Enabling Green Heterogeneous Wireless Networks

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***Abstract*—This paper focuses on a significant research topic "green/energy efficient wireless networks" that has drawn huge attention due to important environmental, financial, and quality-of-experience (QoE) considerations. We mainly target energy efficiency in a heterogeneous wireless medium with overlapped coverage due to the co-existence of different cells (macro, micro, pico, and femto), networks (cellular networks, wireless local areas networks, wireless metropolitan area networks), and technologies (radio frequency (RF) and visible light communications (VLC)). This paper summarizes the authors' research work in green networking via radio resource and network management solutions. First, we present green multi-homing radio resource management mechanisms in downlink and uplink for both RF and RF-VLC heterogeneous networks. These techniques can be adopted at high call traffic load conditions. Then, we present balanced dynamic planning framework that can be adopted at low call traffic load conditions.**

Keywords–Green networking; multi-homing resource allocation; dynamic planning.

I. INTRODUCTION

The increasing demand for wireless communications services during the past decade has led to a wide deployment of wireless access networks [1]. From the network operator point of view, the base station (BS) is the main source of energy consumption in the wireless access network (with almost 57% of the operator total power consumption) [2] [3] [4]. From the user perspective, high energy is consumed by mobile terminals (MTs) in video and data calls. This high energy consumption of BSs and MTs has raised environmental, financial, and quality-of-experience (QoE) concerns.

From an environmental perspective, the telecommunications industry contributes by 2% of the total CO_2 emissions worldwide, and such a percentage is expected to double by 2020 [5]. In addition, the expected lifetime of the MT rechargeable batteries is approximately $2-3$ years and results in $25,000$ tons of disposed batteries annually [6]. Moreover, the high energy consumption in wireless networks presents a source of high heat dissipation and electronic pollution [7]. From a financial point of view, technical reports have demonstrated that the cost of energy bills of service providers ranges from 18% (in mature markets in Europe) to 32% (in India) of the operational expenditure (OPEX) [8] [9] and reach up to 50% of the OPEX for cellular networks outside the power grid [10] [11]. From a user QoE perspective, reports indicate that over 60% of mobile users complain about their limited battery capacity due to the increasing gap between the MT offered battery capacity and the mobile user demand for energy [12].

Such concerns have motivated an increasing demand for energy efficient (green) solutions in wireless access networks. The research efforts carried out in this regard are referred to as green network solutions. The main objectives of such a paradigm are: 1) reducing energy consumption of communication devices (e.g., BSs and MTs) and 2) taking into account the environmental impacts of the proposed solutions. In this paper, we present our most recent research efforts in this direction for both high and low call traffic load conditions. At a high call traffic load condition, radio resource (e.g., power and bandwidth allocation) management techniques are adopted, while network management solutions (e.g., dynamic planning) are applied.

The rest of this paper is organized as follows. Section II reviews the related work in green networks at both high and low call traffic load conditions. Section III summarizes our research contributions for green solutions at a high call traffic load condition via a multi-homing radio resource allocation. Section IV summarizes our research contributions at a low call traffic load condition via a balanced dynamic planning approach. Finally, Section V presents conclusions and future research directions.

II. GREEN SOLUTIONS: STATE-OF-THE-ART

This section reviews state-of-the-art green networking solutions and analytical models from network operator and mobile user perspectives at different traffic load conditions. Overall, two categories can be distinguished for the green networking solutions based on the call traffic load condition. Scheduling techniques are adopted at a high and/or continuous call traffic load, while resource on-off switching techniques are implemented at a low and/or bursty call traffic load [13].

Different scheduling techniques are employed at a high call traffic load condition. BSs can save energy via a margin adaptive strategy where the objective is to minimize the transmission power consumption while ensuring an acceptable service quality for mobile users [14]. Furthermore, in a heterogeneous wireless medium with overlapped coverage from different BSs, energy saving can be achieved by assigning MTs to the BSs that consume the least transmission power [15]. On the other hand, MTs can save energy through sub-carrier allocation and carrier aggregation techniques in orthogonal frequency division multiple access (OFDMA) networks [16],

