulation model adopts the discrete event simulation approach that has been widely used in the mobile telecommunication network studies [6]–[8]. The details of the simulation model are given in the Appendix. To simplify our discussion, we consider two RA classes to represent service coverage in city and suburban areas. The UEs in class 1 RAs (class 2 RAs) have high (low) user density. Denote $\delta = n_1/n_1 + n_2$ as the portion of class 1 RA in the UMTS network. In this paper, $n_1 + n_2 = 25$. For other setups, similar results are observed and will not be presented in this paper. A typical F value ranges from 1000 to 5000 times the signaling message size [3]. We note that the simulation experiments are validated against the analytical models described in Section IV. Tables I–IV indicate that the analytic results for $C_{n,\mathrm{UFR}}$, $C_{n,\mathrm{RMFR}}$, $C_{n,\mathrm{RBS}}$, and $C_{s,\mathrm{NBS}}$, and the simulation experiments, match well. For other parameter setups, the errors

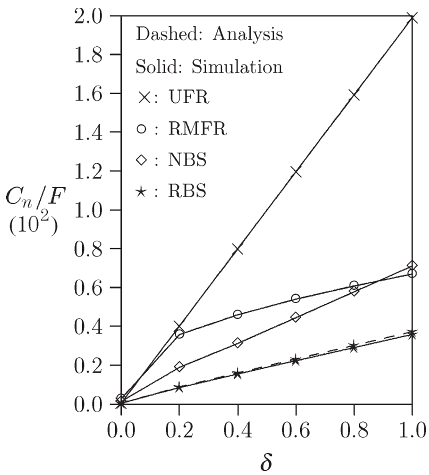


Fig. 5. Effects of δ ($F = 5000$, $b = 100$, $\rho_1 = 50$, $\rho_2 = 1$, $p_1 = 0.05$, and $p_2 = 0.005$).

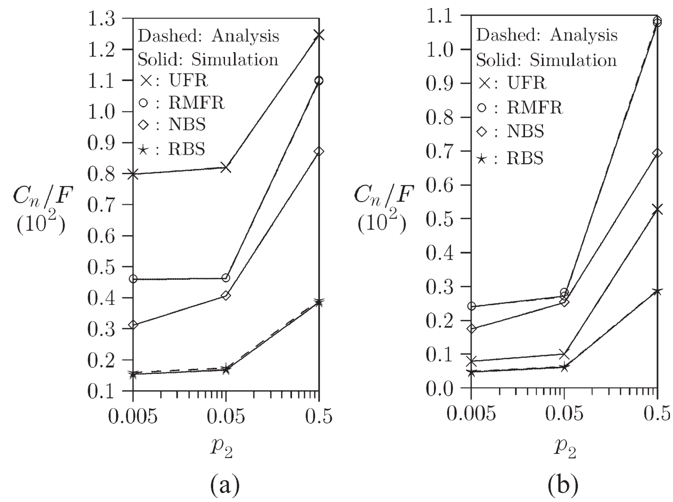


Fig. 6. Effects of p_i ($F = 5000$, $b = 100$, $\delta = 0.4$, $\rho_1 = 50$, and $\rho_2 = 1$).

between analysis and simulation results are within 0.46%, and the details are omitted.

A. Effects of δ

In Fig. 5, $F = 5000$, $b = 100$, $p_1 = 0.05$ (i.e., a class 1 RA has high error transmission probability), $p_2 = 0.005$ (i.e., a class 2 RA has low error transmission probability), $\rho_1 = 50$, and $\rho_2 = 1$. Since $\rho_1 \gg \rho_2$, a larger δ value results in more C-UEs. Therefore, C_n increases as δ increases. Fig. 5 shows that, in most cases, the retransmission costs C_n of the four schemes follow the inequality

$$C_{n,\mathrm{RBS}} < C_{n,\mathrm{NBS}} < C_{n,\mathrm{RMFR}} < C_{n,\mathrm{UFR}}.$$

This phenomenon is explained as follows. In Fig. 5, the expected numbers of C-UEs (which is $\sum_{r=0}^{\infty} \rho_i p_i^{r+1}$) in a class 1 RA and a class 2 RA are about 2.5 and 0.005, respectively. Two facts are observed.

Fact 1: In class 1 RA, more than one joined UEs are expected to erroneously receive a file block. Obviously, multicasting (RMFR, NBS, and RBS) is more efficient than unicasting (UFR).

