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***Abstract*—The increasing popularity of linear services such as mobile TV, broadcasting live and sports events using mobile and portable devices, has led to a dramatic growth of the mobile data traffic. To deal with this traffic explosion, future networks have to increase the capacity offered to mobile communications, while at the same time trying to reduce their energy consumption. Actually, recent studies have shown that network cooperation is a promising candidate to deal with such issues. Based on these facts, this paper addresses the optimization of the energy efficiency of a hybrid network in which a broadcast and a unicast networks cooperate to deliver linear type of services to mobile and portable devices. Two optimization methods have been proposed to analytically find the optimal broadcast coverage area that maximizes the energy efficiency of the hybrid network. Simulation results show that using such a hybrid approach improves the overall energy efficiency.**

I. Introduction

The consumption trend of linear services such as mobile TV or broadcasting of live and sports events has evolved due to the increase usage of portable and mobile devices over the years. Today, users are more and more watching linear services on theirs tablets and smartphones, which are connected to a unicast network. In addition, the increasing popularity of these linear services has led to exponential increases of the mobile data traffic [1]. Consequently future networks will have to deal with this mobile data traffic explosion in order to overcome the increasing demand of network capacity and quality of service. Actually, a potential solution to address these issues is to overlay a unicast network with a broadcast network as shown in recent works [2]–[4]. These later studies have shown that such hybrid approaches provide higher network capacity and better service coverage. Furthermore, we have shown in our previous work [5] that the coverage extension scenario, i.e. when the two networks have different but complementary coverage areas, leads the optimal cooperation strategy in terms of network capacity improvement.

At the same time, the demand for higher capacity and quality of service associated with the increasing number of devices are leading to a rapid increase in energy consumption and operating cost of networks. In cellular networks, the energy efficiency problem is usually addressed by focusing on the network deployment strategies in order to determine the proper cell size and the number of base stations [6], [7] or on the resource management strategies with efficient resource utilization and power allocation [8]. Another technique to improve the energy efficiency is to introduce active/sleep (ON/OFF) modes for base stations [9], which represents the most dominant share of the energy consumption of a network [10]. In this context, some authors (see e.g. [11], [12]) have investigated the energy efficiency of hybrid unicast and broadcast networks. However, these later works assume that the base stations are always switched ON even though there is no data to transmit. Therefore, from a planning perspective, we propose to investigate further the coverage extension scenario by enabling active/sleep (ON/OFF) modes for base stations.

The goal of this paper is to find the optimal planning parameters of the broadcast network that maximizes the energy efficiency of the hybrid network. We propose two optimization methods to find the optimal coverage area of the broadcast network: the first approach optimizes the energy efficiency metric by minimizing the power consumption of the broadcast component whereas the second approach optimizes the energy efficiency metric by maximizing the capacity of the broadcast network. Next, we derive closed form expressions of the optimal broadcast coverage radius for each approach. Finally, we validate the analytical expressions of the optimal broadcast coverage radius by comparing them to the results obtained from simulations of the hybrid network.

II. System Model

A. Hybrid Network Model

As depicted in Fig. 1. The proposed model consists of two OFDM systems: a broadcast network composed of a single High Power High Tower (HPHT) station producing a broadcast signal such as DVB-NGH/T2 Lite or a modified eMBMS signal and a unicast network composed of N_{LPLT} Low Power Low Tower (LPLT)

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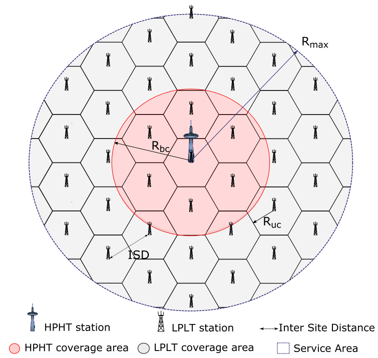

