An Energy-Efficient Resource Allocation Scheme for RLNC-Based Heterogeneous Multicast Communications

Andrea Tassi, Francesco Chiti, Romano Fantacci, and Fabio Schoen

***Abstract*—We propose an energy-efficient resource allocation framework suitable for multicast service delivery over 3GPP's Long Term Evolution Advanced Single Frequency Network evolved Multimedia Broadcast and Multicast Service networks. A key aspect of the considered system model is that multicast communications are delivered according to the Random Linear Network Coding (RLNC) principle. The proposed optimization framework aims at minimizing the transmission energy associated with the delivery of a set of multicast flows. The goal is achieved by jointly optimizing the transmission power and the RLNC scheme of each flow. Furthermore, we present a heuristic strategy that can efficiently find a good-quality feasible solution of the presented resource allocation model.**

***Index Terms*—Power allocation, RLNC, PtM communications.**

I. Introduction

MULTIMEDIA communications over 4G cellular networks are gaining momentum because of the ubiquitous diffusion of mobile devices with remarkable processing capabilities, such as smartphones or tablets. One of the frontiers of multimedia service delivery is represented by the possibility of reliably transmitting multimedia data flows in a broadcast and multicast mode [1]. To this end, this correspondence refers to a 3GPP's Long Term Evolution-Advanced (LTE-A) network of base stations delivering several Point-to-Multipoint (PtM) service flows to a set of User Equipments (UEs) forming a Multicast Group (MG). In particular, LTE-A networks handle PtM service delivery by the evolved Multimedia Broadcast and Multicast Service (eMBMS) framework [2]. This correspondence deals with the Single Frequency Network eMBMS (SFN-eMBMS) transmission mode where multiple contiguous base stations (forming an SFN) are synchronized and deliver PtM services by using the same physical signals. It is worth noting that, in an SFN, an eMBMS transmission appears as it was transmitted by one base station.

Reliable PtM service multicasting has been considered a challenging problem [3]. 3GPP has proposed Application Level-Forward Error Correction (AL-FEC) solutions based on Raptor Codes. However, Magli *et al.* [1] noted that this family of codes requires large source messages to operate close to their capacity. Hence, they typically lead to a communication delay that may not be acceptable. On the other hand, Random Linear Network Coding (RLNC) strategies typically refer to short source messages in order to reduce the decoding complexity and subsequently the communication delay. For this reason, RLNC-based solutions can be viable alternatives to Raptor-based AL-FEC codes especially in case of delay sensitive PtM service delivery [3]. In particular, this correspondence deals with a set of eMBMS flows which are delivered according to the RLNC principle. Furthermore, each eMBMS flow has to be successfully recovered by the MG (i.e., by *all* the UEs of the MG) with a certain probability, and in a predefined time interval.[1]

In addition to reliable packet-loss resilient PtM service delivery issues, there is another factor of paramount importance for both network providers and environment, namely the energy footprint of service delivery. In fact, modern wireless communication networks are responsible for more than the 0.2% of total carbon emissions [4]. In spite of the huge amount of resource allocation strategies aiming at minimizing the transmission power [5], little attention has been paid to reduce the energy footprint of broadcast and multicast communications. This letter draws inspiration from [6] which proposes a resource allocation model suitable for jointly optimizing both the transmission power and the RLNC scheme used to deliver just a single PtM service. This correspondence addresses that issue by proposing an efficient optimization model, which aims at minimizing the overall transmission energy associated with the delivery of multiple PtM service flows over an eMBMS network. Unlike [6], the proposed model achieves this goal by jointly optimizing both the transmission power (of each base station in the SFN) and the RLNC scheme used to deliver each PtM flow at the same time. Finally, we propose an efficient heuristic strategy which can find a good quality feasible solution of the proposed optimization problem, in a finite number of steps.

The rest of the correspondence is organized as follows. Section II describes the considered system model. The proposed optimization model and heuristic strategy are presented in Section III. Section IV inspects the performance of the proposed allocation model. Finally, in Section V, we draw our conclusions.