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while in time division multiple access (TDMA) networks, MTs save energy by opportunistic transmission [17]. Moreover, BSs and MTs can save energy in a heterogeneous wireless medium through multi-homing resource allocation. In this case, the MT simultaneously connects to multiple BSs and aggregates the offered resources from these BSs to achieve the required data rate. BSs can save energy in the downlink by coordinating their transmission power for different radio interfaces of the MT [18]. Similarly, MTs can save energy in the uplink through efficient transmission power allocation to different radio interfaces. In addition, small cell deployment can save energy for both Bss and MTs by dividing the cell into several tiers of smaller cells, and hence, reducing the transmission range for BSs and MTs [19]. In this context, cell-on-edge deployment can achieve more energy saving than uniform cell deployment [19]. The main research challenge here is how to deal with cross-tier interference between macro and small cells [20]. Another approach that reduces the transmission range for BSs and MTs and hence achieves energy saving relies on relays or device-to-device (D2D) communications. When fixed relays are deployed for energy saving, two research issues must be handled, namely, optimal relay placement and relay selection for minimum transmission power consumption [21]. Employing MTs as relays necessitates adopting incentive techniques to motivate selfish mobile users to participate in data forwarding [22]. In D2D communications, mobile nodes in close proximity communicate directly with each other without going through a BS. In this context, interference issues with cellular users should be tackled for in-band underlay D2D communications [23], while efficient radio resource partitioning should be adopted for in-band overlay D2D communications [24], and coordination techniques should be employed for out-band D2D communications [25]. Moreover, BSs and MTs can save energy through efficient scheduling among multiple energy sources. For instance, the network operator can rely on multiple electricity retailers and decides how much electricity to procure from each retailer to power the BSs using minimum cost and CO_2 emissions [26]. Also, using a mixture of on-grid and green energy sources can lead to energy saving by maximizing the utilization of green energy [27]. In this case, complementary renewable sources (e.g., solar cells and wind turbines) can be used to power the BSs [28]. For MTs, multiple batteries can be employed where energy efficiency is improved due to the batteries recovery effect [29].

At a low and/or bursty call traffic load condition, resource on-off switching is adopted for energy saving. Specifically, dynamic planning can be adopted where BSs with low call traffic load can be switched off and the remaining active BSs can support the ongoing calls [30]. Dynamic planning mainly involves two phases, namely, user association and BS operation. In user association, MTs are concentrated in a few BSs to enable switching off lightly loaded BSs [31]. However, such a problem is highly complex due to its mixed-integer nature. Consequently, greedy algorithms are adopted to enable a suboptimal switching decision. In this context, greedy algorithms can be based on user-BS distance decision criterion [32], network impact decision criterion [33], and coverage hole avoidance decision criterion [34]. Following the user association phase, three tasks should be carried out in the BS operation phase, namely, accommodating future traffic loads via bandwidth reservation [5], determining BS wake-

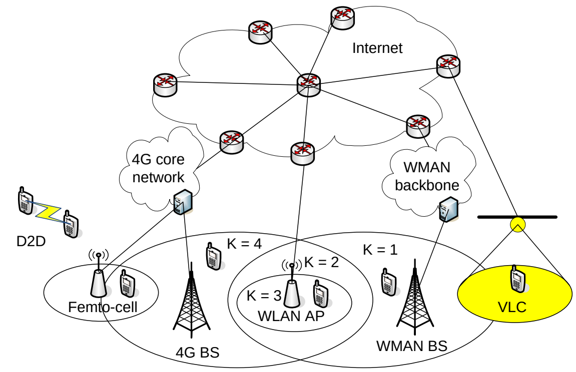


Figure 1. Illustration of a heterogeneous wireless network [30].

up instants [35], and implementing the BS on-off switching decision via BS wilting and blossoming [36]. For MTs, energy saving can be achieved by on-off switching of the MT radio interface according to traffic load condition. For downlink traffic, the MT switches off its radio interface when no data packets are available for the MT at the serving BS [37]. To further elongate the sleep duration, and hence, save more energy, traffic shaping techniques can be adopted either at the MT side [38] or at the BS side [39] to enable a more bursty traffic. For uplink traffic, the MT performs joint optimization of radio interface on-off switching, transmission power control, and modulation and coding scheme selection [40]. In presence of bi-directional traffic, a finite general Markov background process is employed to model the uplink and downlink traffic activity [41].