Fig. 1. Hybrid network model

sites producing a unicast signal according to the LTE standard. It is assumed that all LPLT sites have the same transmission parameters and coverage areas. Therefore, for a given service area, the number N_{LPLT} of LPLT sites is the ratio of the size of the service area to the size of a LPLT cell, which depends on the inter-site distance (ISD) between the LPLT sites. As in [5], we also consider in this paper a transmission of a linear TV service to M users uniformly distributed within a given service area. The service is always available and requested by all M users. A user requires a minimum capacity, denoted as C_{req}, to receive the proposed service. The user terminals are supposed to be equipped so as to be capable of switching its service reception from one network to another. Furthermore, it is also assumed that the propagation model is limited to the effect of the path loss [12]. Small scale fading and shadow fading are not considered in this paper. A log-distance path loss model is then used to evaluate the path loss at any distance from any transmitter station. Therefore the average signal to noise ratio (SNR) at a distance d from a transmitter station is given by $\gamma(d) = \gamma_0 \left(d/d_0\right)^{-\alpha}$, where α is the path loss exponent, and γ_0 is the average SNR of a user located at a distance d_0 from the transmitter station. γ_0 is obtained from $\gamma_0 = \left(P_{tx}/L_p P_n\right)\left(\lambda/(4\pi)\right)^{\alpha}$ where P_{tx} is the average transmission power of the transmitter, P_n refers to the average receiver noise power, λ is the wave length related to the carrier frequency of the transmitted signal and L_p represents the total margins due the propagation and reception environment effects. The total margins are obtained from link-budget evaluations [13].

B. Power Consumption Model

According to [10], [14], base stations represent a dominant share of the total power consumption in unicast and broadcast networks. To evaluate the power consumption of the base stations, a simple and accurate power model is proposed in [10]. The proposed power model is based on a combination of the power consumption of base station components and sub-components such as analog Radio Frequency (RF), baseband (BB) processing, power amplifier and the power system (cooling). Furthermore,

TABLE I
POWER CONSUMPTION PARAMETERS FOR THE LPLT AND HPHT TRANSMITTERS.

BS type	P_{max} [1][W]	Δ_p	P_0 [W]	P_{sleep} [W]
LPLT[2]	40	4.75	260	150
HPHT[3]	5000	3	260	150

[1] transmission power;
[2] These values are extracted from [10], [15];
[3] Derived from the power consumption model [10], [15].

the power model uses a linear function that maps the consumed input power P_{in} of a base station to achieve a certain RF output power P_{max} at the antenna. Therefore, the power consumption P_{in} of a base station can be obtained from the following function [15]

$$P_{in} = \begin{cases} P_0 + \Delta_p P_{max}\rho & \text{if base station is ON,} \\ P_{sleep} & \text{otherwise,} \end{cases} \tag{1}$$

where P_0 is a linear model parameter that represents the power consumption at the zero RF output power , P_{max} is the maximum RF output power at the antenna, P_{sleep} is the power consumption in sleep mode, Δ_p is the slope of the load-dependent power model and depends on the type of the base station, and ρ is the ratio of the number of carriers used to the total number of carriers, also called as the resource usage ratio. Table I shows power consumption model parameters for the different types of base stations used in this study, i.e. LPLT and HPHT transmitters.

III. PERFORMANCE METRICS

A. Capacity Metric

1) Capacity of the broadcast network: In a broadcasting system, all subcarriers available for data transmissions are allocated to all users. Link adaptation is not used for broadcast transmissions. The broadcast network capacity is then determined by the capacity of a user located at the edge of the coverage area. Thus, all users within the broadcast coverage area have the same capacity which depends on the transmission power P_{tx}^{bc} of the HPHT station, the targeted coverage area, and the capacity requirement of the proposed service.

For a targeted service capacity C_{req}, the broadcast network is planned such that

$$B^{bc} \log_2\left(1 + \gamma_0^{bc}\right) \geq C_{req}, \tag{2}$$

where B^{bc} is the transmission bandwidth of the broadcasting system and γ_0^{bc} is the average SNR of a user located at the edge of the broadcast coverage area i.e. at a distance R_{max} from the HPHT site (see Fig. 1).

Thus, it follows that the average capacity of the broadcast network can be expressed as a function of the broadcast coverage radius R_{bc}, which leads to

$$C^{bc}(r_{bc}) = M^{bc} B^{bc} \log_2\left(1 + \gamma_0^{bc} r_{bc}^{-\alpha}\right), \tag{3}$$

where $r_{bc} = (R_{bc}/R_{max})$ and M^{bc} is the number of users that receive the service through the broadcast network.

2) Capacity of the unicast network: As we assume for simplicity that all LPLT sites have the same transmission parameters and coverage areas, we start by focusing on a single LPLT site and then generalize the results to all LPLT sites.