II. System Model

In this correspondence, we consider a SFN composed by a set $\{\mathrm{BS}_1, \ldots, \mathrm{BS}_B\}$ of contiguous base stations. Each base station is connected to the LTE-A core network entities that are in charge of: i) synchronizing and scheduling the eMBMS flow delivery, and ii) allocating the radio resources that all the base stations in the SFN shall apply [2].

SFN-eMBMS communications, as well as LTE-A unicast transmissions, are organized in radio frames (as reported in Fig. 1). A radio frame is a time-frequency structure composed by 10 subframes, each frame has a fixed transmission time duration equal to one Transmission Time Interval (TTI), namely 1 ms. LTE-A service flows are segmented in Transport Blocks

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A. Tassi is with the School of Computing and Communications, Lancaster University, Lancaster, U.K. (e-mail: a.tassi@lancaster.ac.uk).

F. Chiti, R. Fantacci, and F. Schoen are with the Department of Information Engineering, University of Florence, Florence, Italy (e-mail: francesco.chiti@unifi.it; romano.fantacci@unifi.it; fabio.schoen@unifi.it).

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[1]These are typical service requirements for layered video service delivery [3].

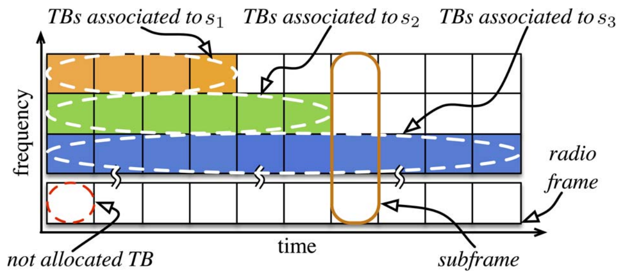

Fig. 1. Example of the considered framed communication delivery for $S = 3$.

(TBs) and are mapped onto the radio frame to be delivered. A TB is a frequency-time unit which spans a variable bandwidth value and has a fixed time duration of 1 TTI.

We assume that the SFN delivers S multicast services (namely, we assume that all the base stations of the SFN deliver at the same time services $s_1, \ldots, s_S$) to M UEs ($\{\text{UE}_1, \ldots, \text{UE}_M\}$), characterized by different propagation conditions, forming a MG. Each eMBMS flow is delivered according to the systematic version of RLNC[2] principle [7]. Considering the s-th eMBMS flow, the TB stream used to deliver it consists of K_s TBs (hereafter called *information TBs*) and C_s *coded TBs* (namely, the SFN firstly delivers the information TBs and then the coded TBs). The j-th coded TB $c_{s,j}$ (associated with the s-th eMBMS flow) is defined as $c_{s,j} = \sum_{i=1}^{K_s} g_{i,j} \cdot t_i$ where: i) coding coefficients $g_{i,j}$ are uniformly randomly selected in a finite field $\mathcal{F}_q$ (of size q), and ii) t_i is the i-th information TB of the s-th service flow. A UE recovers the s-th eMBMS flow as soon as it receives (at least) K_s linearly independent TBs (counting both information and coded TBs). Conversely, if a UE cannot recover the service flow after that K_s information and C_s coded TBs have been transmitted, then the s-th service flow is lost, as no retransmission are allowed.

Let us consider Fig. 1, we assume that each subframe conveys one (information or coded) TB per eMBMS flow. Let P_s be the transmission power of each base station (of the SFN) on a TB associated with the s-th service flow. We assume that the transmission power of each base station (of the SFN) during a time slot cannot be greater than the overall power budget $\hat{P}$, i.e., $\sum_{s=1}^{S} P_s \leq \hat{P}$. In addition, let us define the term $\overline{P} \doteq \hat{P}/S$. The value of P_s can be equivalently expressed as[3] $P_s = m_s \cdot \overline{P}$, for $m_s \in \mathbb{R}^+$. Hence, the following relation holds

$$\sum_{t=1}^{S} P_s \leq \hat{P} \Leftrightarrow \sum_{s=1}^{S} m_s \overline{P} \leq S\overline{P} \Leftrightarrow \sum_{s=1}^{S} m_s \leq S. \qquad (1)$$