III. GREEN MULTI-HOMING RESOURCE ALLOCATION

Currently, the wireless communication medium is a heterogeneous environment with overlapped coverage from different cells (macro, micro, pico, and femto), networks (cellular networks, wireless local area networks (WLANs), and wireless metropolitan area networks (WMANs)), and technologies (radio frequency (RF) and visible light communication (VLC)), as shown in Figure 1.

In a multi-homing access, the MT connects to all available BSs of different networks, and radio resources (e.g., bandwidth and power) are allocated to improve energy efficiency in the networking environment. In the following, we highlight our recent research efforts in green multi-homing resource allocation for uplink and downlink scenarios and for RF and RF-VLC inter-networking environments.

A. Green Uplink Multi-homing

One limitation with the existing mechanisms is that they focus mainly on optimal power allocation to the MT different radio interfaces, assuming an allocated bandwidth. These research efforts aim to exploit the diversity in fading channels and propagation losses between the MT and different BSs to improve the uplink energy efficiency. Further improvement can be achieved due to the disparity in available bandwidth at the BSs of different networks. This necessitates a joint optimization framework for bandwidth and power allocation to maximize uplink energy efficiency. Moreover, the existing aggregation schemes deal with a situation where all radio resources are operated by the same service provider. Thus, centralized radio resource allocation mechanisms can be employed. In a heterogeneous networking environment, the aggregated resources belong to different service providers. As a result, novel decentralized mechanisms should be investigated to enable coordination among MTs and BSs of different networks to satisfy the required QoS in an energy efficient manner. One challenge that faces implementing such a decentralized mechanism is the associated high computational complexity. Finally, the existing research deals with a single-user system where the objective is to maximize energy efficiency for a given mobile user. In practice, multi-user systems exist where multiple mobile users compete on the available bandwidth to satisfy their target service quality in an energy efficient manner. In this context, maximizing the total (sum) energy efficiency of all MTs may not be a good choice since the sum energy efficiency can be maximized while some MTs achieve very low energy efficiency.

In our research [42], we investigate the problem of joint uplink bandwidth and power allocation to maximize energy efficiency of a set of MTs with multi-homing capabilities. In such a multi-user system, the objective is to maximize the performance of the MT that achieves the minimum energy efficiency in the geographical region. For each MT, energy efficiency is defined as the ratio of the total achieved data rate to the total power consumption. The total achieved data rate for each MT is the summation of the data rates achieved on each radio interface of the MT. Power consumption of the MT accounts for both circuit and transmission power consumption, and circuit power consumption has two parts, namely, fixed power consumption and dynamic (bandwidth scaling) power consumption. The resource allocation framework should satisfy the minimum required data rate for each MT and should respect the power consumption constraint for each MT and the bandwidth availability constraint for each BS. The optimization problem in [42] is shown to be a max-min concave-convex fractional program. Through a parametric approach, the problem is transformed into a convex optimization problem. The optimal solution can be obtained using an iterative Dinkelbach-type algorithm. For each step, the convex optimization problem should be solved to determine the joint bandwidth and power allocation that satisfy the aforementioned constraints for a given parameter. The decomposition theory is applied to solve the optimization problem, which is decomposed into a power allocation sub-problem and a bandwidth-allocation sub-problem. Through Lagrangian multipliers, the two sub-problems are iteratively solved to satisfy the minimum required data rate. Due to computational complexity, a sub-optimal framework is designed, which is based on determining the optimal Lagrangian multipliers for maximizing the minimum average energy efficiency while satisfying the average data rate constraint. Such Lagrangian multipliers are then used in an online phase to allocate radio resources to MTs according to the current channel conditions.

Simulation results in [42] have indicated an improved energy efficiency performance over a power only allocation benchmark, as shown in Figure 2, along with an improved satisfaction index for the mobile users.

B. Green Downlink Multi-homing

Cooperative multi-homing radio resource allocation mechanisms can achieve higher energy saving compared with the single-network radio resource allocation mechanisms thanks to the disparity in wireless channels and available radio resources. However, the main limitation with the existing cooperative mechanisms is the assumption that different networks are willing to cooperate unconditionally so as to minimize the total (sum) power consumption in the geographical region. While this assumption can be true when different networks are operated by the same service provider, however, in presence of multi-service providers, cooperation is adopted only if mutual benefits can be achieved. In addition, existing research relies mainly on power allocation to minimize the consumption, and hence, employs solely the disparity in channel conditions. Finally, decentralized radio resource allocation mechanisms should be adopted in such a multi-operator environment.