In contrast to a broadcasting system, in a unicast system the LPLT station allocates a block of subcarriers, i.e. a Resource Block (RB), to a user in the coverage area based on the average SNR γ_m of that user. The number of RBs allocated per user depends on the resource management strategy of the mobile operator and the user quality of service requirements.

However, as in [5], we consider a simple resource allocation strategy that assigns the same number of RBs to all users. In this case the number of RBs allocated to a user m, denoted as RB_m, is chosen such that for all users we have

$$RB_m B_{RB} \log_2(1+\gamma_m) \geq C_{req}, \tag{4}$$

where B_{RB} is the bandwidth of a RB and γ_m is the average SNR of the user at a distance r_m from the serving LPLT site.

Given the maximum number RB_{max} of RBs available in the LPLT site, we have shown in our previous work [5] that the average capacity $\mathbb{E}[C_m^{uc}]$ of a user in a LPLT site can be obtained from

$$\mathbb{E}[C_m^{uc}] = \min\left(RB_m, \frac{RB_{max}}{M_i^{uc}}\right)\mathbb{E}[C_m^{RB}], \tag{5}$$

where M_i^{uc} is the average number of users in the i^{th} LPLT cell and $\mathbb{E}[C_m^{RB}]$ is the capacity of a RB averaged over the distribution of the locations of users in the LPLT cell. Then it follows that the capacity of a LPLT cell is obtained by summing the average capacity of all users in the LPLT cell i,

$$C_i^{uc} = M_i^{uc}\mathbb{E}[C_m^{uc}]. \tag{6}$$

3) Capacity of the hybrid network: From (3) and (6), the average capacity of the hybrid network, denoted as C^H, is obtained from [5] as

$$C^H = C^{bc} + \sum_{i \in \mathcal{N}_{LPLT}} C_i^{uc}, \tag{7}$$

where C^{bc} is the average capacity of the broadcast network derived from (3), and $\mathcal{N}_{LPLT}$ is the set of LPLT sites in the service area. Next, given a uniform distribution of the users in the service area, the average capacity of the hybrid network can be expressed as a function of the broadcast coverage radius as,

$$C^H = M\left[r_{bc}^2 B^{bc}\log_2\left(1+\gamma_0^{bc} r_{bc}^{-\alpha}\right) + (1-r_{bc}^2)\mathbb{E}[C_m^{uc}]\right] \tag{8}$$

B. Power Consumption Metric

1) Power consumption of the broadcast network: The power consumption of the broadcast network is obtained from the linear power model (1) and can be expressed as

$$P_{in}^{bc} = P_0^{bc} + \Delta_p^{bc} P_{tx}^{bc}, \tag{9}$$

setting the resource usage ratio $\rho = 1$ in (1), since all available subcarriers are used for data transmission in a broadcasting system.

2) Power consumption of the unicast network: In a similar way, we derive from (1) the power consumption of a single LPLT site as follows,

$$P_{in,i}^{uc} = P_0^{uc} + \Delta_p^{uc} P_{tx}^{uc} \rho_i^{uc}, \tag{10}$$

where

$$\rho_i^{uc} = \min\left(1, \frac{RB_m M_i^{uc}}{RB_{max}}\right). \tag{11}$$

Observe that for the LPLT sites, the resource usage ratio ρ depends on the number of users in the LPLT cell and the number RB_m of RBs that is allocated to a user.

3) Power consumption of the hybrid network: Finally the average power consumption of the hybrid network can be obtained from (9) and (10),

$$P_{in}^H = P_{in}^{bc} + \sum_{i \in \mathcal{N}_{LPLT}} P_{in,i}^{uc}. \tag{12}$$

Furthermore, given a uniform distribution of the users in the service area, the average power consumed by the hybrid network can be expressed as a function of the broadcast coverage radius as,

$$P_{in}^H = \Delta_p^{bc} P_{tx}^{bc}\left(r_{bc}^{\alpha} - \sigma_{p2} r_{bc}^2 + \sigma_{p1}\right), \tag{13}$$

where

$$\sigma_{p1} = \frac{P_{in,i}^{uc} + P_0^{bc} r_{uc}^2}{\Delta_p^{bc} P_{tx}^{bc} r_{uc}^2} \text{ and } \sigma_{p2} = \frac{P_{in,i}^{uc} - P_{sleep}^{uc}}{\Delta_p^{bc} P_{tx}^{bc} r_{uc}^2}. \tag{14}$$