Due to the fact that PtM communications occur over an SFN, we assume that the impact of the interference (caused by base stations which do not belong to the SFN) is negligible. In addition, let $w_{u,b}$ be the channel gain between the u-th UE (of the MG) and b-th base station (of the SFN). For these reasons, the instantaneous Signal-to-Noise Ratio (SNR) associated with the reception of a TB by UE_u can be expressed as $\gamma_u = \sum_{b=1}^{B} w_{u,b} \cdot P_s$ or, equivalently, $\gamma_u = m_s \cdot \overline{P} \cdot \sum_{b=1}^{B} w_{u,b}$. In addition, let E be the transmission energy of one TB (associated with the s-th service flow) for $P_s = \overline{P}$ (i.e., for $m_s = 1$). In this correspondence, we assume that both information and coded TBs are L bits long and span the same bandwidth, regardless of the service flow. Hence, the overall transmission energy needed to deliver both the information and coded TBs of *all* the service flows is $\sum_{s=1}^{S} m_s \cdot E \cdot (K_s + C_s)$.

In addition, we assume that the TB transmission occurs over a flat Rayleigh communication channel[4] and adopts the Binary Phase-Shift Keying[5] (BPSK). Furthermore, let $\gamma_{o,u}$ and $\overline{\gamma}_{o,u}$ be the instantaneous and average SNR (associated with the reception of a TB) experienced by the u-th UE for $m_s = 1$. For these reasons, the TB error probability associated with UE_u can be expressed as follows[6]:

$$Pe_u(m_s) = 1 - \frac{1}{\overline{\gamma}_{o,u}} \int_0^\infty [1 - p_u(m_s)]^L e^{-\frac{\gamma_{o,u}}{\overline{\gamma}_{o,u}}} d\gamma_{o,u}. \qquad (2)$$

where the BPSK bit error probability is $p_u(m_s) = (1/2)\text{erfc}(\sqrt{m_s \cdot \gamma_{o,u}})$.

Before going into details of the proposed optimization strategy, it can be proved that the probability $F_u(m_s, C_s)$, as a function of m_s and C_s, that a UE recovers the s-th service flow can be expressed as follows [6]:

$$F_u(m_s, C_s) = \sum_{i=K_s}^{K_s+C_s} \binom{K_s + C_s}{i} Pe_u^{K_s+C_s-i}(m_s) \cdot [1 - Pe_u(m_s)]^i \frac{g(i)}{K_s - \max(0, K_s - C_s) + 1} \qquad (3)$$

where the probability that K_s over i (information and/or coded) TBs are linearly independent can be approximated, for sufficiently large values of the field size (namely, $q \geq 2^4$), as $g(i) \simeq 1 + \sum_{h=\max(0,K_s-C_s)}^{K_s-1} \prod_{t=0}^{\min(K_s,i-h)-1} [1 - (1/q^{\max(K_s,i-h)-t})]$. Furthermore, the s-th service flow is recovered by all the UEs of the MG with a probability which is $\Phi(m_s, N_s) = \prod_{u=1}^{M} F_u(m_s, N_s)$ [6].

III. Power Allocation and RLNC Optimization for Energy Efficient Multicast Communications

The proposed resource allocation aims at jointly optimizing P_s (i.e., the value of m_s) and C_s such that: i) the overall transmission energy of each base station is minimized, and ii) service flows can be recovered within a certain time by any UE of the MG (at least) with a probability $\hat{\Phi}$. As a result, the proposed Minimum Energy (ME) resource allocation model can be expressed as follows:

$$(\text{ME}) \quad \min_{\substack{m_1,\ldots,m_S \\ C_1,\ldots,C_S}} \sum_{s=1}^{S} m_s E(K_s + C_s) \qquad (4)$$

$$\text{subject to} \quad \Phi(m_s, C_s) \geq \hat{\Phi}, \quad s \in \{1, \ldots, S\} \qquad (5)$$

$$\sum_{s=1}^{S} m_s \leq S, \qquad m_s \in \mathbb{R}^+ \qquad (6)$$

$$0 \leq C_s \leq \hat{C}_s, \quad C_s \in \mathbb{N}, \quad s \in \{1, \ldots, S\} \qquad (7)$$

[2]We adopt the systematic version of RLNC because the computational complexity of the decoding process is significantly smaller than that of the classic RLNC [7].

