Green Radio Communications in a Heterogeneous Wireless Medium

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***Abstract*—Recently, there has been a growing interest in developing energy efficient wireless communication networks, due to environmental, financial, and quality-of-experience considerations, for both mobile users and network operators. The developed solutions in this regard are referred to as green communications, so as to reflect the importance of their environmental dimension. Great potentials for energy efficient communications lie in the today's heterogeneous wireless medium with overlapped coverage from different networks, given the vast diversity in fading channels and propagation losses among mobile terminals and base stations, and in available resources and operating frequency bands at different networks. In such a networking setting, we propose a joint bandwidth and power allocation approach, for uplink and downlink communications, that can promote energy savings for both mobile users and network operators. We discuss several challenging issues, including design and implementation issues. In addition, we present a case study of uplink communications for illustration purposes.**

INTRODUCTION

With the increasing demand on wireless communication services, there exists a wide deployment of wireless access networks. In addition, there are great advances in mobile terminal (MT) design and manufacturing. MTs are currently equipped with processing and display capabilities to support not only voice services but also video streaming and data applications. Moreover, MTs can use their multiple radio interfaces to access different types of wireless networks, such as cellular networks and wireless local area networks (WLANs).

The great evolution in wireless communications and services results in high energy consumption for both mobile users and network operators. For mobile users, there are around 3 billion MTs in the world with annual power consumption of $0.2 - 0.4$ GW [1]. For network operators, the main source of energy consumption is the base stations (BSs), which are responsible for 57% of the total energy consumption in network infrastructures [2], [3], with an average annual energy consumption of about $4.5 - 9$ MWh per BS [1]. The high energy consumption, for mobile users and network operators, has raised environmental, financial, and quality-of-experience (QoE) concerns.

From an environmental perspective, it is estimated that the telecommunication industry is responsible for 2% of the total CO_2 emissions worldwide, and this percentage is expected to double by 2020 [4]. Moreover, the MT rechargeable batteries have an expected lifetime of about 2 to 3 years, which results in high annual disposed batteries, raising high environmental (and financial) concerns. From a financial perspective, mobile operators spend almost half of their operating expenses on energy costs [4]. Finally, from a user QoE perspective, it has been reported that more than 60% of mobile users complain about their limited battery capacity. The problem is further complicated as the gap between the demand for energy and the MT offered battery capacity is increasing exponentially with time [5]. Due to the aforementioned concerns, there is a growing interest in developing energy efficient wireless communication networks. Such energy efficient solutions are referred to as green communication networks.

Currently, the wireless communication medium is a heterogeneous environment with overlapped coverage from different networks [4]. In this networking setting, several opportunities can be exploited to enhance energy efficiency in wireless communications for both mobile users and network operators. This is mainly due to the vast diversity in fading channels and propagation losses among mobile terminals and base stations, and in available resources and operating frequency bands at different networks. In literature, existing green solutions mainly focus on diversity in fading channels and propagation losses and deal with how to optimally allocate transmission power at BSs and MTs, given an allocated bandwidth, to improve energy efficiency. However, further enhancement can be achieved by incorporating the diversity in available resources (e.g., bandwidth) and operating frequency bands through joint bandwidth and power allocation in such a networking environment.

In this article, we discuss energy efficiency in a heterogeneous wireless medium. Specifically, the contributions of this article are as follows:

- We propose a joint bandwidth and power allocation approach, for both uplink and downlink communications, which maximizes energy efficiency for mobile users and network operators using multi-homing capabilities of MTs in a heterogeneous wireless access medium.
- We discuss the challenging design and implementation issues of the proposed joint approach.
- We present a case study to support energy efficient uplink communications for MTs with best effort multi-homing service to illustrate the improved performance of the proposed joint approach, in comparison with power only allocation scheme.

The heterogeneous wireless medium is presented in the next section. Then, the related works are reviewed and the proposed joint approach is highlighted. Design and implementation issues are then discussed. Finally, the case study is investigated and conclusions and future research are given.