C. Energy Efficiency Metric

The energy efficiency (EE) of the hybrid network is defined as the ratio of the capacity (7) to the power consumption (12) of the hybrid network, which writes

$$EE^H = \frac{C^H}{P_{in}^H}. \tag{15}$$

IV. Optimizing the Energy Efficiency

A. Problem formulation

In our previous work [5] on the capacity of the hybrid network, we have shown that the congestion of the hybrid network could be avoided by offloading the data traffic from the unicast component to the HPHT broadcast component of the hybrid network. We have then determined, from a planning perspective, the optimal broadcast coverage radius that maximizes the overall capacity of the hybrid network for a given service area. In this paper, we propose to optimize the energy efficiency metric of the hybrid network. Actually, considering the energy saving aspects, the LPLT sites within the coverage area of the broadcast network could be turned off to save more energy since there is no data to transmit. In the light of these observations, the aim of this study is to find the optimal broadcast coverage radius that maximizes the energy efficiency (EE) metric of the hybrid network. The related energy efficiency maximization problem states

$$(P1): \quad \max_{0 \leq r_{bc} \leq 1} \quad EE^H(r_{bc}),$$

Recall that $r_{bc} = R_{bc}/R_{max}$ is the normalized radius of the broadcast coverage area. From (15) it follows that the energy efficiency of the hybrid network is maximized either by increasing the capacity (7) of the hybrid network for a fixed transmit power of the broadcast component or by reducing the power consumption (12) of the broadcast component for a given capacity requirement. The following sections present these two different optimization approaches.

B. Proposed Solution to $(P1)$

1) Power consumption minimization approach: In this section, we propose to minimize the power consumption of the broadcast component with respect to a targeted capacity at the edge of the broadcast coverage radius based on the service requirement. This approach is called the *pwr-min approach*. In the *pwr-min approach*, the transmission power of the HPHT transmitter is set according to that targeted capacity C_{req}, which leads to the minimum SNR γ_0^{bc} using (2). Furthermore, using (8) and (13), the energy efficiency (15) of the hybrid network can be expressed as a function of the normalized broadcast coverage radius, denoted as x. Thus $\forall\, x \in]0, 1]$, the objective function writes

$$f_p(x) = \left(\frac{M\mathbb{E}[C_m^{uc}]}{\Delta_p^{bc} P_{tx}^{bc}}\right) \frac{1 + \sigma_c x^2}{x^\alpha - \sigma_{p2} x^2 + \sigma_{p1}}, \quad (16)$$

$$\text{where, } \sigma_c = \frac{B^{bc} \log_2\left(1 + \gamma_0^{bc}\right)}{\mathbb{E}[C_m^{uc}]} - 1, \quad (17)$$

is a parameter resulting from the difference between the average capacity of the broadcast component and the unicast component of the hybrid network, σ_{p1} and σ_{p2} are parameters related to the power and system models. These parameters are considered as input parameters of the problem $(P1)$.

It can be shown from (16) that the function $f_p(x)$ is a convex function for all $x \in [0, 1]$ and $\alpha \geq 2$. Therefore the optimal broadcast coverage radius r_{bc}^* is obtained by finding the root of the derivative function $f_p'(x)$, which leads to

$$x^{\alpha-2} - \sigma_c \left(\frac{2}{\alpha} - 1\right) x^\alpha = \frac{2}{\alpha}\left(\sigma_c \sigma_{p1} + \sigma_{p2}\right). \quad (18)$$

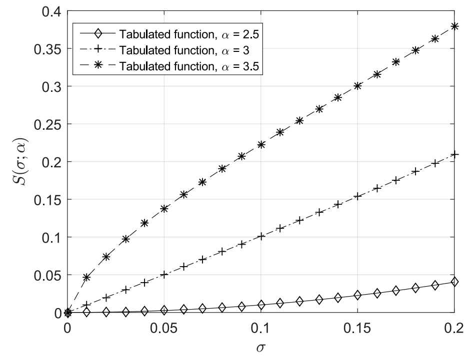

Fig. 2. Illustration of the tabulated function $S(\sigma; \alpha)$ for practical values of σ and for $\alpha = 2.5$ and $\alpha = 3$.