In our research [43], we investigate developing a win-win cooperative joint radio resource (e.g., bandwidth and power) allocation mechanism that ensures mutual power saving for all cooperating network operators. The problem is formulated as a Nash bargain game that maximizes energy saving for cooperating networks (compared with the non-cooperative case) while ensuring that mutual power saving is achieved for all participants. An asymmetric Nash bargain game is employed to enable different networks to have different influence (bargain power) to affect the resulting power saving for each network. The rationale behind such an approach is to account for the fact that some networks may have more capabilities (e.g., available bandwidth) than other networks and this factor should be accounted for in the problem formulation. The joint bandwidth and power allocation framework should satisfy the minimum required data rate of mobile users and the total bandwidth and power consumption constraints for the BSs. The Nash bargain game in [43] is shown to have a unique bargain point, and the problem is transformed into an equivalent convex optimization program. Using the decomposition theory, the joint bandwidth and power allocation framework is decomposed into two subproblems for bandwidth allocation and power allocation that are iteratively solved until the minimum required data rate is satisfied.

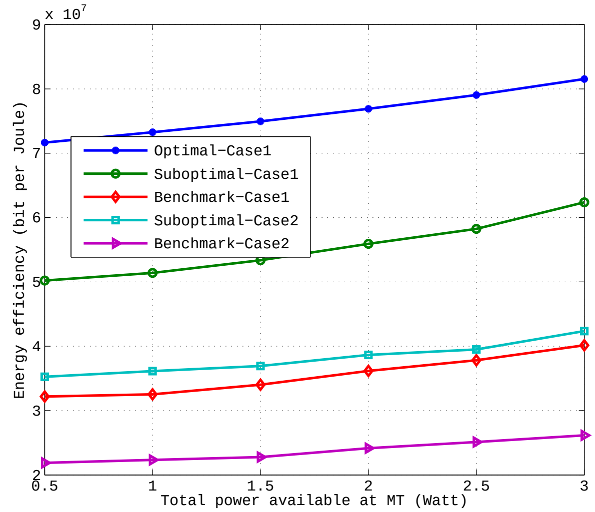


Figure 2. Average achieved energy efficiency versus total power available at each MT [42].

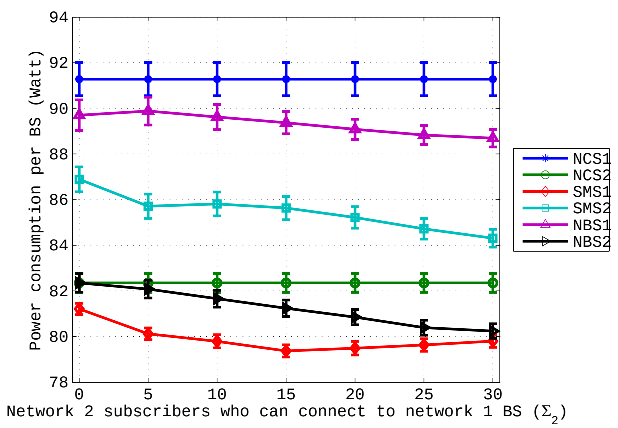


Figure 3. Power consumption for each BS versus the number of network 2 subscribers who can connect to the BSs of both networks [43].

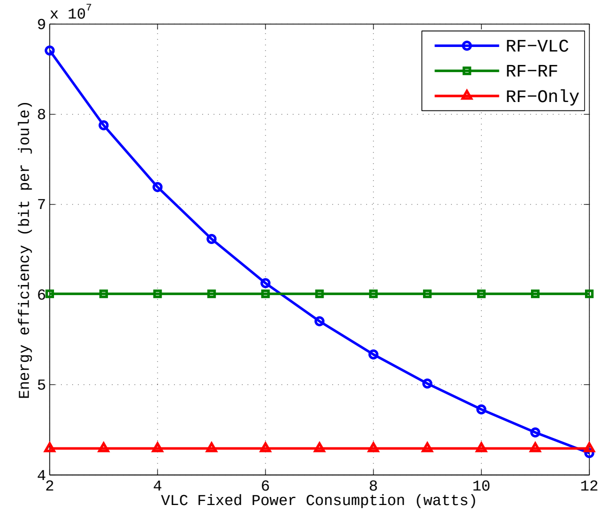


Figure 4. Energy efficiency against the fixed power of the VLC system [44].

