ENERGY-EFFICIENT MULTIMEDIA TRANSMISSIONS THROUGH BASE STATION COOPERATION OVER HETEROGENEOUS CELLULAR NETWORKS EXPLOITING USER BEHAVIOR

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ABSTRACT

Wireless multimedia traffic has increased considerably in recent years, and it has become urgent to propose new approaches to deliver multimedia application in an energy-efficient manner. In wireless networks, observations show that some multimedia streams requested by users in a certain geographical area for a certain period exhibit very similar behavior. By exploiting the similarity, we can significantly reduce power consumption in wireless cellular networks. In this article, we present the description of *user behavior* in HCN and then propose an architecture for multimedia transmission over HCN. Based on this architecture, an energy-efficient multimedia transmission scheme is proposed to optimize energy efficiency by exploiting user behavior. In this scheme macrocells and small cells cooperatively multicast/unicast multimedia steams without QoS degradation. Illustrative results indicate that the exploitation of user behavior and base station cooperation is able to bring green multimedia transmission for HCN.

INTRODUCTION

The rapidly increasing number of wireless devices is one of the primary contributors to traffic growth. Every year several new devices in different form factors and increased capabilities and intelligence are being introduced in the market. By 2017, there will be 8.6 billion handheld or personal mobile-ready devices and 1.7 billion machine-to-machine connections [1] (e.g., GPS systems in cars, asset tracking systems in shipping and manufacturing sectors, and medical applications making patient records and health status more readily available). Cellular network capacity should be improved accordingly [2]. Among the increased wireless traffic, due to much higher bit rates than other mobile content types, mobile multimedia, especially video on demand (VoD) [3], will generate much of the mobile traffic growth through 2017. According to Cisco's prediction [1], mobile video will grow at a compound annual growth rate (CAGR) of 75 percent between 2012 and 2017, the highest growth rate of any mobile application category that can be forecast.

Meanwhile, it is estimated that wireless traffic contributes to a 20 percent increase in energy consumption, 80 percent of which is multimedia traffic related [4]. In turn, multimedia energy consumption is rising at 16 percent per year, doubling every six years. It is estimated that energy costs alone account for as much as half of the annual operating expenditure (OPEX). This has prompted concerted efforts by major operators to drastically reduce carbon emissions by up to 50 percent over the next 10 years. Clearly, there is an urgent need for a new disruptive paradigm of green media to bridge the gap between wireless technologies and multimedia applications.

To address the serious energy problem in information communications technology (ICT), there are several major projects targeting green communications worldwide (e.g., the EU EARTH project and GreenTouch), the targets of which are to reduce energy consumption considerably compared to current levels. One key scenario is focused on multimedia transmissions. In November 2012 the EU Project METIS [5] was launched to lay the foundation of the fifth generation (5G); one of its key challenges is to fulfill the previous requirements under a similar cost and energy dissipation as in today's cellular systems.

In this article, in order to reduce the energy consumption due to growing multimedia applications in future heterogeneous cellular networks (HCNs), we show how to effectively utilize the characteristics of both multimedia traffic and

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cellular networks. Considering the broadcast nature of wireless transmission in cellular networks, one of the fundamental ideas to improve energy efficiency for multimedia transmission is to use broadcast/multicast to serve users with identical or similar requests.

Characteristics of Heterogeneous Cellular Networks

In HCNs, the new carrier type (NCT) and small cell enhancement (SCE) have been actively discussed in Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) Release 12 [6]. Through decoupling of control and data traffic, the macrocell base station (MBS) mainly provides very wide area coverage and low/medium data traffic, while many small-cell BSs (SBSs) with a network control terminal (NCT) controlled by an MBS provide only data traffic, almost all the control information is transmitted through the MBS. In this way, by minimizing control channel and reference signal overhead, the HCN can increase spectrum flexibility and reduce interference, thereby increasing energy efficiency. User equipment devices (UEs) with dual connectivity can simultaneously receive flows from both MBSs and SBSs. The main characteristics of both the MBS and SBS are summarized as follows:

- *Macrocell BS:* Provide wide area coverage, low/medium data rate service, and control/signaling traffic
- *Small-cell BS (SBS):* Provide high data rate, especially in hotspot/indoor environments, as the access point for traffic offloading from macrocells; powerful Xn interface between MBS and SBS; controlled by MBS

Characteristics of Multimedia Traffic in Wireless Networks

In wireless networks the social characteristics of users mean that some “hot” multimedia streams requested by users in a certain geographical area for a certain period will exhibit similar behavior. For example, in a macrocell with several hotspots, the same service/traffic will probably be requested by many users, especially multimedia streams with a tolerant delay bound or “pushed” multimedia streams.