Now, considering the following change of variable $u = x\left[\sigma_c\left(2/\alpha - 1\right)\right]^{1/2}$, it follows from (18) that

$$u^{\alpha-2}\left(1 - u^2\right) - \sigma = 0, \quad (19)$$

where

$$\sigma = \frac{2}{\alpha}\left(\sigma_c \sigma_{p1} + \sigma_{p2}\right)\left[\sigma_c\left(\frac{2}{\alpha} - 1\right)\right]^{\frac{\alpha}{2}-1}, \quad (20)$$

Observe that the solution to (19) depends only on the input parameters of the optimization problem σ and α. Since α is determined by the propagation and reception environment chosen by the broadcast operators, the optimal broadcast coverage radius mainly depends on σ, which is regarded as a cooperation decision parameters. Let $S(\sigma; \alpha)$ be the solution to (19). Based on numerical analysis, for example the Newton's method, the solution $S(\sigma; \alpha)$ can be tabulated for all values of σ and α. For instance, Fig. 2 shows the function $S(\sigma; \alpha)$ for practical values of σ and for $\alpha = 2.5$ and $\alpha = 3$. From Fig. 2 it can be seen that for practical values of σ and α the solution $S(\sigma; \alpha)$ is closed to zero. In addition, when $\sigma \to 0$, $S(\sigma; \alpha) \to 0$. Therefore the solution to (19) may for example be approximated by $u_0 = \sigma^{1/(\alpha-2)}$. A better approximation u_1 of the solution can be found by considering the following change of variable $u_1 = u_0(1 + \varepsilon_0)$, where ε_0 plays the role of an adjustment function. Then, replacing u in (19) leads to

$$1 - u_0^2(1 + \varepsilon_0)^2 = (1 + \varepsilon_0)^{-(\alpha-2)}. \quad (21)$$

Next, expecting $u \to 0$, we assume $\varepsilon_0 \to 0$ and can therefore easily use a first order Taylor expansion of (21) to obtain $\varepsilon_0 \sim u_0^2/(\alpha - 2)$, and then get the expression of u_1 as

$$u_1 = u_0\left(1 + \frac{u_0^2}{\alpha - 2}\right). \quad (22)$$

We can iterate the procedure to derive a closest approximation of the solution, which leads to

$$u_2 = u_0\left(1 + \frac{u_0^2}{\alpha - 2} + \frac{2u_0^4}{(\alpha - 2)^2}\right). \quad (23)$$

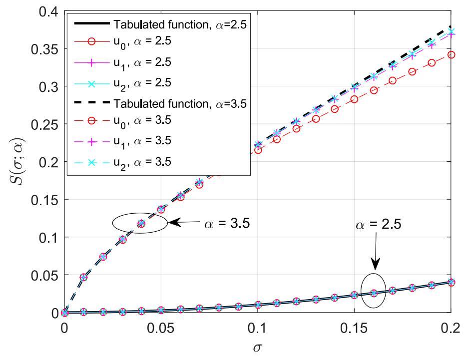

Fig. 3. Illustration of the tabulated function $S(\sigma;\alpha)$ and its first, second and third order approximations; these functions are represented for practical values of σ and for $\alpha \in \{2.5; 3.5\}$.

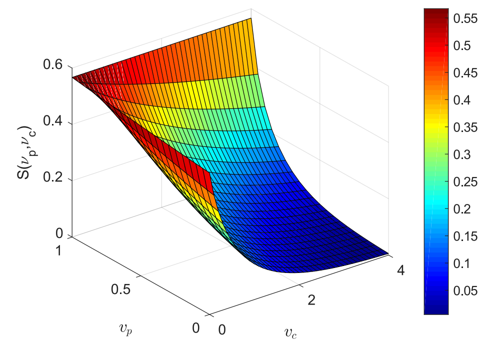

Fig. 4. Illustration of the tabulated function $S(\nu_p, \nu_c)$ for $\alpha = 3.5$ and $\gamma_0^{bc} = -20$ [dB].