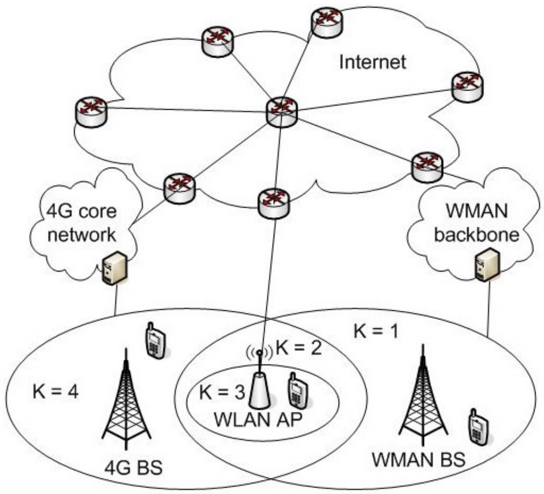

Fig. 1. An illustration of a heterogeneous wireless networking environment.

System Model

In this section, we present the heterogeneous wireless networking environment, including the wireless networks, mobile terminals, available resources, and propagation attenuation.

Wireless Networks

The heterogeneous wireless medium is composed of a set $\mathcal{N} = \{1, 2, \ldots, N\}$ of wireless networks with different access technologies. Examples of these networks include fourth-generation (4G) cellular networks, wireless metropolitan area networks (WMANs), and WLANs, as shown in Figure 1. In such a networking environment, different networks are assumed to be operated by different service providers. Also, different networks operate in different radio frequency bands. Every network has a set of BSs or access points (APs), $\mathcal{S}_n = \{1, 2, \ldots, S_n\}$ for network n, to provide service coverage, radio resource management, user mobility management, and access to the Internet.

With overlapped coverage from the BSs/APs of different networks, different service areas can be distinguished. The set of service areas is denoted as $\mathcal{K} = \{1, 2, \ldots, K\}$. Each service area, $k \in \mathcal{K}$, is covered by a unique subset of BSs/APs of various networks. For instance, as shown in Figure 1, service area 2 is covered by the cellular network and the WMAN, while service area 3 is covered by all the three networks.

Network n ($\in \mathcal{N}$) BS/AP s ($\in \mathcal{S}_n$) has a transmission capacity of C_{ns}. A cooperative networking environment is considered, where the BSs/APs of different networks are connected through a backbone that enables them to exchange their signalling information. This backbone can be provided through the public network (the Internet).

Mobile Terminals

The networking environment has a set, $\mathcal{M} = \{1, 2, \ldots, M\}$, of MTs. Network n BS/AP s has a subset of MTs, $\mathcal{M}_{ns} \subset \mathcal{M}$, that lies in its coverage area.

Each MT is equipped with multiple radio interfaces, and has a multi-homing capability for multiple simultaneous associations with different networks. Hence, a given application of the MT, e.g., data downloading/uploading or video streaming, can be served on the uplink/downlink using multiple networks. This has the following advantages [6]: Firstly, using the multi-homing capability, the available resources at different networks can be aggregated to support bandwidth hungry applications through multiple threads at the application layer; Secondly, multi-homing calls enable better mobility support, to ensure at least one of the used radio interfaces will remain active during the call; Finally, the multi-homing support can reduce the call blocking rate and improve the system capacity.

Each MT, $m \in \mathcal{M}$, has its own home network, but can also get service from other available networks at its location, using the multi-homing capability. The subset of MTs, $\mathcal{M}_{ns}$, in coverage area of network n BS/AP s is divided into $\mathcal{M}_{ns1}$ whose home network is network n, which are denoted as network subscribers, and $\mathcal{M}_{ns2}$ whose home network is not network n, which are denoted as network users.

Radio Resources and Propagation Attenuation

Let B_{nsm}^{UL} (B_{nsm}^{DL}) denote the allocated bandwidth from network n BS/AP s to MT m on the uplink (downlink), where the allocated bandwidth is equal to 0 for $m \notin \mathcal{M}_{ns}$.

Let P_{nsm}^{UL} (P_{nsm}^{DL}) denote the allocated transmission power for communication between MT m and network n BS/AP s on the uplink (downlink). In addition, let Q_{nsm} denote the fixed circuit power that is required to keep the radio interface active for communication between MT m and network n BS/AP s, with $P_{nsm}^{\text{UL}} = P_{nsm}^{\text{DL}} = Q_{nsm} = 0$ for $m \notin \mathcal{M}_{ns}$. The maximum power is denoted by P_{mT} for MT m and P_{nsT} for network n BS/AP s.