It should be noted that in one small cell (one hotspot), the number of users requesting similar multimedia streams may be small. However, from a macrocell (with many hotspots) point of view, the number of aggregated users may be large enough for a multicast transmission mode. Therefore, through exploiting such *user behavior* [7], proper control of a multicast scheme for such multimedia transmission can significantly reduce power consumption for multimedia delivery in wireless networks [8]. However, since user requests occur at different moments, in traditional multicast transmission a subsequent user will miss the previous part of the media stream that has already been transmitted for an early arriving user. In order to guarantee the quality of service (QoS), the transmitter can deliver the missing fraction of the media stream through initiating a separate stream called a *patching stream* [9].

In [10], a crosslayer approach for multimedia transmission in wireless networks was presented. Many current studies focus on homogeneous wireless networks. Efficient multimedia transmission in heterogeneous networks is an important problem in the current wireless environment. In [11], a detailed survey of energy-efficient multimedia streaming is given and discussed. In [12, 13], the authors give BS operation/user association and power allocation in wireless networks, respectively. These works focus on energy saving algorithms exploiting the delay-tolerant characteristics of multimedia traffic.

In this article, different from the previous works, considering both the characteristics of wide coverage of MBSs and high data rate of SBSs, we propose an energy-efficient multimedia multicast transmission scheme through macro/small BS cooperation in HCN. In this scheme, through analyzing user behavior and collecting multimedia requests in a hotspot area, the MBS will first multicast the multimedia stream. The subsequent arriving users during a certain time window period (this time window will be further optimized) requesting the same stream will immediately join the multicast group; meanwhile, the missing fraction of the stream will be delivered by the SBS through initiating separate patching streams (each missing stream is unicasted for each user). During the multimedia delivery, macro-cell and small-cell will cooperatively multicast/unicast the multimedia steams. For the multimedia transmission, the whole bandwidth will be dynamically allocated for MBS with unicasting stream, MBS with multicasting stream and SBS with patching stream. By theoretical analysis and simulations, we show that the proposed multimedia transmission scheme through BS cooperation can significantly improve energy efficiency.

The scope of this article is hence to study the green multimedia transmission in future HCNs taking into account user behavior, and to explain how user behavior can be exploited to improve the energy efficiency of multimedia transmission. Next, we present the characterization of user behavior in HCNs. Then the architecture for multimedia transmission over HCNs is presented, based on which an energy-efficient multimedia transmission scheme with BS cooperation is proposed to improve energy consumption exploiting user behavior. After that, we describe extensive simulations that have been carried out to verify such architecture and schemes. The conclusion of the article is then presented in the final section.

Heterogeneous Cellular Networks and User Behavior Description

Heterogeneous Cellular Networks

To meet rapidly growing demands for high-data-rate wireless broadband services, a significant effort has been made toward the development of LTE-Advanced networks, which have been shown to offer considerably higher data rates than the existing 3G networks. Meanwhile network coverage and the high data rate require-

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The optimal density of small cells, the sleeping mode control for small cells, homogeneous/heterogeneous CoMP, the coordination of macro and small cells may be determined based on the users characteristics. In this way, understanding such user behavior is very crucial for the design of LTE-A HCN systems.