Fact 2: In class 2 RA, it is likely that there is no UE or at most one UE erroneously receiving the file block. Therefore, UFR and the proposed RBS can more efficiently retransmit CFB than RMFR and NBS.

We observe that Fact 1 is more significant than Fact 2 in terms of retransmission cost, and hence, UFR incurs the largest retransmission cost. The transmission disadvantage of UFR becomes more significant as δ increases. Since RMFR and NBS encounter the retransmission scoping problem, Fig. 5 shows that the proposed RBS scheme outperforms RMFR and NBS. When $\delta \leq 0.8$, $C_{n,\mathrm{NBS}}$ is smaller than $C_{n,\mathrm{RMFR}}$. When $\delta > 0.8$, the results reverse due to the following facts. In NBS, all CFBs are multicasted to the new multicast group (consisting of all C-UEs), and RMFR multicasts all CFBs to all joined UEs. Therefore, NBS is better than RMFR when δ is small. On the other hand, to form a new multicast group, NBS incurs more signaling messages than RMFR. Since the multicast costs for both NBS and RMFR are roughly the same when δ is large, RMFR outperforms NBS due to the low signaling cost.

B. Effects of p_i

In Fig. 6, $F = 5000$, $b = 100$, $\delta = 0.4$, $\rho_1 = 50$, and $\rho_2 = 1$. It is trivial that C_n is an increasing function of p_2 and p_1. A nontrivial observation is that when $p_2 < 0.05$, C_n is insignificantly affected by p_2. When $p_1 = 0.005$, the average number of C-UEs for a file block in a class 1 RA is $\sum_{r=0}^{\infty} \rho_1 p_1^{r+1} \approx 0.25$. There is at most one C-UE in a class 1 RA. Therefore, UFR and RBS are more efficient than RMFR and NBS. The retransmission costs for the four schemes have the following relationship:

$$C_{n,\mathrm{RBS}} < C_{n,\mathrm{UFR}} < C_{n,\mathrm{NBS}} < C_{n,\mathrm{RMFR}}.$$

On the other hand, when $p_1 = 0.05$, the average number of C-UEs in a class 1 RA is $\sum_{r=0}^{\infty} \rho_1 p_1^{r+1} \approx 2.5$. Two or more C-UEs are expected in a class 1 RA, and RMFR, NBS, and RBS are more efficient than UFR. Consequently, the retransmission costs for the four schemes follow the order

$$C_{n,\mathrm{RBS}} < C_{n,\mathrm{NBS}} < C_{n,\mathrm{RMFR}} < C_{n,\mathrm{UFR}}.$$

C. Effects of the Block Size

For a file of fixed size, when the block size increases, a file block is more likely to erroneously be transmitted. On the other hand, the number of block transmissions decreases as the block size increases. Suppose that the error transmission probability for a file block with size 100 is p_i^*. We assume that the error transmission probability for a file block with size b is computed by

$$p_i(b) = 1 - (1 - p_i^*)^{\frac{b}{100}}.$$

In Fig. 7, $F = 5000$, $\rho_1 = 50$, $\rho_2 = 1$, $p_1^* = 0.05$, and $p_2^* = 0.005$. The figure shows that for RMFR, NBS, and RBS, C_n slightly increases as b increases. For UFR, C_n significantly increases as b increases.

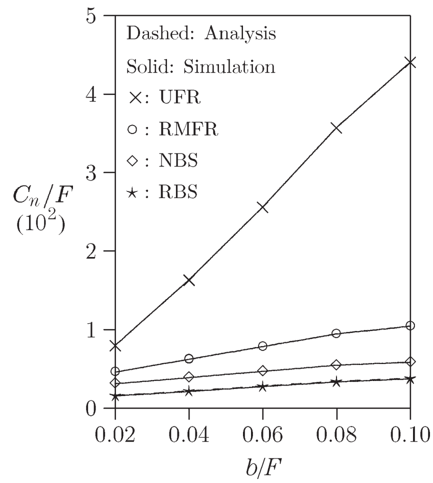


Fig. 7. Effects of b ($F = 5000$, $\rho_1 = 50$, $\rho_2 = 1$, $\delta = 0.4$, $p_1^* = 0.05$, and $p_2^* = 0.005$).