Simulation results in [43] have demonstrated the effectiveness of the proposed win-win cooperative approach. While more power saving can be obtained using the sum minimization solution (SMS) as compared with both the Nash bargain solution (NBS) and the non-cooperative solution (NCS), the NBS is more practical as it provides incentives to network operators to participate in a cooperative framework. As shown in Figure 3, the SMS for the second network (SMS2) is always higher than the non-cooperative solution (NCS2), indicating that it is not beneficial for network 2 to cooperate with network 1 under the SMS framework. On the other hand, the NBS2 is always less than or equal to the NCS2, indicating mutual benefits (power saving) for both network operators.

C. RF-VLC Inter-networking

Most of the existing research in heterogeneous networks is based on RF network integration as in WLAN and cellular networks and macro-femto cells. One challenging issue in such scenario is spectrum congestion in RF networks. On the other hand, VLC is introduced as a promising technology that uses visible light for communications, and hence, offers larger spectrum availability and can achieve high data rates. More importantly, VLC consumes almost no transmission power since VLC uses illumination energy, which is already used for lighting, for communications. However, VLC suffers from reliability issue in absence of line-of-sight (LoS) component and cannot support uplink transmission. Such limitations of VLC networks motivates RF-VLC network integration to exploit the potential benefits of both networks and address their limitations. In literature several Rf-VLC integration objectives are investigated, namely, load balancing, throughput maximization, and uplink support. However, the existing research does not investigate Rf-VLC network integration for energy efficient (green) communications.

In our research [44], we investigate energy efficient integration of a VLC access point (AP) with a femto AP. MTs aggregate the offered resources from both APs to satisfy the required data rate using the multi-homing capability. The achieved data rate from each AP is averaged over the LoS availability probability mass function. For the RF network, the MT experiences LoS and non-LoS (NLoS) channels with probabilities κ_1 and $(1-\kappa_1)$, respectively. On the other hand, for the VLC network, the MT do not receive any data rate for NLoS channel (with probability $1-\kappa_2$) and receives data rate only for LoS channel (with probability κ_2). For each MT, the total achieved data rate is the summation of the average data rate achieved using VLC and femto APs, which should satisfy a minimum required data rate. The total communication power consumption for the APs has two components, namely, VLC and femto AP power consumption. The VLC component mainly includes a fixed power consumption that captures the consumed power for signal processing, since no power is consumed in data transmission. For the femto AP, both transmission and fixed power consumption components are accounted for. The objective in [44] is to maximize the total energy efficiency (i.e., a ratio of total achieved throughput to total power consumption) in the geographical region through joint bandwidth and power allocation. The total allocated bandwidth and power for each AP should satisfy the maximum available bandwidth and power. The problem is shown to be a fractional concave-convex program that can be transformed into a convex optimization problem using a parametric approach. Using a Dinkelbach-type algorithm and decomposition theory, the optimal joint resource allocation can be obtained.

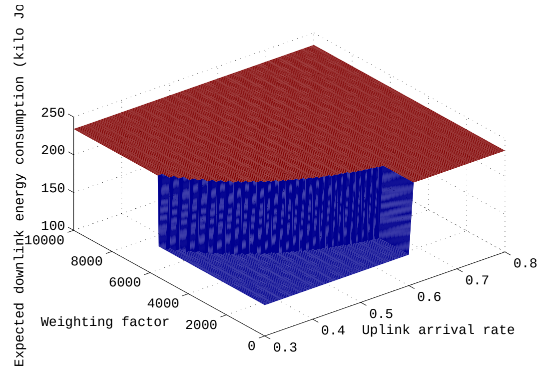
Simulation results have demonstrated the improved energy efficiency performance for the RF-VLC network compared with multi-homing among RF only networks and in absence of multi-homing. Such an improved performance mainly depends on the amount of VLC fixed power consumption as shown in Figure 4.