[3]In this correspondence, we refer with $\mathbb{R}^+$ to the set composed by strictly positive real numbers, and $\mathbb{N}$ to the set of non-zero natural numbers.

[4]In particular, we refer to a pedestrian environment where users are characterized by a speed of 3 km/h [2].

[5]The theoretical derivation we propose is quite general and can be extended to other modulation schemes and channel models.

[6]We assume that both channel gains and $\overline{\gamma}_{o,u}$ (for $u = 1, \ldots, M$) values are available at the LTE-A core network side.

where the constraint (5) ensures that the MG recovers each flow with a probability which is not smaller than $\hat{\Phi}$. From (1), the constraint (6) ensures that the instantaneous transmission power of each base station is not greater than $\hat{P}$. The constraint (7) upper-bounds the maximum transmission time duration of each flow. Unfortunately, the presence of the coupling constraint (6) turns ME into a computationally complex mixed integer non-linear optimization problem.[7] To this end, this correspondence proposes the Heuristic ME (HME) strategy that can efficiently find a good quality feasible solution of ME in a finite number of steps.

In order to efficiently define the HME strategy, it is worth deriving the upper- and lower-bound of the optimum solution of the proposed ME model. To this end, let us define the Unconstrained Transmission Power (UTP) model. It can be directly obtained by ME in which we relax the constraint (6) (i.e., $\sum_{s=1}^{S} m_s$ is no longer constrained). For these reasons, the UTP model is equivalent to a set of S independent problems, where the s-th one can be expressed as follows:

$$(\text{P-}s) \quad \min_{m_s, C_s} m_s E(K_s + C_s) \tag{8}$$

$$\text{subject to} \quad \Phi(m_s, C_s) \geq \hat{\Phi}, \quad m_s \in \mathbb{R}^+ \tag{9}$$

$$0 \leq C_s \leq \hat{C}_s, \qquad C_s \in \mathbb{N}. \tag{10}$$

It was shown that the solution of a problem belonging to the same class of P-s can be efficiently found as follows [6]:

(i) for any value of C_s (where $0 \leq C_s \leq \hat{C}_s$) set m_s such that $\Phi(m_s, C_s) = \hat{\Phi}$.

(ii) choose the (m_s, C_s) pair (among those which have been computed in the previous step) which minimizes the objective function (8).

Hence, the solution of P-s can be efficiently derived in a finite number of steps and belongs to the set $\mathcal{L}_s \doteq \{(m_s, C_s) \in \mathbb{R}^+ \times \mathbb{N} | 0 \leq C_s \leq \hat{C}_s \wedge \Phi(m_s, C_s) = \hat{\Phi}\}$.[8] Finally, it is straightforward to note that the solution of the UTP problem can be efficiently found in a finite number of step, as well.

In addition, we consider a special case of UTP, hereafter called Fixed Transmission Power (FTP), in which the transmission power P_s is fixed to $\overline{P}$ (i.e., $m_s = 1$ for $s \in \{1, \dots, S\}$). The model can be expressed as $\arg\min_{C_s \in [0, \dots, \hat{C}_s]} \{E \cdot (K_s + C_s) | \Phi(1, C_s) \geq \hat{\Phi}\}$, for $s \in \{1, \dots, S\}$.

Let us prove the following proposition.