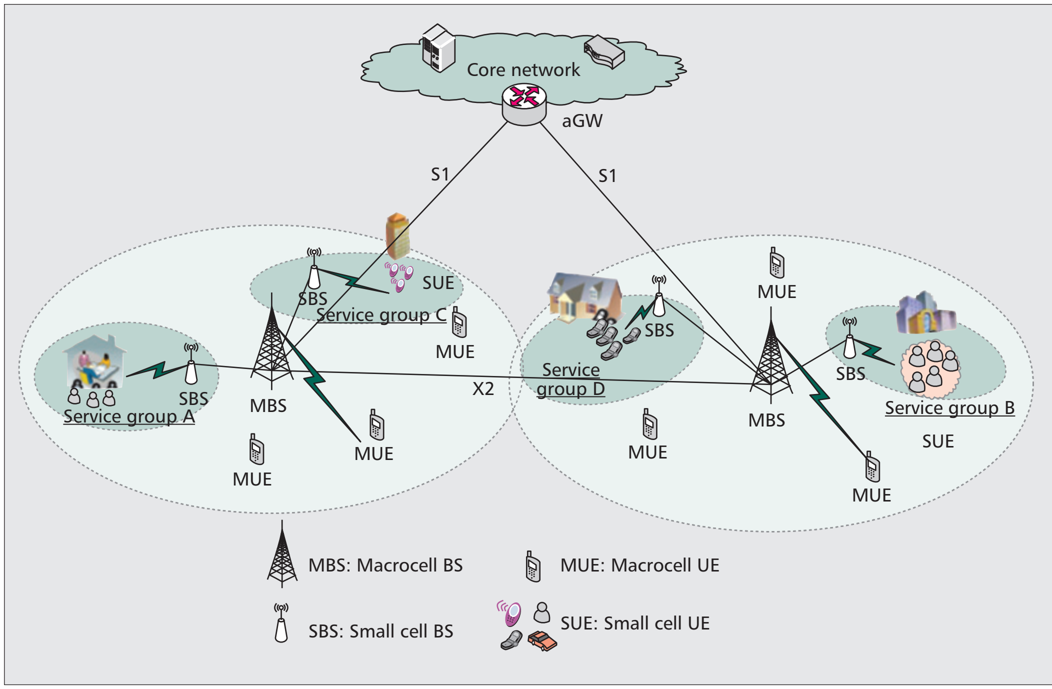

Figure 1. Architecture of heterogeneous cellular networks.

ment, especially in hotspot and indoor environments, have brought new challenges to LTE systems. In recent study and standard specifications [6], the heterogeneous network (HetNet) and its enhancement, the intelligent HetNet, have been proposed and studied.

Since last year, research on cellular networks has been carried out by academia, industry, and operators (e.g.,, EU Project METIS 2020 [5] and China's National 863 Project for 5G). The major purpose of 5G is to meet heterogeneous traffic and QoS/quality of experience (QoE) requirements in heterogeneous scenarios, from high-data-rate multimedia traffic to machine-to-machine (M2M) traffic of only several bits; thus, the key technologies for 5G are the new HCN architecture. In future HCNs, there will be different kinds of BSs with different capabilities, which can generally be classified into two basic categories: macrocell and small cell BSs. Figure 1 shows the architecture of HCN. To meet the traffic and QoS demands of more users, the spectral efficiency as well as energy efficiency of HCN should be improved considerably compared with to the current 4G systems.

In Fig. 1, under the coverage of one MBS, several SBSs are deployed dynamically according to some criteria (i.e., spectral efficiency, energy efficiency, QoE). Within the coverage of one MBS, due to the social habits of people, the users (both macro-UE, denoted as MUE, and small-UE, denoted as SUE) and their traffic volume will probably be unequally distributed and exhibit convergent patterns in both the temporal and spatial domains. Under this condition, these small cells can be managed smartly. For example, the optimal density of small cells, the sleeping mode control for small cells, homogeneous/heterogeneous CoMP, and the coordination of macro- and small cells may be determined based on the users' characteristics. In this way, understanding such user behavior is very crucial for the design of LTE-A HCN systems. In the next section, the user behavior in HCNs, describing users' distributions and characteristics, is presented and studied.

User Behavior for Various Service Groups in Heterogeneous Cellular Networks

In heterogeneous cellular networks, the services/traffic requested by different users vary and change dynamically in the temporal/spatial domain. A large amount of traffic of the same multimedia services are requested by users distributed in various small areas (hotspot regions) due to the social pattern among users [7]. As shown in Fig. 1, in each macrocell there are two service groups, which are assigned two small cells for coverage. The users in each service group gather in a small area. From a macrocell point of view, the number of users with the same multimedia streams within a certain time window may be large enough, which will probably bring some advantages. Therefore, such a user pattern exhibits strong social phenomena, denoted as *user behavior*, which characterizes the general behavior, pattern, and rules of a group of users as a social manner.

To better describe the user behavior in HCNs, we take the Gini coefficient [14] in statistics and economics for reference. The Gini coefficient (also known as the Gini index or Gini ratio) is a measure of statistical dispersion intended to represent the income distribution of a nation's residents. The Gini coefficient is commonly used as a measure of inequality of income or wealth. In [7], based on the Gini coefficient we have studied the user social pattern and utilize the user social pattern as a method to optimize system performance. In this article, we