Eventually, a general approximation of order $n \leq 3$ of the solution $S(\sigma;\alpha)$ is given by

$$S(\sigma;\alpha) \sim \sigma^{\frac{1}{\alpha-2}} \left(1 + \sum_{k=0}^{n-1} \frac{k}{(\alpha-2)^k} \sigma^{\frac{2k}{\alpha-2}}\right). \quad (24)$$

Fig. 3 plots the solution $S(\sigma;\alpha)$ and its first, second and third order approximations for practical values of σ and for $\alpha = 2.5$ and $\alpha = 3.5$. As evident from the results, the second and third order approximations turn out to be very tight, which motivates us to make use of (24) for the derivation of the analytical solution of $(P1)$. Hence, since $S(\sigma;\alpha)$ is the solution to (19), the optimal broadcast coverage radius is obtained by applying the following inverse transform $x = u/\left[\sigma_c(2/\alpha-1)\right]^{1/2}$ to $S(\sigma;\alpha)$, which leads to

$$r_{bc}^* = \frac{\sigma^{\frac{1}{\alpha-2}}}{\sqrt{\sigma_c\left(\frac{2}{\alpha}-1\right)}} \left(1 + \sum_{k=0}^{n-1} \frac{k}{(\alpha-2)^k} \sigma^{\frac{2k}{\alpha-2}}\right) \quad (25)$$

2) Capacity maximization approach: In this section we study the second optimization approach of the energy efficiency. This approach is called *capa-max approach*. Indeed, instead of reducing the transmission power of the broadcast component, we increase the capacity of the broadcast component while the transmission power is kept constant.

Given a uniform distribution of the location of the users in the service area, the energy efficiency (15) of the hybrid network can be expressed as a function of the normalized broadcast coverage radius r_{bc} using (8) and (13). Thus $\forall x \in]0,1]$, the objective function in this case is written as

$$f_c(x) = \left(\frac{MB^{bc}}{\Delta_p^{bc} P_{tx}^{bc} \ln 2}\right) \frac{x^2 \ln\left(1 + \frac{\gamma_0^{bc}}{x^\alpha}\right) + (1-x^2)\nu_c}{1 - \sigma_{p2}x^2 + \sigma_{p1}}, \quad (26)$$

where $\nu_c = (\mathbb{E}[C_m^{uc}] \ln 2)/B^{bc}$.

It can be shown from (26) that the energy efficiency is a convex function of the broadcast coverage radius. Therefore the optimal broadcast coverage radius r_{bc}^* is obtained by finding the root of the derivative function $f_c'(x)$. In other words, r_{bc}^* is the solution to $f_c'(x) = 0$ which leads to

$$\frac{1}{\nu_p} \ln\left(1 + \frac{\gamma_0^{bc}}{x^\alpha}\right) + \frac{\alpha\left(x^2 - \frac{1}{\nu_p}\right)}{2\left(1 + \frac{x^\alpha}{\gamma_0^{bc}}\right)} = \nu_c\left(\frac{1}{\nu_p} - 1\right) \quad (27)$$

where $\nu_p = \sigma_{p2}/(1+\sigma_{p1})$. By definition we have $0 \leq \nu_p \leq 1$ and $\nu_c \geq 0$.

Next, considering the following two transforms $t = 1 + \gamma_0^{bc} x^{-\alpha}$ and $z = \alpha/(2t)$. Then, it follows from (27) that

$$z - \ln z + \nu_p \phi(z) \left(\frac{\alpha}{2} - z\right)^{1-\frac{2}{\alpha}} = g\left(\alpha, \nu_p, \nu_c\right), \quad (28)$$

where $g\left(\alpha, \nu_p, \nu_c\right) = \alpha/2 - \ln\left(\alpha/2\right) + \nu_c\left(1 - \nu_p\right)$ and $\phi(z) = \left(\gamma_0^{bc} z\right)^{2/\alpha}$. Note that the solution of (28) depends on γ_0^{bc} the minimum SNR of the broadcast component, α the pathloss exponent of the broadcast propagation environment, ν_p and ν_c which refers to the cooperation decision parameters as in [5]. In general, the parameters γ_0^{bc} and α are respectively obtained from the targeted capacity at the edge of the service area and the targeted reception environment, which are predetermined by the broadcast operators. Therefore, given the parameters γ_0^{bc} and α, let $S(\nu_p, \nu_c)$ be the solution of equation (28). The solution $S(\nu_p, \nu_c)$ can be tabulated by using the Newton's method to find the solution of (28) as a function of ν_p and ν_c for all values of ν_p and ν_c. An illustration of the tabulated function $S(\nu_p, \nu_c)$ is given in Fig. 4.