The channel power gain between MT m and network n BS/AP s on the uplink (downlink) is denoted by h_{nsm}^{UL} (h_{nsm}^{DL}), which captures both the channel fast fading and path loss. Let the distance between MT m and network n BS/AP s be d_{nsm} and the path loss exponent be α. Hence, the path loss between MT m and network n BS/AP s is given by $d_{nsm}^{-\alpha}$, $d_{nsm} > d_f$ where d_f is the far-field distance of the transmitting antenna. The one-sided noise power spectral density is denoted by N_0.

Green Radio Resource Management

In literature, various energy efficient resource allocation schemes are proposed to satisfy the mobile user required quality-of-service (QoS) at reduced energy consumption. Two categories of solutions can be distinguished in the heterogeneous networking environment, for single-network access and multi-homing access, respectively. First, we review these two types of resource allocation schemes, then we propose joint bandwidth and power allocation.

Single-Network Access

In single-network access energy efficient downlink resource allocation, mobile users connect to a single wireless access network from the available networks in the heterogeneous wireless medium. The assigned network BS/AP to the MT should reduce the total power consumption for all networks. One example of energy efficient single-network access is given in [7], where besides the MT-BS energy efficient assignment problem, each BS may choose between two modes of operation to further save energy, namely point-to-point or point-to-multi-point. For uplink communications, various energy efficient resource allocation schemes are investigated for orthogonal frequency division multiple access (OFDMA) networks, e.g., [8] and [9]. The main objective in these works is to perform sub-carrier allocation and power control to maximize energy efficiency within the OFDMA network. However, the single-network access resource allocation schemes do not fully exploit the available resources in the heterogeneous wireless medium, where an MT can communicate through multiple radio interfaces with different channel conditions and radio bandwidths to enhance the energy efficiency.

Multi-Homing Access

In this case, an MT connects to all available BSs/APs of different networks, and radio resources are allocated to enhance energy efficiency in the networking environment. For instance, in [10], it has been shown that the power-rate curve can be divided into two regions, one with a slow increase in power consumption with the data rate growth, and the other with a dramatic increase in power consumption with data rate growth. Hence, a multi-homing threshold of data rate is determined to start multi-homing transmission for downlink communications in [10]. The multi-homing threshold is based on a ratio of channel gains between the MT and BSs/APs of different networks.

Joint Bandwidth and Power Allocation

In literature, multi-homing energy efficient resource allocation mechanisms, e.g., [10], mainly deal with how to optimally allocate uplink/downlink transmission power by adapting to different channel conditions and path losses among MTs and BSs/APs, given an allocated bandwidth. In addition to exploiting channel conditions and path losses from different BSs/APs in a heterogeneous wireless medium, other resources can be used to enhance energy efficiency, such as the available bandwidths and different operating frequency bands at different BSs/APs. Hence, the resulting energy efficiency can be further improved through a joint bandwidth and power allocation approach. Different MTs can be allocated different amounts of bandwidths on the uplink (downlink), based on the MT (BS) maximum power and the channel conditions, which will affect the associated transmission power allocation.

While joint bandwidth and power allocation approaches have been investigated in literature for OFDMA networks in terms of joint sub-carrier allocation and power control, the existing works are mainly limited to single-network access. As a result, the solutions cannot be directly applied to the heterogeneous networking environment due to the following facts. Firstly, in OFDMA single-network access, the networking environment does not have different service areas with service coverage from unique BSs/APs. Secondly,

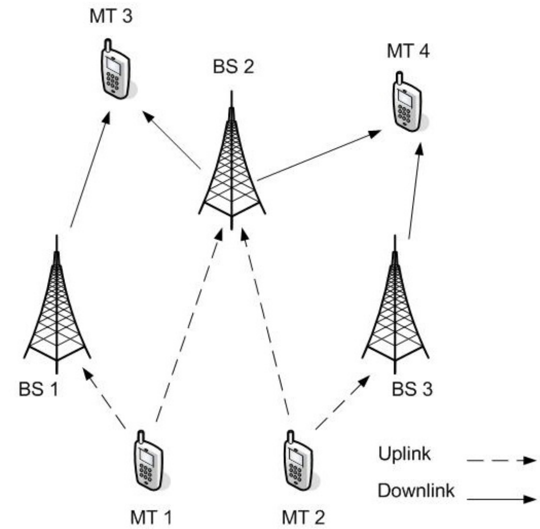

Fig. 2. An illustration of multi-homing uplink and downlink radio communications in a heterogeneous wireless medium.

in a heterogeneous wireless medium, the MT is located at different distances from the BSs/APs of different networks (and hence suffer from different path losses), which affects the resource allocation decision, different from single-network access where an MT is served by only one BS/AP. Finally, in single-network access, the resource allocation decision does not need coordination among BSs/APs of different networks, different from the heterogeneous networking environment. Hence, the heterogeneous networking settings need to be taken into consideration in developing a joint bandwidth and power allocation approach to maximize energy efficiency.