IV. BALANCED DYNAMIC PLANNING FRAMEWORK

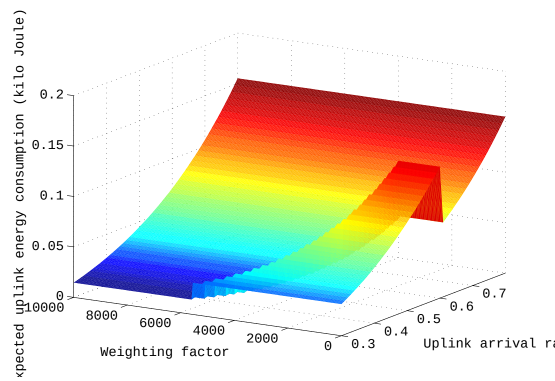
At a low call traffic load condition, network operators can save energy by switching off lightly loaded BSs and the traffic is supported by the remaining active cells. The existing research mainly focus on improving energy saving for network operators (i.e., in the downlink) with no investigation on the incurred energy consumption in the uplink and its impact on service quality deterioration for uplink mobile users. Specifically, the existing dynamic planning mechanisms switch off the BSs that can balance energy saving for network operators with service quality of downlink mobile users. However, such an approach can lead to inefficient MT-BS association in the uplink (i.e., from mobile user perspective) due to switching off nearby BSs resulting in larger transmission distances for uplink mobile users. Consequently, MTs suffer from battery drain at a faster rate leading to call dropping, i.e., deterioration of service quality for uplink users. As a result, a balanced dynamic planning approach is required to account for energy saving and service quality both in the downlink and uplink.

In our research [45], we present a balanced dynamic planning framework that is based on a two-timescale decision problem. Consider a cluster of two BSs with overlapped coverage. Since BS operation (i.e., on-off switching) does not occur at same rate as the MT association, time is partitioned into two timescales. The BS operation occurs at a slow rate (with scale of hours) according to temporal fluctuations in call traffic load density. On the other hand, the MT association occurs at a faster rate (with scale of minutes) according to user arrivals and departures. The slow timescale system state represents the uplink and downlink call traffic load densities, which can be inferred from historical traffic load patterns. Based on the slow timescale state, the slow timescale decision specifies the BS operation mode while satisfying a target call blocking probabilities in the uplink and downlink. The fast timescale state represents the number of mobile users in the uplink and downlink. Two $Geo/Geo/M/M$ queues captures temporal fluctuations in number of MTs in the uplink and downlink. Following the fast timescale state and the slow timescale decision, the fast timescale decision controls the transmission powers of the BSs and MTs. The decision problem objective is to balance the expected uplink and downlink energy consumption based on a weighting factor. Such a weighting factor captures the significance of uplink energy consumption and its impact on uplink service quality degradation.

Simulation results have demonstrated the effectiveness of the balanced dynamic planning approach compared with traditional approaches that accounts only for downlink service quality. Unlike the traditional approaches, the balanced approach switching decision depends on the uplink arrival rate and the weighting factor, as shown in Figures 5a, which leads to improved energy saving for the MTs, as shown in Figures 5b.



(a) Downlink-Balanced Approach



(b) Uplink-Balanced Approach

Figure 5. The expected energy consumption versus the arrival rate of uplink users and the weighting factor [45].

V. Conclusions and Future Research

Radio resource scheduling techniques are adopted at a high call traffic load condition to improve energy efficiency for network operators and mobile users. Green multi-homing techniques in the uplink, downlink, and for RF-VLC internetworking have been investigated. Emphasis is given to decentralized joint bandwidth and power allocation to maximize energy efficiency. At a low call traffic load condition, balanced dynamic planning can be implemented to achieve energy saving for network operators while not jeopardizing service quality for uplink users due to high energy consumption in the uplink.

While most existing research focus on saving energy either for the network operators or the mobile users, future research directions should consider joint energy saving for network operators and mobile users. For instance, BSs and MTs can save energy at low call traffic load condition via on-off switching mechanisms. The existing research allows an MT to switch off its radio interface for energy saving while dealing with buffer delay and/or overflow at the BS. However, the impact of BS on-off switching is not considered. In addition, the existing opportunistic scheduling mechanisms result in energy saving either for network operators or mobile users. However, opportunistic scheduling MTs with bidirectional traffic should ensure energy saving for both network operators and mobile users.

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