Based on the above discussion, the proposed RBS scheme outperforms other schemes.

VI. Conclusion

This paper has proposed analytic and simulation models to study the MBMS file repair schemes in the UMTS network. The 3GPP proposed three file repair schemes, i.e., UFR, RMFR, and RBS. These schemes introduce extra data traffic and signaling overhead during retransmission. This paper has proposed a new scheme called RBS. In this scheme, a CFB is multicasted only to the UEs that erroneously receive the CFB, and the retransmission scoping problem is resolved.

This paper has shown that when more than one joined UE erroneously receives the file blocks, the RMFR, NBS, and RBS schemes are more efficient than UFR. When there is at most one UE erroneously receiving the file block, UFR and RBS can retransmit the CFBs more efficiently than RMFR and NBS do. To conclude, the proposed RBS scheme can significantly outperform the other three 3GPP schemes.

Appendix
Simulation Models

This appendix describes the discrete event simulation model for the four file repair schemes, i.e., UFR scheme, RMFR scheme, NBS File Repair scheme, and RBS File Repair scheme. Denote $\mathrm{RA}_{x,y}^{(i)}$ as an RA, where i is the class type of the RA, x identifies the ID of the SGSN serving the RA, and y specifies the ID of the RA. We define three types of events.

1) The ARRIVAL event represents a UE arrival to an RA. This event includes three fields. The x field identifies the SGSN serving the UE. The y field specifies the RA where the UE resides. The i field indicates the class of the RA.
2) The DEPART event represents a UE departure from an RA. The event list consists of three fields, i.e., x, y and i, which are the same as those in the ARRIVAL event.
3) The SESSION event represents an MBMS file multicast to the joined UEs.

Each event has a timestamp to indicate the time when this event occurs. The events are inserted into an event list and are deleted/processed from the list in a nondecreasing timestamp order. During the execution of simulation, a simulation clock t_s is maintained to indicate the progress of the simulation. Fig. 8 illustrates the timing diagram for MBMS file transmission in a class i RA. In this figure, we define several variables for the simulation:

1) $t_{a,i}$: the UE interarrival time to a class i RA, which is exponentially distributed with the mean $1/\lambda_i$;
2) $t_{u,i}$: the RA residence time for a UE in a class i RA, which has a general distribution with the mean $1/\mu_i$;
3) t_f: the MBMS file transmission interarrival time, which is exponentially distributed with the mean $1/\lambda_f$.

Three output measures are investigated in our models, including the cost C_t for CFB transmissions, the cost C_s for signaling message transmission, and the net repair cost $C_n = C_t + C_s$. All costs are normalized by the signaling message size. The following five variables are used to calculate the C_t, C_s, and C_n values:

1) M_g: the number of CFBs delivered from BM-SC to GGSN;
2) M_s: the number of CFBs delivered from GGSN to SGSNs;
3) M_R: the number of CFBs delivered from SGSNs to RAs;
4) S_s: the number of file repair request messages and file repair response messages;
5) S_t: the number of signaling messages required to establish and delete the delivery tree.

We run N_S sessions in each simulation experiment and compute the following outputs:

$$E[M_g] = \frac{M_g}{N_S}, \quad E[M_s] = \frac{M_s}{N_S}, \quad E[M_R] = \frac{M_R}{N_S}$$
$$E[S_s] = \frac{S_s}{N_S}, \qquad E[S_t] = \frac{S_t}{N_S}$$
$$C_t = b\,(E[M_g] + E[M_s] + E[M_R])$$
$$C_s = E[S_s] + E[S_t], \qquad C_n = C_t + C_s$$

where b is file block size, and we assume that the signaling message size is 1.

Fig. 9 illustrates the main flowchart of our simulation model. At Step 1, the initial values for the input parameters (e.g., l, n_i, λ_i, μ_i, etc.) are set up, and the event list is set to NULL. An ARRIVAL event for each $\mathrm{RA}_{x,y}^{(i)}$ and a SESSION event are generated and inserted into the event list (see Steps 2 and 3). Step 4 removes the next event e from the event list. Step 5 checks the type of event e.