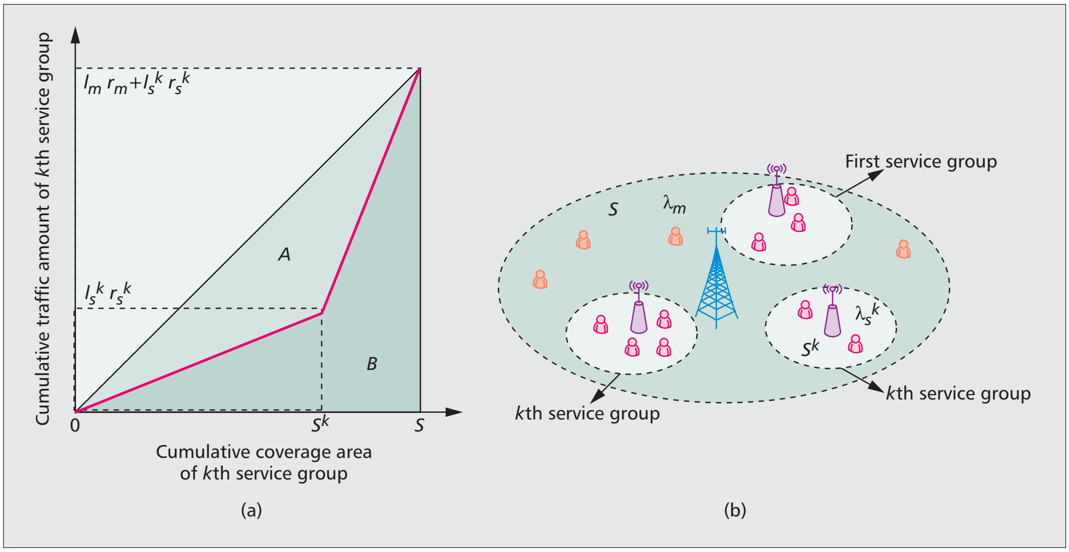

Figure 2. Illustration of user behavior modeling. a) graphical representation of user behavior for the kth service group; b) service groups in a macrocell scenario.

In a traditional unicast transmission scheme, in response to each user's request for the media stream, the transmitter will allocate a separate channel to deliver the data to each user. It will result in the serious wastage of transmission power when some of the users request the same media stream in a hotspot area.

further extend the user behavior to more general cases.

In the macrocell coverage area of an HCN, there are K service groups as shown in Fig. 2b, the user behavior in such a system is modeled as $\mathbf{h}$: = $\{h_1, h_2, \ldots, h_k, \ldots h_K\}$, where h_k is the coefficient of the kth service group. Let λ_s^k, r_s^k and s^k be the user traffic request density, average rate requirement per user, and coverage area of the kth service group (i.e., the kth hotspot), respectively. Let λ_m, r_m, and S be the user traffic request density, rate requirement per user, and coverage area of the macrocell, respectively. To better understand the description of our model, we redraw the graphical representation of the Gini coefficient in Fig. 2a. Based on the definition of the Gini coefficient, the user behavior for the kth service group h_k can be defined as $h_k = A/(A + B)$, where A and B are the region area in Fig. 2a. In this way, B is the sum of a triangle and a trapezium, that is, $B = \lambda_s^k r_s^k (S - (1/2)s^k) + 1/2\lambda_m r_m (S - s^k)$. Correspondingly, $A = 1/2S(\lambda_s^k r_s^k + \lambda_m r_m) - B$. Thus, the user behavior coefficient for the kth service group is derived as

$$h_k = \frac{A}{A+B} = \frac{\lambda_s^k r_s^k}{\lambda_m r_m + \lambda_s^k r_s^k} - \frac{s^k}{S}$$

Through user behavior coefficients for various service groups $\mathbf{h}$, we can describe the characteristics and inequality of various services in a hotspot area. In the next section, we use the user behavior coefficient as a basis for green multimedia transmission in heterogeneous cellular networks.

Multimedia Transmission in Heterogeneous Cellular Networks

In HCNs, from the perspective of the air interface between a BS and a user, there are three major kinds of transmission mode in current multicast service transmission, as shown in Fig. 3.

Unicast Multimedia Transmission

For conventional unicast transmission, despite the characteristics of multimedia traffic requested by users, all the multimedia traffic is transmitted using unicast mode, that is, unicast multimedia transmission (UMT) mode, as shown in Fig. 3a. In a traditional unicast transmission scheme, in response to each user's request for the media stream, the transmitter will allocate a separate channel to deliver the data to each user. It will result in serious waste of transmission power when some of the users request the same media stream in a hotspot area.

Traditional Multicast Multimedia Transmission

In Internet video-on-demand (VoD) multimedia transmission, if the service requests come at different moments, the transmitter can collect all the requests during a short time window and deliver a single media stream by multicast transmission (called batching multicast [15]); thus, the transmission power consumption can be reduced. However, these batching multicast schemes inevitably cause some delay due to the fact that the user must wait for the media stream data before the time window expires. In order to provide true real-time service for media stream transmission, multicast with a patching stream scheme (called patching multicast) has been proposed in [9]. In response to the first user's request, the transmitter delivers the requested media stream using multicast transmission. Later users that initiate a new request for the same media stream will immediately join the multicast group and receive the ongoing multicast media stream, buffering the received data. Meanwhile, the fraction of the media stream that has been already transmitted in the multicast media stream before this user's request will be delivered with unicast transmission. We call this traditional multicast multimedia transmission (TMMT) scheme, as shown in Fig. 3b.

