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A bandwidth allocation and energy-optimal transmission rate scheduling scheme in multi-services wireless networks ☆

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ABSTRACT

The energy-saving of mobile devices during their application offloading process has always been the research hotspot in the field of mobile cloud computing (MCC). In this paper, we focus on the scenario where multiple mobile devices with MCC and non-MCC services coexist. A bandwidth allocation and the corresponding transmission rate scheduling schemes are proposed with the objectives of simultaneously maximizing the overall system throughput and minimizing the energy consumption of individual mobile device with MCC service. To allocate the bandwidth to all mobile devices, two different algorithms are proposed, i.e., 0–1 integer programming algorithm and Lagrange dual algorithm. The transmission rate scheduling scheme for mobile device with MCC service is presented based on reverse order iteration method. The numerical results suggest that energy consumed by individual mobile device with MCC service can be remarkably saved while the overall system throughput can also be maximized. Moreover, the results show that 0–1 integer programming algorithm can get greater system throughput but has higher computational complexity, which means the algorithm is more suitable for small-scale systems, whereas Lagrange dual algorithm can achieve a good balance between the performance and computational complexity.

1. Introduction

The constant emergence of wireless applications places greater demands on the capabilities of mobile devices, such as computation, storage and battery life. Due to the limited physical size, however, mobile devices themselves cannot fully meet the requirements of these applications. Mobile cloud computing (MCC) technology offers an opportunity to solve the problem. On the MCC platform, as illustrated in Fig. 1, each mobile device is associated with a clone in the cloud, which can execute the mobile applications on behalf of the device [1–3]. A mobile device can transmit the data that is needed by the application through the wireless networks to the cloud for execution. This is commonly referred as application offloading [1–3]. However, comparing with the vigorous development of wireless applications, the short battery life has always been the bottleneck of mobile devices [1–12]. Consequently, much attention has been devoted to conserving the energy for mobile devices during their application offloading process.

Although there are many factors that may affect the energy consumption, the two major ones should be the transmission power and the transmission time [4–9]. Since the energy is the accumulation of transmission power over time, it can be optimized based on a tradeoff between the transmission power and the transmission time. The transmission power is related to the transmission rate and the channel states during the transmission process [6]. Authors in [11] design an algorithm for multi-stage big data processing platforms to adaptively determine and cache the most valuable intermediate datasets that can be reused in the future. Thus, no matter what kind of wireless network technology is adopted, the optimization of the energy is essentially the scheduling of the transmission rate following the basic idea that the mobile device should transmit more data when the channel state is “good” and transmit less data when the channel state is “bad” [4–9].

Following the above idea, in order to save the energy consumption during application offloading, the relation among the energy

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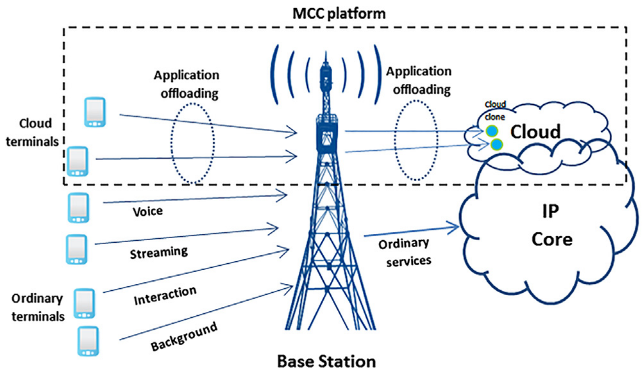

Fig. 1. Architecture of a wireless network with cloud and ordinary terminals.

consumption, the transmission rate, and the channel states first needs to be established. According to the existing literatures, the relation is mostly based on empirical energy-rate formula [4,8,9] or practical systems, such as the widely-used Long-Term Evolution (LTE) cellular systems [6,7]. Then, a certain method should be adopted to calculate the optimal energy consumption and the corresponding transmission rate in each time slot. Dynamic programming (DP) method [4,8], heuristic method [5] and some other common-used method are usually used in existing literatures. These methods are mainly designed to overcome the influence caused by the stochastic feature of the wireless fading channels on the estimation of energy consumption.