Consider an uplink communications scenario in the heterogeneous networking environment, as illustrated in Figure 2 using MTs 1 and 2. The MTs are located at different distances from the three BSs and experience different channel conditions. In addition, the three BSs have different available bandwidths. In this scenario, the MT with low battery energy and/or bad channel conditions (e.g., MT 1) can be allocated larger bandwidth from different BSs (BSs 1 and 2) than the MT with high available battery energy and/or better channel conditions (e.g., MT 2 which obtains its required bandwidth from BSs 2 and 3), so as to satisfy the required QoS of both MTs, using a multi-homing service. This in turn can reduce energy consumption for the MT suffering low available energy and/or bad channel conditions (MT 1), leading to improved energy efficiency for the networking environment. Hence, the objective of resource allocation is to enhance energy efficiency for the MTs while satisfying their required QoS. In this context, the main factors affecting the resource allocation decision are the MT available energy and required QoS, and the available bandwidths at the BSs, along with channel conditions.

Similarly, for a downlink communications scenario, as illustrated in Figure 2 using MTs 3 and 4, the BSs/APs can allocate their available bandwidths to MTs so as to increase energy efficiency for the different networks. Unlike the uplink communications scenario, the main factors affecting the resource allocation decision include the BS/AP maximum transmission power in addition to their available bandwidths and MTs' required QoS, along with channel conditions.

The joint bandwidth and power allocation approach can be regarded as a cross-layer design since bandwidth is allocated at the network layer from BSs/APs of different networks while transmission power (and circuit power for MTs) is allocated at the physical layer. Such a cross-layer design can exploit opportunistic communication on wireless links, for a set of MTs with different channel conditions and available energy, to enhance energy efficiency of the networking environment. This is possible through back and forth information flow between the network and physical layers. The novelty of the proposed cross-layer design is that it spans not only different layers but also different entities, i.e., BSs/APs of different networks and MTs. Coordination is required among different layers and entities (MTs and networks on one side and different networks on the other side) in the joint bandwidth and power allocation approach. Different networks should coordinate their allocated resources (bandwidth on uplink and downlink and transmission power on the downlink) so as to maximize energy efficiency. Hence, the proposed joint bandwidth and power allocation approach is a cross-layer design in a cooperative networking setting.

In such a networking environment, to develop an energy efficient joint bandwidth and power allocation approach, several challenging issues need to be addressed, as discussed in the next section.

Challenging Issues

There are various technical challenges towards developing a joint bandwidth and power allocation approach. Further studies are required to deal with single-user versus multi-user system, single-operator versus multi-operator system, fairness, centralized versus decentralized architecture, number of MT radio interfaces versus number of available networks, conflicting performance metrics, and computational complexity.

Single-user versus Multi-user System

In literature, several works that investigate energy efficiency for MTs focus on a single-user, e.g., [5], [8], [11]. Hence, given an MT that is allocated a fixed amount of bandwidth, the main objective is to allocate uplink transmission power so as to maximize the MT energy efficiency. As a result, the system model under consideration does not capture the effect of interference among different MTs operating in the same frequency band [9]. Also, a single-user system does not capture the competition among different MTs on radio resources (e.g., bandwidth [12]) so as to satisfy their target QoS at an improved energy efficiency.

Joint bandwidth and power allocation calls for a multi-user system to model the competition among different MTs on the available bandwidth at the BSs/APs of different networks, given their different channel conditions and path losses. For instance, in Figure 2, MTs 1 and 2 (3 and 4) compete on the available bandwidth at BS 2 on the uplink (downlink) to enhance their energy efficiency. However, such a multi-user system further complicates the analysis. Instead of maximizing energy efficiency for a single MT, the objective now is to enhance energy efficiency for a set of MTs, which leads to the fairness issue, as to be discussed.