Meanwhile, in these traditional multicast multimedia transmission schemes, the system bandwidth is always assumed to be unlimited; thus, no requests will be refused, which is unreasonable in wireless communication networks. Furthermore, in these schemes the transmission bandwidth for each media stream is also assumed to be fixed, which will lead to serious waste of transmission power due to the underutilization of system bandwidth. For these reasons, applying traditional multimedia multicast schemes to the heterogeneous cellular wireless environment without considering the characteristics of HCNs and user behavior is unlikely to provide satisfactory results with respect to energy efficiency. We need to find a new paradigm for energy-efficient multimedia transmission in HCNs.

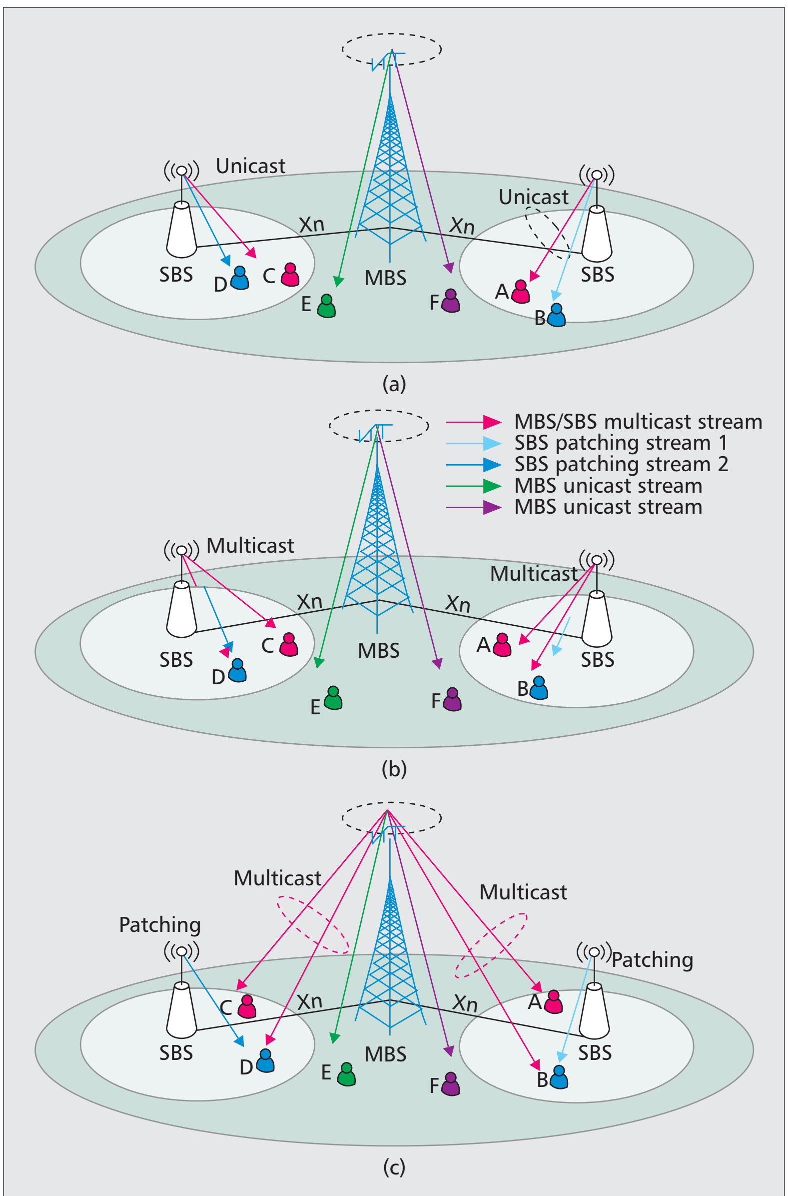

Figure 3. Illustration of multimedia service transmission in heterogeneous cellular networks: a) unicast multimedia transmission; b) traditional multicast multimedia transmission; c) proposed paradigm for multimedia transmissions through base station cooperation exploiting user behavior.

Proposed Paradigm for Multimedia Transmissions through Base Station Cooperation Exploiting User Behavior

In an HCN environment, macro- and small cells together provide two-tier coverage; small cells in the coverage of their home macrocell are deployed/managed by the macrocell according to hotspot traffic characteristics. Usually, the small cells provide high data rates locally in hotspot regions, while macrocells provide wide-area coverage in non-hotspot regions. The interface between macro- and small cells is called the Xn interface in 3GPP, which has high capacity and low latency [6]. Therefore, the joint scheduling of macro-/small cells can provide considerable flexibility. To further improve the energy efficiency for multimedia transmission, MBS and SBS cooperation can be used. As shown in Fig. 3c, We propose a paradigm for user behavior-aware multimedia transmissions through BS cooperation (MTBSC).