Since $S(\nu_p, \nu_c)$ is the solution to (28), the optimal broadcast coverage radius is obtained by applying successively the following inverse transforms $t = \alpha/(2z)$ and $x = \left[\gamma_0^{bc}/(t-1)\right]^{1/\alpha}$ to $S(\nu_p, \nu_c)$, which leads to

$$r_{bc}^* = \left(\frac{\gamma_0^{bc}}{\frac{\alpha}{2S(\nu_p,\nu_c)} - 1}\right)^{\frac{1}{\alpha}}. \quad (29)$$

TABLE II
SIMULATION SETTINGS

Parameter	Value	
Service requirement	$C_{req} = 2$ Mbps	
Target receiver	Portable outdoor	
Service area	$R = 15\ km$	
Distribution of users	Uniform	
Maximum number of users	up to 20000	
	Unicast	**Broadcast**
Network infrastructure	LPLT	HPHT
Network layout	hexagonal grid	single cell
Pathloss exponent	$\alpha = 2.3$	$\alpha = 2.9$
SNR gap (Γ)	3 dB	3 dB
Propagation losses (L_p)	5 dB	9 dB
Transmission power (EIRP)	1000 W	34 kW
Carrier frequency	760 MHz	690 MHz
Bandwidth	10 MHz	8 MHz
Maximum number of RBs in 10 MHz bandwidth	$RB_{max} = 50$	-
Number of RBs per user	$RB_m = 1$	-
Inter site distance (ISD)	2 km	-

V. NUMERICAL RESULTS

To validate the two optimization methods proposed in Sections IV-B1 and IV-B2 to solve the optimization problem $(P1)$, we plot the energy efficiency functions given by (26) and (16). Then, we verify that the optimal broadcast coverage radius given by the analytical expressions (29) and (25) leads to the optimal value of the energy efficiency functions (26) and (16) respectively.

A. Simulation Settings

We consider a delivery of one linear service to a number M of users in a service area. The users are uniformly distributed in the service area as shown in Fig. 1. A minimum capacity $C_{req} = 2\ Mbps$ is required to access the service. Furthermore, a parameter Γ, also known as the SNR gap, is introduced to evaluate the effective capacity of a modulation scheme from the theoretical Shannon capacity [16]. The SNR gap is set to $\Gamma^{bc} = \Gamma^{uc} = 3$ dB. According to (2) and (4), we set the minimum SNR γ_0^{bc} required to receive the service through the broadcast network and the number of resource blocks (RBs) assigned to a user in a LPLT cell RB_m using the minimum service capacity requirement C_{req}. The simulation parameters used are summarized in Table II.

B. Simulation Results

Fig. 5 gives the evolution of the average energy efficiency of the hybrid network as a function of the broadcast coverage radius. The results are presented for the broadcast power consumption minimization approach (Section IV-B1) and the broadcast capacity maximization approach (Section IV-B2).

For both approaches, it can be seen that the analytical expressions of the optimal broadcast coverage radius

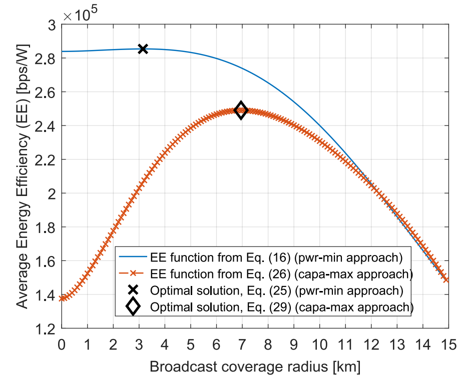

Fig. 5. Average energy efficiency vs broadcast coverage radius; results are presented for the capa-max and pwr-min approaches with $M = 10000$ and $RB_m = 1$.