Proposition 1: Let (m_s^*, C_s^*), (m_s', C_s') and (m_s'', C_s''), for any $s \in \{1, \dots, S\}$, be the optimum solutions of ME, UTP and FTP models, respectively. The relation $\sum_{s=1}^{S} m_s' \cdot E \cdot (K_s + C_s') \leq \sum_{s=1}^{S} m_s^* \cdot E \cdot (K_s + C_s^*) \leq \sum_{s=1}^{S} m_s'' \cdot E \cdot (K_s + C_s'')$ holds.

Proof: The solution of the FTP model meets the constraints of ME (i.e., any solution of the FTP model is at least a suboptimal solution of ME). In addition, the ME model represents a special case of the UTP one. Hence, the proof follows from the fact that $\mathcal{M}'' \subseteq \mathcal{M}^* \subseteq \bigcup_{s=1}^{S} \mathcal{M}_s'$, where $\mathcal{M}^*$, $\mathcal{M}_s'$ and $\mathcal{M}''$ are the feasible sets of ME, P-s and FTP models, respectively. ■

From Proposition 1, it follows that if the optimum solution of the UTP model meets the constraint (6) then $\{(m_1', C_1'), \dots, (m_S', C_S')\}$ is the optimum solution of the ME problem, as well.

[7] It is beyond the scope of this letter to optimize a system where each base station may deliver the same service by using a different transmission power.

[8] In the rest of the correspondence, $\mathcal{L}_s(C_s)$ represents the value of m_s such that $(m_s, C_s) \in \mathcal{L}_s$.

Procedure 1 Heuristic Minimum Energy Strategy

1: Initialize: $m_s^{**} \leftarrow m_s'$, $C_s^{**} \leftarrow C_s'$ and $o_s \leftarrow m_s' \cdot E \cdot (K_s + C_s')$, for $s \in \{1, \dots, S\}$
2: **while** $\{\sum_{s=1}^{S} m_s^{**} > S$ **do**
3:     **for** $\{s \leftarrow 1, \dots, S$ **do**
4:         **if** $C_s^{**} + 1 \leq \hat{C}_s$ **then**
5:             $\tilde{m}_s \leftarrow \mathcal{L}_s(C_s^{**} + 1)$
6:             $\tilde{o}_s \leftarrow \tilde{m}_s \cdot E \cdot (K_s + C_s^{**} + 1)$
7:         **else**
8:             $\tilde{o}_s \leftarrow \infty$
9:         **end if**
10:     **end for**
11:     **if** $\tilde{o}_s = \infty, \forall s \in \{1, \dots, S\}$ **then**
12:         $m_s^{**} \leftarrow 1$ and $C_s^{**} \leftarrow C_s'', \forall s \in \{1, \dots, S\}$
13:         **return** $(m_s^{**}, C_s^{**}), \forall s \in \{1, \dots, S\}$
14:     **end if**
15:     $i \leftarrow \arg\min\{\tilde{o}_1 - o_1, \dots, \tilde{o}_S - o_S\}$
16:     $C_i^{**} \leftarrow C_i^{**} + 1$
17:     $m_i^{**} \leftarrow \tilde{m}_i$
18: **end while**
19: **if** $\sum_{s=1}^{S} m_s^{**} \cdot E \cdot (K_S + C_s^{**}) > \sum_{s=1}^{S} E \cdot (K_s + C_s'')$ **then**
20:     $m_s^{**} \leftarrow 1$ and $C_s^{**} \leftarrow C_s'', \forall s \in \{1, \dots, S\}$
21: **end if**
22: **return** $(m_s^{**}, C_s^{**}), \forall s \in \{1, \dots, S\}$

However, if $\sum_{s=1}^{S} m_s' > S$, then the optimum solution of the UTP problem is not feasible from the point of view of the ME model. In that case, solving the proposed ME model is not a trivial task because any optimum value of m_s depends on C_s (for any service). For this reason, all the optimization variables have to be *jointly optimized across services* in order to minimize the overall transmission energy of the system. In order to fulfill that goal, we propose the HME strategy, defined by Procedure 1, which can efficiently find a feasible solution of the ME model.