If event e is an ARRIVAL event, Step 6 increases $N(e.x, e.y)$ by 1. The variable $N(x, y)$ counts the number of UEs in RA y of SGSN x. Step 7 generates the RA residence time $t_{u,i}$ for this UE in $\mathrm{RA}_{x,y}^{(i)}$ and a DEPART event (corresponding to this ARRIVAL event) with timestamp $t_s + t_{u,i}$ and then inserts the generated event into the event list. Step 8 generates the next ARRIVAL event for $\mathrm{RA}_{x,y}^{(i)}$, where the timestamp is set to $t_s + t_{a,i}$ and then inserts the event into the event list. The simulation goes back to Step 4.

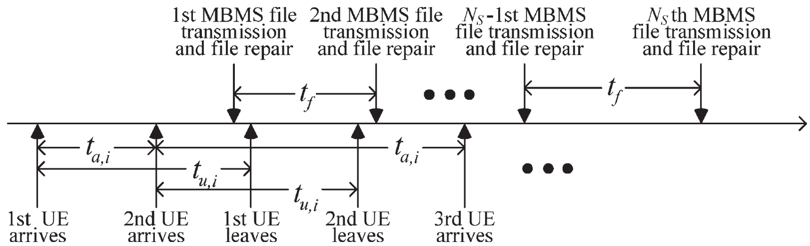


Fig. 8. Timing diagram in class i RA.

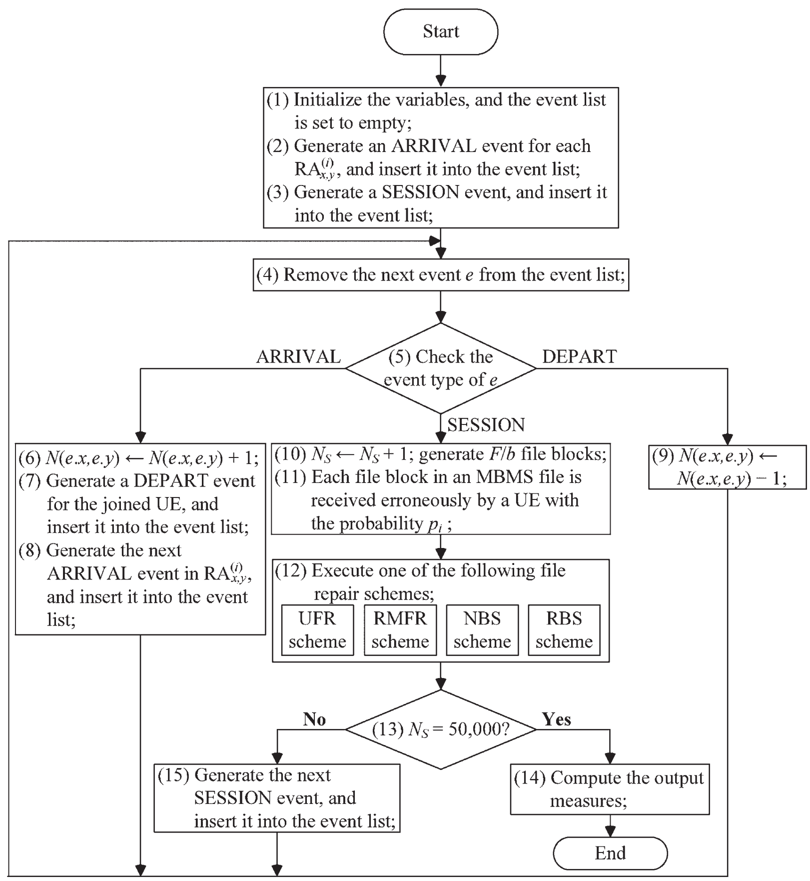


Fig. 9. Main flowchart of the simulation model.

If event e is a DEPART event, Step 9 decreases $N(e.x, e.y)$ by 1. Then, the simulation proceeds to Step 4.

If event $e.type$ is SESSION, Step 10 increases N_S by 1 and generates F/b file blocks for this session. For each file block, Step 11 generates an erroneous file block transmission to each joined UE with probability p_i. Step 12 executes one of the four file repair schemes to be elaborated upon later. Step 13 checks if N_S is equal to 50 000. If so, the output measures are computed at Step 14, and the simulation terminates. Otherwise (i.e., $N_S < 50\,000$), Step 15 generates the interarrival time t_f for the next MBMS file transmission and the next SESSION event with timestamp $t_s + t_f$ and inserts the generated event into the event list. Then, the simulation flow goes back to Step 4. At Step 12, the pseudoprograms for the file repair schemes are described as follows.