However, we can know from Shannon formula that the relation between the energy consumption and the transmission rate in each time slot is affected not only by the channel states but also by the transmission bandwidth. Authors in [6] reach the conclusion that under the same condition, the energy consumption is inversely proportional to the bandwidth the mobile device occupies. Authors in [8] further figure out a specific threshold policy, i.e., when the allocated bandwidth is less than a threshold, application offloading can save energy; otherwise the application should be executed locally. When investigating the energy-saving of mobile devices during application offloading, few researches consider the allocation of bandwidth of the actual system, which means they don't consider the influence of other mobile devices with non-MCC services, such as voice, streaming, interaction and background [13]. However, in actual wireless networks, this is a vital factor.

For simplicity, the mobile devices with MCC services will be referred to as cloud terminals and the mobile devices with non-MCC services will be called ordinary terminals below. As shown in Fig. 1, the bandwidth has to be allocated among cloud terminals and ordinary terminals, and the allocation criterion is to maximize the system throughput while ensuring the transmission rate requirement of them [13,14,17]. Accordingly, in a wireless network that accommodates ordinary terminals and cloud terminals, it is required to develop a bandwidth allocation scheme and the corresponding transmission rate scheduling scheme to satisfy the aforementioned allocation criterion and simultaneously minimize the energy consumption of every individual cloud terminal. To the best of our knowledge, there are no research about this.

Considering the bandwidth allocation for both cloud and ordinary terminals will bring some problems. First, the objectives of the designed scheme, namely, minimizing the energy consumption of individual cloud terminal and maximizing the overall system throughput, i.e., the sum of the transmission rate of the ordinary terminals, are incompatible. Second, the objectives are not unified in time scale. The energy consumption of a cloud terminal is an accumulated value over time whereas the system throughput is an instantaneous value in a scheduling period (i.e., time slot). The disunity in time scale makes the common-used greedy algorithm hard to be adopted. Third, the coexistence of multiple cloud terminals whose active time slot and deadline are different makes the problem more complex.

To address the problems above, we first formulate the bandwidth allocation principle into a multi-objective optimization model. As the energy consumed by an individual cloud terminal should be less than a threshold, otherwise executing the application locally will save more energy [8], we consequently change the objective of minimizing the energy consumption to the constraint that the energy consumption should be less than a threshold. Then, for cloud terminals, we utilize the reverse order iteration method to obtain the optimal transmission rate in each time slot and the corresponding optimal energy consumption which only depend on the allocated bandwidth in each time slot. Namely, we convert the model into a bandwidth allocation problem in each time slot and the time scales of objectives are unified. In order to solve the bandwidth allocation problem, we propose two algorithms in this paper, i.e., 0–1 integer programming algorithm and Lagrange dual algorithm.

The main contributions are summarized as follows.

(1) We investigate the energy-optimal transmission rate scheduling scheme of application offloading in multi-services wireless networks
(2) We propose a transmission rate scheduling scheme for cloud terminals based on reverse order iteration method.
(3) We propose two different bandwidth allocation algorithms.

The remainder of this paper is organized as follows. Section 2 describes the system models. In Section 3, we first find the relationship among the optimal transmission rate, the minimum energy consumption and the allocated bandwidth for each cloud terminal, and then we propose two different algorithms to allocate bandwidth. Section 4 gives the numerical results and analysis. Section 5 concludes this paper.

2. System model

In this paper, we consider the Single-Carrier Frequency Division Multiple Access (SC-FDMA) technology, which is used in the LTE network as its uplink multiple access technology. We only discuss the bandwidth allocation and the rate scheduling scheme in uplink transmission and the sub-channels we mention in the following parts are those who can really transmit data. In SC-FDMA networks, the sub-channels allocated to a certain terminal must be adjacent to each other and the transmission power of these sub-channels must be equal [13,14]. Note that the proposed scheme can also apply to Orthogonal Frequency Division Multiple Access (OFDMA) networks through minor modifications on the transmission power adjustment among sub-channels allocated to a terminal.

The relation between the transmission rate and the transmission power of a mobile terminal in SC-FDMA networks can be expressed as [13,15]

$$R_t = \sum_{k \in \mathcal{K}_t} B \times \log_2 \left[1 + \frac{P_t}{K_t} \times \frac{g_{k,t}}{N_0 \times B} \right] \quad (1)$$

where R_t, P_t denotes the transmission rate and the transmission power in time slot t, respectively; $\mathcal{K}_t$ denotes the set of sub-channels allocated to the terminal with the bandwidth B of each sub-channel and K_t denotes the number of sub-channels in $\mathcal{K}_t$; $g_{k,t}$ denotes the channel gain of sub-channel k in time slot t; N_0 denotes the noise power spectral density.