Single-operator versus Multi-operator System

Most existing works for a heterogeneous wireless medium assume a single network operator. This is evident from how different MTs are treated in the context of radio resource management. In literature, all MTs are treated equally by different networks in the heterogeneous networking environment. However, this does not take into consideration the fact that different MTs are the subscribers of different operators. Hence, with multi-homing services, each operator wants to first support its own subscribers and ensures that they are satisfied with maximum required QoS, while at the same time it supports the subscribers of other networks. For instance, in the context of joint bandwidth and power allocation, a network operator may allocate bandwidth to a mobile user of another operator only if this does not degrade energy efficiency of its own subscribers. This calls for service differentiation among network subscribers and users. One way to accomplish such a service differentiation is through a priority mechanism [6]. In this case, every network operator gives a higher priority in allocating its resources to its own subscribers as compared to the other users. However, such a priority mechanism may degrade the overall energy efficiency of the networking environment as it limits the exploitation of the available resources. Further studies are required on how to maximize the overall energy efficiency, while at the same time supporting service differentiation among network subscribers and users in the networking setting.

Other implications for modeling a multi-operator system are related to fairness and implementation complexity, as discussed in the following.

Fairness

For energy efficient uplink communications in a multi-user and multi-operator system, a popular problem formulation is to maximize the sum energy efficiency for the users in the system, e.g., [8], [9], [12]. However, this objective provides no fairness guarantee for energy efficiency among different MTs. The sum energy efficiency can be maximized by dramatically improving energy efficiency only for a subset of users. One approach to promote fairness is by maximizing the geometric mean of energy efficiency for all MTs, which introduces proportional fairness among all users [12]. However, such a definition is appropriate only for a single-operator system where all MTs are the subscribers of the same network. In a multi-operator system, given that MTs are the subscribers of different networks, it is required to guarantee fairness among the subscribers of the same operator and among the users of other operators. How to incorporate such a notion of fairness in the problem formulation needs further investigation.

As for energy efficient downlink communications, most existing studies make no distinction in the amounts of saved

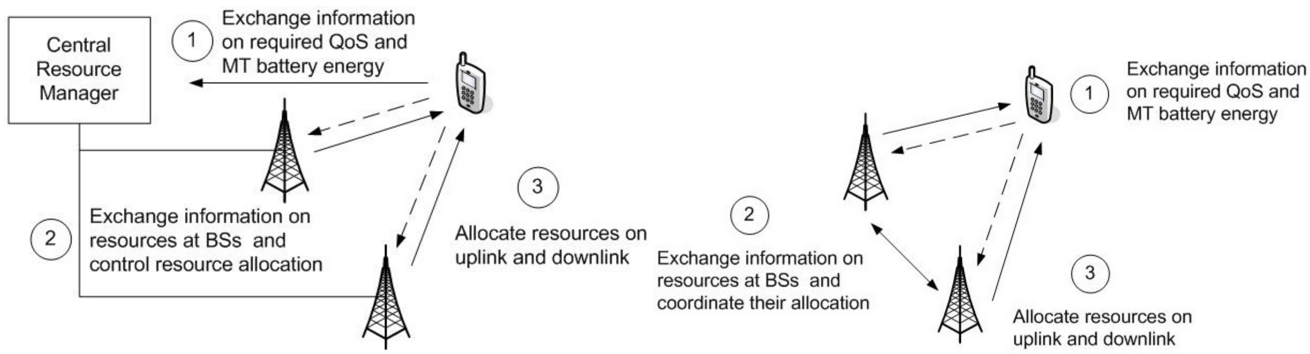

Fig. 3. Centralized and decentralized implementations.

energy for different operators, with the main objective to reduce the total energy consumption in the networking environment [4]. However, this can be satisfied by minimizing energy consumption of one operator at the expense of energy consumption of another operator. It is desired that green communications result in mutual benefits for all operators. The degree of cooperation among different operators is determined based on the attained utility by each operator. How to motivate various operators to cooperate among each other to enhance the overall energy efficiency in the networking environment while maximizing the achieved utility for each operator should be studied.