In this scheme, through analyzing user behavior and collecting multimedia requests in a hotspot area, the MBS first multicasts the multimedia stream, the subsequent arriving users during a certain time window period requesting the same stream immediately join the multicast group, and the missing fraction of the stream is delivered by the SBS through initiating separate patching streams (each missing stream is unicast for each user), since the multimedia stream is buffered at the SBS. During multimedia delivery, the macrocell and small cell cooperatively multicast/unicast the multimedia streams; hence, we call this BS cooperation. This kind of transmission is different from device-to-device (D2D) transmission mode, where the multimedia is buffered at the user side.

Since both a macrocell and small cells participate in the transmission process, the interface Xn is enhanced to support real-time streaming transmission. In the current deployment, Xn is always a fiber link, and its delay and transmission rate can be guaranteed. In the next section, a detailed description of the proposed paradigm is presented, and the optimal time window and bandwidth allocation scheme for energy saving are also derived.

Energy-Efficient Multimedia Transmission through Base Station Cooperation in HCNs

Scheme Description

The key idea of the proposed energy-efficient multicast scheme is to combine all the same requested media streams using multicast transmission and guarantee the QoS requirement at the same time. Unlike the traditional multicast scheme using fixed bandwidth for each media stream transmission, in the proposed approach the transmitter dynamically allocates the system bandwidth according to the number of ongoing transmission media streams. The whole bandwidth W is divided into three categories:

- W_{Mm}: Bandwidth for an MBS with a multicasting stream
- W_{Mu}: Bandwidth for an MBS with a unicasting stream

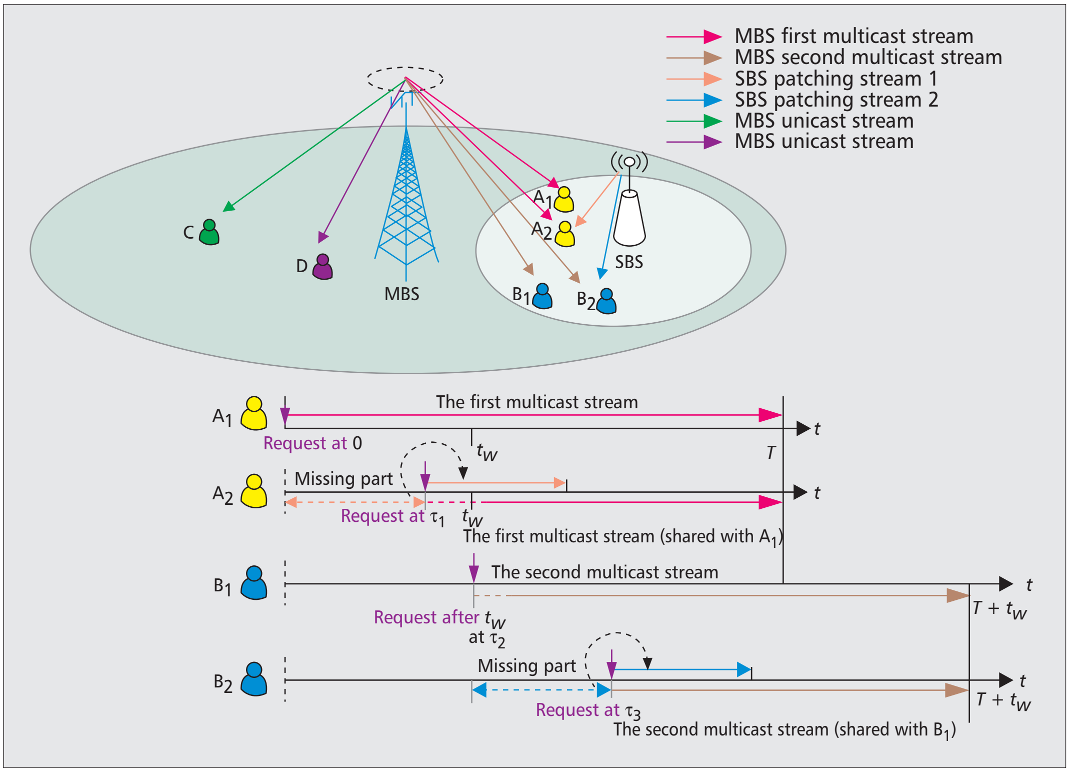

Figure 4. Detailed illustration of the proposed paradigm for energy-efficient multimedia transmission through base station cooperation.

Unlike the traditional multicast scheme using fixed bandwidth for each media stream transmission, in the proposed approach the transmitter will dynamically allocate the system bandwidth according to the number of ongoing transmission media streams.

- W_{Su}: Bandwidth for an SBS with a unicasting patching stream

The bandwidth allocation scheme is further optimized to maximize the total energy efficiency while satisfying the QoS requirements. Figure 4 shows the proposed paradigm for energy-efficient multicast streaming transmission with BS cooperation.