The HME strategy (defined in Procedure 1) bases on the fact that if the number of coded TB transmissions C_s increases, then the value of m_s (such that $\Phi(m_s, C_s) = \hat{\Phi}$) should decrease (i.e., $\mathcal{L}_s(a) \leq \mathcal{L}_s(b)$ if $a > b$). For this reason, the HME strategy iteratively perturbs one component (m_s', C_s') at a time of the optimum solution of UTP[9] by setting $C_s' = C_s' + 1$ and $m_s' = \mathcal{L}_s(C_s' + 1)$. Hence, after some iterations, the procedure returns a feasible solution of ME. In particular, let $\{(m_1^{**}, C_1^{**}), \dots, (m_S^{**}, C_S^{**})\}$ be the solution returned by Procedure 1. The procedure comprises the following steps:

(i) $\{(m_1^{**}, C_1^{**}), \dots, (m_S^{**}, C_S^{**})\}$ is set equal to the optimum solution of the UTP model, if the constraint (6) is met then the procedure returns the optimum solution of ME (which is equal to the solution of UTP).

(ii) Otherwise, the while-loop body (lines 2–18) aims at computing the product $\tilde{o}_s = \mathcal{L}_s(C_s^{**} + 1) \cdot E \cdot (K_s + C_s^{**} + 1)$ for any service (lines 3–10) and finding the service index associated with the smallest $\tilde{o}_s - o_s$ value ([line 15]).

(iii) The while-loop iterates until the constraint (6) is met [line 2] or, if at any loop step there is no $\tilde{m}_s$ such that $(\tilde{m}_s, C_s^{**} + 1) \in \mathcal{L}_s$ (lines 11–14).

[9] During each iteration, the HME strategy perturbs the component which alters as little as possible the optimum value of the UTP problem (namely, $\sum_{s=1}^{S} m_s' \cdot E \cdot (K_s + C_s')$).

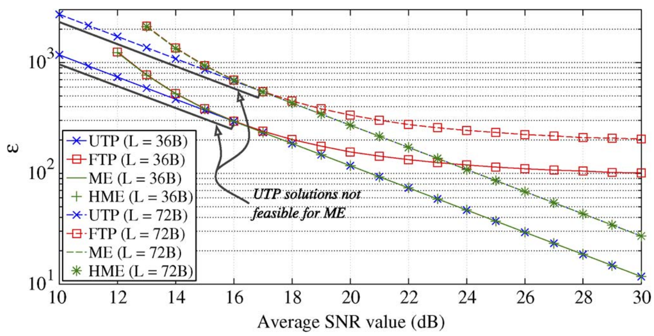

Fig. 2. Normalized overall transmission energy vs. $\tilde{\gamma}_o$.

(iv) The if-then statement (lines 19–21) checks if $\{(m_1^{**}, C_1^{**}), \ldots, (m_S^{**}, C_S^{**})\}$ is worse than $\{(m_1'', C_1''), \ldots, (m_S'', C_S'')\}$. If so, the procedure returns the the optimum solution of FTP.

It is worth noting that, the Procedure 1 returns after a number of iteration of the while-loop (lines 2–18) which is equal to or less than $\sum_{s=1}^{S} \hat{C}_s$.

IV. Numerical Results

We consider a scenario where the SFN delivers $S = 3$ eMBMS flows to a MG composed by $M = 30$ UEs. Each UE may experience different propagation conditions. To this end, the value of $\overline{\gamma}_{o,u}$ spans the interval [0, 40] dB. Each eMBMS flow is delivered according to the systematic version of RLNC. In particular, we considered a finite field of size $q = 2^8$. We consider two different (information/coded) TB sizes, namely L is equal to 36 or 72 bytes. The number of information TBs associated with each flow is $K_1 = 20$, $K_2 = 30$ and $K_3 = 40$. Furthermore, we assume that $\hat{C}_s = 20 \cdot K_s$ (for $s \in \{1, \ldots, S\}$). Finally, we set $\hat{\Phi}$ equal to 0.9. The performance evaluation refers to the normalized overall transmission energy associated with the delivery of all the eMBMS flows, defined as $\epsilon = (1/\overline{E}) \cdot \sum_{s=1}^{S} m_s \cdot E \cdot (K_s + C_s)$, where $\overline{E}$ is the transmission energy of one (information or coded) TB with the smallest L ($L = 36$ B) and $m_s = 1$.