Centralized versus Decentralized Implementation

Joint bandwidth and power allocation can be implemented in a centralized or decentralized architecture, as shown in Figure 3. In the centralized implementation, a central resource manager is responsible for the resource allocation decisions. The central resource manager has global information of the available resources (e.g., radio bandwidth and maximum transmission power) at BSs/APs of different networks. Also, the central resource manager has information about the required QoS of all MTs in service, the available energy of each MT for uplink communications, and the channel conditions among the MTs and BSs/APs of different networks. Given the gathered information, the central resource manager allocates resources from different networks so as to maximize energy efficiency in the overall networking environment and satisfy the required QoS for all MTs. However, the central resource manager is not a practical solution when different networks are operated by different service providers [6]. A central resource manager that controls the operation of BSs/APs of different networks raises some concerns: 1) The central resource manager creates a single-point of failure, hence if it fails the whole multi-homing service fails; 2) The operator in charge of the operation and maintenance of the central resource manager will control the resources of other networks; and 3) Changes are required in the structures and operations of different networks in order to account for the central resource manager.

Given the aforementioned concerns, a decentralized resource management is a more practical and flexible solution. In a decentralized implementation, BSs/APs of different networks make their resource allocation decisions based on their available local information. Better resource allocation decisions can be made through information exchange among BSs/APs of different networks on one side and between BSs/APs and MTs on the other side. However, high signalling overhead is expected in a dynamic environment with user arrivals and departures and channel time varying conditions. In addition, a decentralized mechanism may not converge to an optimal solution in such a dynamic environment. Hence, further investigation is required on how to reduce the associated signalling overhead and guarantee the decentralized solution convergence given the data traffic dynamics, user mobility, and channel conditions.

Number of MT Radio Interfaces versus Number of Available Networks

Existing research works for a heterogeneous wireless medium assume that the number of MT radio interfaces is equal to the number of available BSs/APs from different networks. This reduces the computational complexity of the problem from a resource allocation perspective as we deal with a non-linear program (instead of dealing with a mixed-integer non-linear program in case of unequal number of radio interfaces and available BSs/APs). However, the assumption may not be realistic. An MT may have a cellular and WLAN radio interfaces, yet it lies in the coverage area of multiple BSs/APs of cellular networks and WLANs. In this scenario, the MT should select one cellular network BS and one WLAN AP from all available BSs and APs. One solution is exhaustive search, where the MT tries all combinations of cellular network BS and WLAN AP and selects the pair that maximizes energy efficiency while satisfying the required QoS. However, in a multi-user multi-operator system, such an approach incurs high computational complexity, and requires high signalling overhead in a decentralized architecture. Hence, more efficient techniques should be developed to properly select BSs and APs among all the available ones.

Conflicting Performance Metrics

Maximizing energy efficiency may conflict with other performance metrics. In general, the objective is to enhance energy efficiency while not violating a target performance metric. In this case, the cross-layer design can involve other layers, in addition to the network and physical layers. For instance, some performance metrics that can be measured at the application layer include:

- Delay time: Maximizing energy efficiency results in reducing the transmission power which in turns reduces the achieved data rate. A reduced data rate can violate a required transmission deadline for delay sensitive applications. As a result, it is required to satisfy a target delay time;
- Video quality: For video streaming applications, using a lower transmission data rate for enhanced energy efficiency may result in video packets missing their transmission deadlines. Hence, the achieved video quality is degraded. As a result, it is required to maintain the resulting video quality higher than a target value.

In this case, coordination is required among at least three layers of the networking protocol stack, which further complicates the approach. One way to simplify the cross-layer design is to map the target performance metric to a required signal-to-noise ratio (SNR). This reduces the number of involved layers in the cross-layer design back to two layers, namely network and physical layers. Hence, the problem in hand is how to jointly allocate bandwidth at the network layer and transmission power at the physical layer to radio interfaces of different MTs from BSs/APs of different networks, so as to maximize energy efficiency in the networking environment while satisfying a target SNR for each MT.

Computational Complexity

The joint bandwidth and power allocation approach has a higher computational complexity as compared to a power only allocation scheme. From a resource allocation perspective, the increased computational complexity is mainly due to the increased number of decision variables (bandwidth and power allocation for all radio interfaces in the joint approach versus only power allocation for all radio interfaces) and constraints. Specifically, in uplink resource allocation, the joint bandwidth and power allocation should include the network-side constraints (e.g., the total allocated bandwidth satisfying the BS/AP transmission capacity) in the problem formulation, whereas the power only allocation mainly deals with the MT-side constraints in terms of the MT available energy and required QoS.