Step 1 **—** For a hotspot region where users exhibit similar traffic requests (user behavior with coefficient h), user A1 first requests a multimedia stream (of length T). As a response, the MBS initiates a multicast media stream (red solid arrows in Fig. 4) to deliver the requested data using W_{Mm} bandwidth.

Step 2 **—** Subsequent user A2 submits a new request for the same media stream at time t1, which falls in the multicast time window t_w; then A2 immediately joins this multicast group, receiving the ongoing multicast media stream (red dotted arrows). If another user B1's request falls outside t_w, B1 will initiate the second multimedia stream. The length of t_w is hence used to control the delay, and total energy consumption is also optimized.

However, due to the requested delay, A2 and B2 will miss the previous parts of the media stream that have already been transmitted before their requests (black dotted double arrows).

Step 3 **—** In order to "catch up" the multimedia stream, the SBS (controlled by the MBS through the Xn interface) immediately delivers the missing fraction of the media stream (green and blue solid arrows) through initiating separate unicast patching stream with W_{Su} bandwidth.

Step 4 **—** Users A2 and B2 first play the unicast patching media stream during the period [τ_1, $2\tau_1$] and buffer the ongoing multicast part for later playback. This scheme effectively utilizes macrocell and small cell cooperation. Energy and spectral efficiency can be optimized.

Performance Analysis

In this subsection we focus on the performance analysis for one small cell scenario (r and R denote the radius of the small cell and macrocell, respectively), and the superscript k is thus neglected for simplicity. The multiple SBS scenario can be derived following similar reasoning. The power model used in this article is $P(d) = K(d/d_0)^{-\alpha}$, where d is the distance between the BS and UE, K is the pathloss factor, and d_0 is the reference distance. In our proposed scheme, the total bandwidth is divided into three categories; therefore, the total power consumption should be calculated according to the three links, MBS-MUE, MBS-SUE, and SBS-SUE. In our scheme, different multicast time windows t_w will greatly impact the power consumption, so we denote the total power consumption as $P = P(t_w) = P_{Mm} + P_{Mu} + P_{Su}$.

We consider the total energy consumption during the multimedia transmission (of length T) through BS cooperation and then formulate the energy efficiency maximization problem as

$$\begin{aligned} &\underset{t_w, W_{Mu}, W_{Mm}, W_{Su}}{\text{Maximize}} && \mathbf{EE} = \frac{Throughput}{P} \\ &\text{Subject to} && W_{Mu} + W_{Mm} + W_{Su} = W. \end{aligned} \quad (1)$$

By solving the problem of EE in Eq. 1, we can obtain a suboptimal bandwidth allocation method as follows,

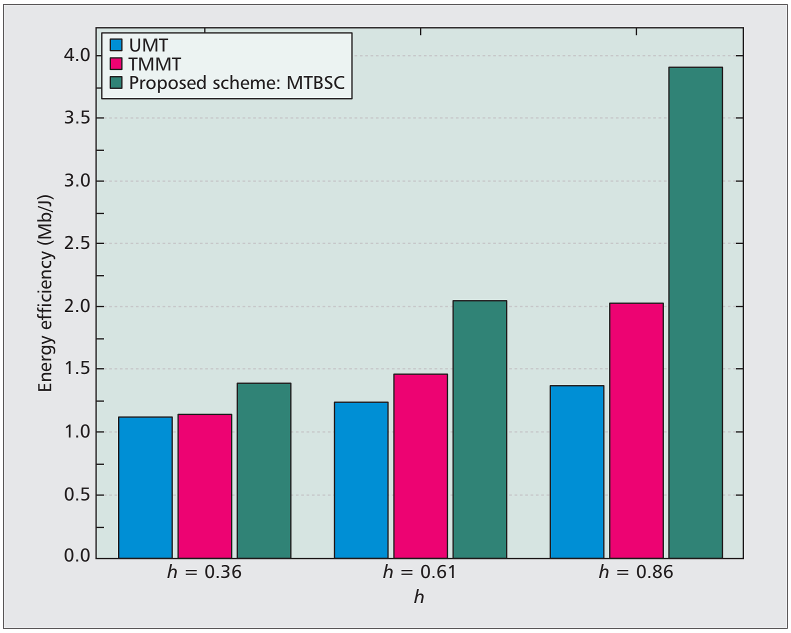

Figure 5. Energy efficiency vs. user behavior coefficient h for three multimedia transmission schemes in HCNs.