Let $\tilde{\gamma}_o$ be the *average SNR associated with the MG* (for m_s=1) defined as $\tilde{\gamma}_o = (1/M) \sum_{u=1}^{M} \overline{\gamma}_{o,u}$. Fig. 2 shows ϵ as a function of $\tilde{\gamma}_o$. The figure compares both the UTP and FTP models to the proposed ME and HME strategies, for different values of L. We note that the performance gap between the ME and HME models is negligible.[10] This clearly shows the effectiveness of the proposed heuristic strategy. In addition, we note that as the value of $\tilde{\gamma}_o$ increases: i) the performance of the ME (and HME) model tends to overlap that of the UTP strategy, and ii) the performance of the ME, HME and UTP strategies significantly diverges from that of the FTP one. For instance, for $\tilde{\gamma}_o = 30$ dB and $L = 72$ B, the value of ϵ associated with the FTP strategy is 8.5 times greater than that of the other strategies. In addition, as reported in Fig. 2, it is worth noting that for $L = 36$ B ($L = 72$ B) the resource allocation solution derived by the UTP model is not feasible from the point of view of ME (namely, the constraint (6) is not met) for $\tilde{\gamma}_o \leq 16$ dB($\tilde{\gamma}_o < 17$ dB).

[10] ϵ values associated with the HME strategy are at most 0.07% greater than those derived by the ME model.

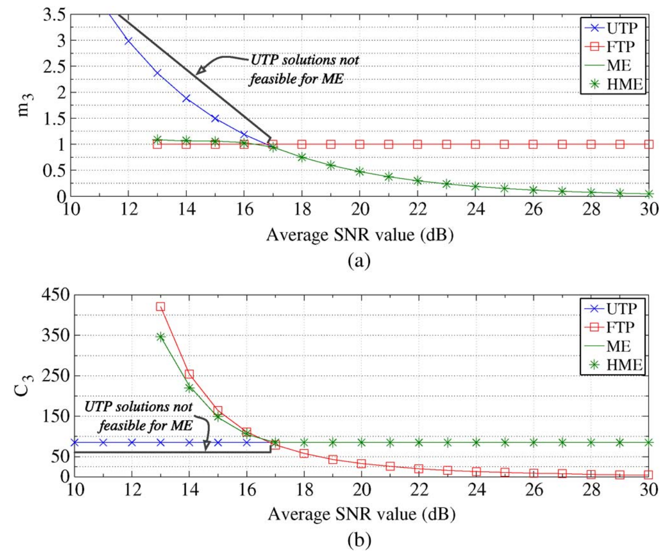

Fig. 3. m_s and C_s values of s_3 vs. $\tilde{\gamma}_o$ (for $L = 72$ bytes). (a) m_3 values; (b) C_s values.

Furthermore, Fig. 3(a) and 3(b) show the value of m_s and C_s of the service s_3 (for $L = 72$ bytes) as a function of $\tilde{\gamma}_o$, respectively. We note that, due to the fact that the UTP strategy does not have any constraint on the overall transmission power, the value of m_s increases as $\tilde{\gamma}_o$ decreases. Hence, values of C_s obtained by the UTP strategy mainly remain constant. On the other hand, the FTP model can only optimize the value of C_s, hence it decreases as $\tilde{\gamma}_o$ increases. In addition, figures show that both m_3 and C_3 values associated with the proposed ME and HME strategies are lower- and upper-bounded by the UTP and FTP models, respectively. Finally, we also note that the performance gap between ME and HME is negligible.

V. Conclusion

In this correspondence we propose an optimum (ME) and heuristic resource allocation model (HME) aiming at minimizing the overall transmission energy of a set of eMBMS flows delivered according to the systematic version of RLNC. We clearly showed that HME can derive good quality feasible solutions of ME in a finite number of steps.

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