For computational efficiency, the joint bandwidth and power allocation problem can be decomposed into two steps, focusing on the network-side and the MT-side, respectively [13]. In the first step, bandwidth is allocated from the BSs/APs of different networks, on the uplink/downlink, to the MTs, given the required QoS of MTs. Hence, this step mainly focuses on the network-side resource allocation (bandwidth) and constraints while satisfying the required QoS, which can be implemented in the network layer. Based on the allocated bandwidth, power allocation is performed in the second step so as to enhance energy efficiency of the MTs in the uplink and the BSs/APs in the downlink. For uplink resource allocation, this step mainly focuses on the MT-side constraints (MT total available energy) and can be implemented in the physical layer. The resource allocation approach iteratively executes these two steps until energy efficiency is maximized.

A Case Study

In this section, we present a case study of the joint bandwidth and power allocation for uplink communications. The main purpose is to demonstrate the superior performance of the joint bandwidth and power allocation in comparison with power only allocation. In this first step of research, we do not include a priority mechanism in the problem formulation to differentiate network subscribers and other users. Hence, all MTs are treated equally by all operators. Also, it is assumed that the number of radio interfaces for each MT is the same as the number of available BSs/APs at its location and a central resource manager is used for resource allocation decisions. The problem deals with a set of best effort services, such as in a data upload scenario. Since we focus only on an uplink scenario, we omit the superscripts UL and DL from all mathematical symbols.

Consider a heterogeneous wireless networking environment, as shown in Figure 1. For a given MT m, energy efficiency, η_m, is defined as the total achieved data rate per unit power consumption. The achieved data rate, R_m for MT m, is defined as the sum of the achieved data rates on all radio interfaces of the MT, based on Shannon formula. In addition, the MT total power consumption, P_m, is given by the sum of transmission and circuit power consumptions over all active radio interfaces of the MT. In the multi-user system, we aim to promote fairness among users based on the max-min formulation. Hence, we want to determine the bandwidth allocation from BSs/APs to a set of MTs and the transmission power allocation from these MTs to their multiple radio interfaces to maximize the minimum energy efficiency among all MTs in service. The allocated bandwidth from different BSs/APs should not violate their transmission capacity. Moreover, the total power consumption of MT m should satisfy its maximum power level. Hence, the joint bandwidth and power allocation problem is given by

$$
\begin{aligned}
\max_{B_{nsm}, P_{nsm}} \quad & \{\min_{m\in\mathcal{M}} \eta_m\} \\
s.t. \quad & \sum_{m\in\mathcal{M}_{ns}} B_{nsm} \le C_{ns}, \quad \forall n \in \mathcal{N}, s \in \mathcal{S}_n \\
& \sum_n \sum_s \{P_{nsm} + Q_{nsm}\} \le P_{mT}, \quad \forall m \in \mathcal{M} \\
& B_{nsm}, P_{nsm} \ge 0, \quad \forall n, s, m
\end{aligned}
\tag{1}
$$

with

$$
\eta_m = \frac{\sum_n \sum_s B_{nsm} \log_2 (1 + \frac{P_{nsm} h_{nsm}}{N_0 B_{nsm}})}{\sum_n \sum_s \{P_{nsm} + Q_{nsm}\}}.
$$

The problem formulation in (1) is referred to as a *max-min fractional program* [14]. The problem has an objective function with concave numerator and affine denominator with linear constraints, leading to a *concave-convex fractional program*. A parametric approach and a Dinkelbach-type algorithm can be used to solve (1) [14].

TABLE I
SYSTEM PARAMETERS

Parameter	B_1	B_2	α	N_0	$Q_{n,m}$	M
Value	10 MHz	5 MHz	4	-174 dBm/Hz	100 mW	5

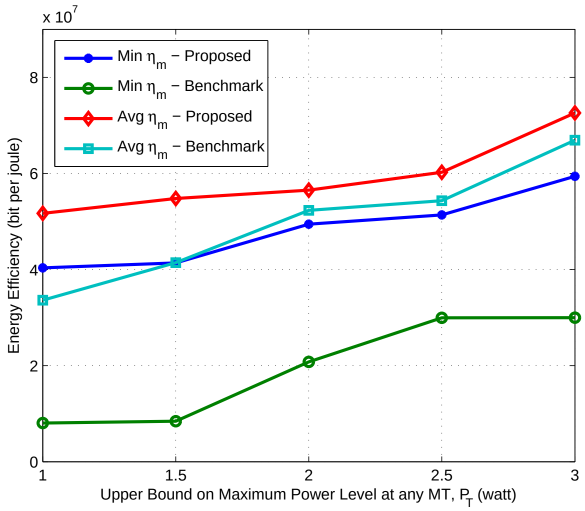

Fig. 4. Energy efficiency versus the upper bound of the maximum power level, P_T, at any MT [13].