UFR Scheme: Fig. 10 presents the pseudocodes for the UFR scheme. For each $RA^{(i)}_{x,y}$, we execute the following steps. At Line 2, we check the $N(x, y)$ value for $RA^{(i)}_{x,y}$. If $N(x, y) > 0$ (i.e., there are joined UEs in this RA), for

Scheme UFR
begin
1. **for** each $RA^{(i)}_{x,y}$ **do**
2. **if** $N(x, y) > 0$ **then**
3. **for** each joined UE **do**
4. **if** the UE is a C-UE **then**
5. $S_s \leftarrow S_s + 6$;
6. $n_c \leftarrow$ the number of CFBs requested by the C-UE;
7. $M_g \leftarrow M_g + n_c$;
8. $M_s \leftarrow M_s + n_c$;
9. $M_R \leftarrow M_R + n_c$;
10. generate an erroneous CFB transmission with p_i ;
11. **if** there is any C-UE **then** return to Line 1;
end

Fig. 10. UFR scheme.

Scheme RMFR
begin
1. **for** each file block k **do** $F(k) \leftarrow 0$;
2. **for** each $RA_{x,y}^{(i)}$ **do**
3. **if** $N(x,y) > 0$ **then**
4. **for** each joined UE **do**
5. **if** the UE is a C-UE **then**
6. $S_s \leftarrow S_s + 6$;
7. **for** each requested CFB k **do** $F(k) \leftarrow 1$;
8. $n_c \leftarrow$ the number of CFBs with $F(k) = 1$ value;
9. $n_R \leftarrow$ the number of RAs containing joined UEs;
10. $n_s \leftarrow$ the number of SGSNs containing joined UEs;
11. $M_g \leftarrow M_g + n_c$;
12. $M_s \leftarrow M_s + n_c n_s$;
13. $M_R \leftarrow M_R + n_c n_R$;
14. **for** each CFB **do**
15. **for** each C-UE requesting this CFB **do**
16. generate an erroneous CFB transmission with p_i ;
17. **if** there is any C-UE **then** return to Line 1;
end

Fig. 11. RMFR scheme.

Scheme NBS
begin
1. empty the CRT_G and CRT_S lists;
2. **for** each file block k **do** $F(k) \leftarrow 0$;
3. **for** each $RA_{x,y}^{(i)}$ **do**
4. **if** $N(x,y) > 0$ **then**
5. **for** each joined UE **do**
6. **if** the UE is a C-UE **then**
7. $S_s \leftarrow S_s + 6$;
8. $S_t \leftarrow S_t + 27$;
9. insert x value of the $RA_{x,y}^{(i)}$ into CRT_G;
10. insert y value of the $RA_{x,y}^{(i)}$ into CRT_S;
11. **for** each requested CFB k **do** $F(k) \leftarrow 1$;
12. $n_c \leftarrow$ the number of CFBs with $F(k) = 1$ value;
13. $n_R \leftarrow$ the number of RAs in the CRT_S list;
14. $n_s \leftarrow$ the number of SGSNs in the CRT_G list;
15. $M_g \leftarrow M_g + n_c$;
16. $M_s \leftarrow M_s + n_c n_s$;
17. $M_R \leftarrow M_R + n_c n_R$;
18. **for** each CFB **do**
19. **for** each C-UE requesting this CFB **do**
20. generate an erroneous CFB transmission with p_i ;
21. **if** there is any C-UE **then** return to Line 1;
end

Fig. 12. NBS scheme.

Scheme RBS
begin
1. **for** each file block k **do**
2. empty the $\mathrm{CRT}_G(k)$ and $\mathrm{CRT}_S(k)$ lists;
3. **for** each $RA_{x,y}^{(i)}$ **do**
4. **if** $N(x,y) > 0$ **then**
5. **for** each joined UE **do**
6. **if** the UE is an C-UE **then**
7. $S_s \leftarrow S_s + 6$;
8. **for** each requested CFB k **do**
9. insert x value of the $RA_{x,y}^{(i)}$ into $\mathrm{CRT}_G(k)$;
10. insert y value of the $RA_{x,y}^{(i)}$ into $\mathrm{CRT}_S(k)$;
11. **for** each requested CFB k **do**
12. $n_R \leftarrow$ the number of RAs in the $\mathrm{CRT}_S(k)$ list;
13. $n_s \leftarrow$ the number of SGSNs in the $\mathrm{CRT}_G(k)$ list;
14. $M_g \leftarrow M_g + 1$;
15. $M_s \leftarrow M_s + n_s$;
16. $M_R \leftarrow M_R + n_R$;
17. **for** each C-UE requesting this CFB **do**
18. generate an erroneous CFB transmission with p_i ;
19. **if** there is any C-UE **then** return to Line 1;
end