$$\frac{W_{Su}}{W_{Mm}} = \frac{(\alpha+2)K_s s^{-\alpha/2}}{2K_m\left(1/2\sqrt{S}+\sqrt{s}\right)^{-\alpha}}$$
$$\frac{W_{Mu}}{W_{Mm}+W_{Su}} = \frac{\lambda_m r_m}{\lambda_s r_s}, \tag{2}$$

where α denotes the pathloss exponent; K_s and K_m denote the path loss factor in small and macro cells environment, respectively. Through further deduction and based on the bandwidth allocation method in Eq. 2, we obtain the optimal multicast time window t_w^{opt} of the proposed approach for maximizing energy efficiency,

$$t_w^{opt} \approx \sqrt{\frac{K_s r^{-\alpha}}{K_m(R/2+r)^{-\alpha}}}\sqrt{\frac{\alpha+2}{\lambda_s}T}. \tag{3}$$

Illustrative Results

In this section, we evaluate the proposed MTBSC scheme. The radius of small- and macrocells are set as r = 400 m and R = 1000 m, respectively. The total bandwidth W = 40 MHz, path loss exponent α = 4, multimedia stream length T = 30 s, the average data rate requirement per user of macro- and small cells is set as 400 kb/s, and the user behavior coefficient is changed through varying the user traffic density in both macro and small cells.

In Fig. 5, we compare the energy efficiency for our proposed scheme (MTBSC) and the two baseline schemes, the conventional unicast (UMT) and multicast schemes (TMMT) under various user behavior coefficient h. As shown in Fig. 5, the energy efficiency of our proposed scheme outperforms that of the UMT and TMMT schemes significantly, especially when h is high. This can be explained as follows. When the degree of convergence is high in a hotspot area, more users' multimedia stream requests can be delivered through multicasting with BS cooperation. When h = 0.61, the energy efficiency can be improved by 40 percent compared to the TMMT scheme; when h increases to 0.86, the energy efficiency can even be improved as much as 89 percent compared to the TMMT scheme. The performance improvement is also due to the fact that our proposed scheme can exploit the idle system bandwidth.

To evaluate the effects of the multicast time window t_w on system energy efficiency, we compare the energy efficiency performance for different user behavior coefficients h under various lengths of t_w in Fig. 6. It can be seen that the theoretical analytical results are very close to the simulation results, which demonstrates the effectiveness of the derived optimal t_w^{opt} for maximal energy efficiency in Eq. 3. From Fig. 6, it can be seen that energy efficiency is a convex function of the time window for various user behavior coefficients. Hence, in practical multimedia transmission in HCNs, we can set the optimal time window and bandwidth allocation to achieve green multimedia transmission.

Conclusions

This article presents the description of *user behavior* in heterogeneous cellular networks. We propose an architecture for multimedia transmission over HCNs. In the delivery of multimedia services, since multimedia requests occur at different moments, a subsequent user misses the previous part of the multimedia stream that has been already transmitted. The transmitter then delivers the missing fraction of the media stream in an on-demand manner by initiating a separate patching stream. Based on this architecture, an energy-efficient multimedia transmission scheme through base station cooperation has been proposed to optimize the energy efficiency by exploiting user behavior, and heterogeneous networks, where macrocells and small cells cooperatively multicast/unicast the multimedia steams without QoS degradation. Illustrative results indicate the exploitation of user behavior and base station cooperation is able to bring green multimedia transmission to HCNs.

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BIOGRAPHIES

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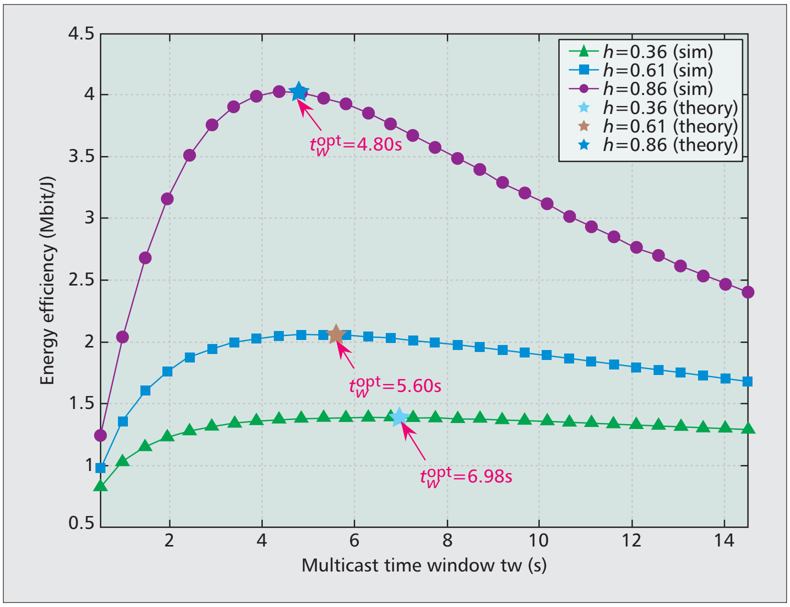

Figure 6. Performance of the proposed scheme: energy efficiency vs. time window (t_w) under various user behaviors h.

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