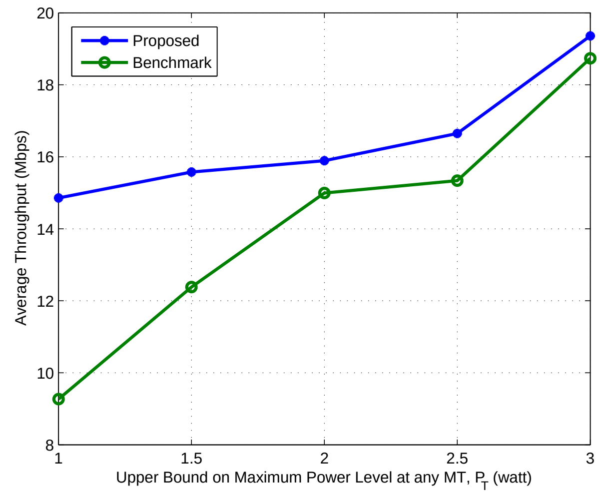

Fig. 5. Throughput versus the upper bound of the maximum power level, P_T, at any MT [13].

In the following, we compare the performance of the proposed joint bandwidth and power allocation approach with power only allocation. In the power only allocation scheme as benchmark, every BS/AP uniformly distributes its total available bandwidth to all MTs in its coverage. As the bandwidth is already allocated from all BSs/APs to each MT, there exists no interaction among different MTs in power allocation. As a result, every MT independently allocates its transmission power to its radio interfaces so as to maximize its own energy efficiency, i.e., the benchmark is a single-user system, different from the proposed approach which is a multi-user system.

We evaluate the performance of the proposed approach, by solving (1), and benchmark via computer simulations, in a service area that is covered by two BSs from two networks, i.e., $n = \{1, 2\}$. MTs are distributed randomly in the service area and the wireless channels between the radio interfaces of different MTs and the BSs suffer from Rayleigh fading. The system parameters used in the simulation are given in Table I. Let P_T denote the upper bound of the MT maximum power level. In the simulations, we vary P_T and study the system performance in terms of the achieved energy efficiency and throughput. Each MT has a maximum power level P_{mT} randomly chosen in the range $[0, P_T]$.

Some simulation results are shown in Figures 4 and 5. The proposed approach clearly outperforms the benchmark, as the proposed approach jointly optimizes bandwidth and power allocation among different MTs to maximize the minimum achieved energy efficiency. On the other hand, in the benchmark, each MT only performs power allocation, independent of other MTs, to maximize its own energy efficiency. Moreover, the fairness consideration of the proposed approach is demonstrated versus the benchmark, as the gap between the minimum achieved energy efficiency and the average energy efficiency is much smaller for the proposed approach, than that for the benchmark. Finally, the achieved throughput of the proposed approach is higher than the benchmark, as the proposed approach allocates bandwidth based on channel conditions of different MTs.

CONCLUSIONS AND FUTURE RESEARCH

Environmental, financial, and QoE considerations have motivated research in the area of energy efficient (green radio) communications. The heterogeneous wireless access medium has great potentials in improving energy efficiency while satisfying the QoS of mobile users. Multi-homing services can aggregate bandwidth from different networks, enable better mobility support, and reduce energy consumption for mobile users and network operators. In addition to exploiting different channel conditions and path losses among MTs and BSs/APs of different networks, the available bandwidth and operating frequency bands at different networks can further enhance energy efficiency. Hence, a joint bandwidth and power allocation approach results in a significant advantage in energy efficient communications over the power only allocation scheme. In joint bandwidth and power allocation for uplink and downlink communications in a heterogeneous networking setting, there are many challenging technical issues that need further studies, including fairness in energy efficiency among MTs, achieving mutual benefits among network operators, decentralized implementation with reduced signalling overhead, conflicting performance metrics, and implementation complexity.

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