Fig. 13. RBS scheme.

each joined UE, Line 4 determines whether it is a C-UE. If so, Lines 5–9 update the following variables: $S_s \leftarrow S_s + 6$; n_c is set to the number of CFBs requested by this C-UE; $M_g \leftarrow M_g + n_c$; $M_s \leftarrow M_s + n_c$; and $M_R \leftarrow M_R + n_c$. Line 10 generates an erroneous CFB transmission to this C-UE with probability p_i. After Lines 1–10 have been executed for each RA, Line 11 checks whether there is any C-UE. If so, Scheme UFR returns to execute the **for** loop (i.e., the next retransmission run; Lines 1–10). Otherwise, Scheme UFR ends.

RMFR Scheme: In this scheme, the variables n_R and n_s count the numbers of RAs and SGSNs to which a CFB is transmitted. We use k to denote the ID of a file block. For $1 \leq k \leq F/b$, the flag $F(k)$ indicates whether CFB k should be retransmitted. $F(k) = 1$ implies that the retransmission for CFB k is requested. Fig. 11 illustrates the pseudocodes for the RMFR scheme. The details are not presented here.

NBS Scheme: Fig. 12 shows the pseudocodes for the NBS scheme. In this scheme, two lists (CRT_G and CRT_S) are created to count the number of SGSNs and RAs to which the CFBs are transmitted, respectively. The details are not elaborated upon here.

RBS Scheme: Fig. 13 illustrates the pseudocodes for the RBS scheme. In this scheme, the lists $\mathrm{CRT}_G(k)$ and $\mathrm{CRT}_S(k)$ are created to count the number of SGSNs and RAs to which a CFB k is transmitted. The details are not elaborated upon here.

ACKNOWLEDGMENT

The authors would like to thank the editor and the three anonymous reviewers. Their comments have significantly improved the quality of this paper.

REFERENCES

[1] 3GPP, *3rd generation partnership project; Technical specification group service and system aspects; Multimedia Broadcast/Multicast Service (MBMS); Architecture and functional description (rel. 6)*, Nov. 2004.

[2] 3GPP, *3rd Generation partnership project; Technical specification group services and system aspects; Multimedia Broadcast/Multicast Service (MBMS); Protocols and codecs (rel. 6)*, Jun. 2005.

[3] 3GPP, *3rd generation partnership project; Technical specification group core network and terminals; Mobile radio interface layer 3 specification; Core network protocols; stage 3 (rel. 7)*, Jun. 2006.

[4] K. Heikki, A. Ari, L. Lauri, N. Siamak, and N. Valtteri, *UMTS Networks: Architecture, Mobility, and Services*. Hoboken, NJ: Wiley, 2002.

[5] S. K. Kasera, G. Hjalmtysson, D. F. Towsley, and J. F. Kurose, "Scalable reliable multicast using multiple multicast channels," *IEEE/ACM Trans. Netw.*, vol. 8, no. 3, pp. 294–310, Jun. 2000.
[6] P. Lin and G.-H. Tu, "An improved GGSN failure restoration mechanism for UMTS," *Wirel. Netw.*, vol. 12, no. 1, pp. 91–103, Feb. 2006.
[7] P. Lin, Y.-B. Lin, C.-H. Gan, and J.-Y. Jeng, "Credit allocation for UMTS prepaid service," *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 306–316, Jan. 2006.
[8] Y.-B. Lin, "Performance modeling for mobile telephone networks," *IEEE Netw.*, vol. 11, no. 6, pp. 63–68, Nov. 1997.
[9] Y.-B. Lin, "A multicast mechanism for mobile networks," *IEEE Commun. Lett.*, vol. 5, no. 11, pp. 450–452, Nov. 2001.
[10] Y.-B. Lin and A.-C. Pang, *Wireless and Mobile All-IP Networks*. Hoboken, NJ: Wiley, 2005.
[11] A.-C. Pang and Y.-K. Chen, "A multicast mechanism for mobile multimedia messaging service," *IEEE Trans. Veh. Technol.*, vol. 53, no. 6, pp. 1891–1902, Nov. 2004.