given by (25) and (29) match the optimal solutions obtained from numerical evaluations of the energy efficiency using the functions (16) and (26). Furthermore, it is also noticed that the maximum energy efficiency is achieved when the unicast and broadcast networks cooperate to deliver the service. Indeed, the optimal broadcast coverage radius is $R_{bc}^* \approx 3$ km for the power minimization approach and $R_{bc}^* \approx 7$ km for the capacity maximization approach. As shown in our previous work [5] on the optimization of the hybrid network capacity, the results presented in Fig. 5 show that enabling cooperation between a unicast and a broadcast networks improves the delivery of linear services in terms of energy efficiency. However, by comparing the two optimization approaches, it is observed that higher energy efficiency is achieved by using the broadcast power consumption minimization approach to optimize the energy efficiency of the hybrid network. As shown in Fig. 5, the power consumption minimization approach outperforms the capacity maximization approach. This is explained by the fact that the latter approach trades some amount of energy against some capacity increase. For the same reason, it is also noticed that the two optimization approaches do not lead to the same optimal broadcast coverage radius $R_{bc}^* \approx 3$ km for the minimization of the power consumption of the broadcast component and $R_{bc}^* \approx 7$ km for the capacity maximization of the broadcast component. Therefore, for the proposed scenario, the general trend for the hybrid network planning optimization advocates for a broadcast radius between 20% and 50% of the total coverage area.

Next, to investigate further the difference between the two optimization approaches, Fig. 6 shows the evolution of the maximum energy efficiency achieved with the optimal broadcast coverage radius as a function of the number of users in the service area. As for Fig. 5, the results are presented for the power minimization approach and for the capacity maximization approach. As shown in Fig. 6, the performance of the two optimization approaches depends on the number M of users in the

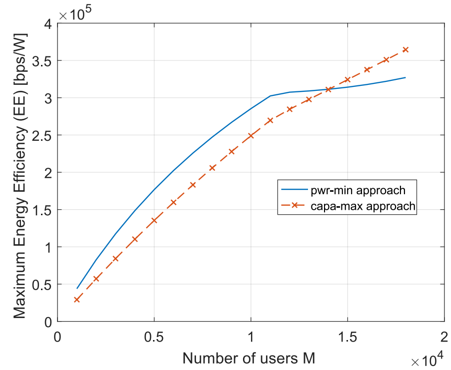

Fig. 6. Maximum energy efficiency vs number of users M; comparison between the capa-max and pwr-min approaches with $RB_m = 1$.

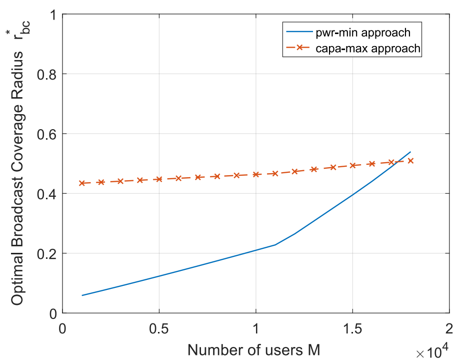

Fig. 7. Optimal broadcast coverage radius vs number of users M; comparison between the capa-max and pwr-min approaches with $RB_m = 1$.

service area. Actually, for a small number of users, the power minimization approach gives better results than the capacity maximization approach. However when the number of users M is high, the capacity maximization approach outperforms the power minimization approach.

On the other hand, focusing on the sensitivity of the optimal broadcast coverage radius to the number of users M in the service area, Fig. 7 represents the evolution of the optimal broadcast coverage radius as a function of M. The results are presented for the two optimization approaches. It can be observed that the optimal broadcast coverage radius (26) obtained using the capacity maximization approach is less sensitive to the variation of the number of users in the service area than the optimal broadcast coverage radius (16) obtained with the power minimization approach. Therefore, from a network planning point of view, the capacity maximization approach may be more appropriate than the power minimization approach to optimize the energy efficiency of a hybrid unicast-broadcast network.

VI. Conclusion

In this paper we have studied the optimization of the energy efficiency of a hybrid network where a broadcast and a unicast networks cooperate to deliver a linear service to users in a given service area. We have proposed two optimization methods to find the optimal coverage area of the broadcast network. The first approach optimizes the energy efficiency metric by maximizing the capacity of the broadcast network. The second approach optimizes the energy efficiency metric by minimizing the power consumption of the broadcast component. We have then derived closed form expressions of the optimal broadcast coverage radius for each approach which have been further validated through numerical evaluations. The results have revealed that networks cooperation improves the average energy efficiency of the hybrid network. For the simulated parameters, the optimal operating point of the hybrid network in terms of the broadcast coverage area have been found to be of about 40% of the total coverage area.

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