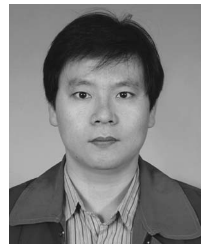
Yen-Cheng Lai (S'08) received the B.S. degree in computer science from Tamkang University, Taipei, Taiwan, R.O.C., in 2002 and the M.S. and Ph.D. degrees in computer science and information engineering from the National Taiwan University, Taipei, in 2004 and 2008, respectively.

He is currently a Postdoctoral Researcher with the Institute of Applied Mechanics, National Taiwan University. His current research interests include the design and the analysis of PCS networks, wireless Internet services, mobile computing, performance modeling, and wireless PAN/LAN/WAN.

Phone Lin (M'02–SM'06) received the B.S.C.S.I.E. and Ph.D. degrees from the National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 1996 and 2001, respectively.

From August 2001 to July 2004, he was an Assistant Professor with the Department of Computer Science and Information Engineering (CSIE), National Taiwan University (NTU), Taipei, Taiwan. Since August 2004, he has been an Associate Professor with the Department of CSIE and the Graduate Institute of Networking and Multimedia, National Taiwan University. He has published more than 20 international SCI journal papers [most of which are IEEE TRANSACTIONS and Association for Computing Machinery (ACM) papers]. His current research interests include personal communications services, wireless Internet, and performance modeling.

Dr. Lin is an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, a Guest Editor for the *IEEE Wireless Communications* Special Issue on Mobility and Resource Management, and a Guest Editor for the *ACM/Springer MONET* Special Issue on Wireless Broad Access. He is also an Associate Editorial Member for the *Wireless Communications and Mobile Computing Journal*. He has received many research awards. He was elected Best Young Researcher at the 3rd IEEE ComSoc Asia-Pacific Young Researcher Awards in 2007. He was a recipient of the 2004 Research Award for Young Researchers from the Pan Wen-Yuan Foundation in Taiwan, the 2004 K. T. Li Young Researcher Award from the ACM Taipei Chapter, the 2005 Wu Ta You Memorial Award of the National Science Council in Taiwan, the 2005 Fu Suu-Nien Award from NTU for his research achievements, and the 2006 Young Electrical Engineering Award of the Chinese Institute of Electrical Engineering. He was listed in *Who's Who in Science and Engineering* in 2006.



Yi-Bing Lin (M'96–SM'96–F'04) received the B.S.E.E. degree from the National Cheng Kung University, Tainan, Taiwan, R.O.C., in 1983 and the Ph.D. degree in computer science from the University of Washington, Seattle, in 1990.

He is the Dean and the Chair Professor with the College of Computer Science, National Chiao Tung University, Hsinchu, Taiwan. He has authored over 200 journal articles and more than 200 conference papers. He is the author of the books *Wireless and Mobile Network Architecture* (Wiley, 2001), *Wireless and Mobile All-IP Networks* (Wiley, 2005), and *Charging for Mobile All-IP Telecommunications* (Wiley, 2008). His current research interests include mobile computing and cellular telecommunications services.

Dr. Lin is a Senior Technical Editor of the *IEEE Network*. He serves on the editorial boards of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He has been the General or Program Chair for several conferences, including the Association for Computing Machinery (ACM) International Conference on Mobile Computing and Networking in 2002. He was the Guest Editor for several journals, including the IEEE TRANSACTIONS ON COMPUTERS. He is an Institute for Scientific Information highly cited author in the area of computer science. He has received numerous research awards, including the 2005 National Science Council Distinguished Researcher and the 2006 Academic Award of Ministry of Education, Taiwan. He is a Fellow of the ACM, the American Association for the Advancement of Science, and the Institution of Electrical Engineers.

Lu-Tsung Chang received the M.S. degree from National Taiwan University, Taipei, Taiwan, R.O.C., in 2006.

He currently is an Engineer with MediaTek Inc., Hsinchu, Taiwan, where he develops software for WiMAX. His research interests include personal communications services, wireless Internet services, and wireless PAN/LAN/WAN.