Asymmetric Uplink-Downlink Assignment for Energy-Efficient Mobile Communication Systems

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***Abstract*— Mobile operators are facing increasing energy prices to operate their networks. At the same time, the demand for broadband wireless access is steadily increasing, driven by the success of smart phones and new services like machine-to-machine communication. In this paper we propose and evaluate a novel asymmetric user assignment scheme, which enables operators to save energy, while satisfying the capacity demands. The main innovation is to separate the association of users to base stations in uplink and downlink, such that in macro/micro overlay scenarios parts of the radio access network can be switched off.**

Based on system-level simulations we show that our scheme enables energy savings of up to 15% and 60% over typical macro and micro cell deployments, respectively. We further discuss its technical feasibility and implications on the system design. All numerical results are obtained in accordance with the guidelines and requirements of IMT-Advanced systems.

I. Introduction

A. Motivation

Traditionally, cellular networks provide voice and high-data-rate services to mobile terminals with an interactive interface towards its users. However, machine-to-machine (M2M) communication changes this paradigm as an increasing number of autonomic modules are connected with mobile communication networks and offer non-interactive as well as uni-directional services such as metering and surveillance. A recent study forecasted that the number of M2M terminals will grow from about 40,000 in 2010 to around 12 million by 2015 [1].

The energy consumption of mobile communications systems contributes to a great extent to the operators' operational expenditures (OPEX) [2] and causes a significant amount of CO2 emissions [3]. Hence, the energy-consumption of mobile networks must be reduced while still guaranteeing the required Quality-of-Service (QoS) of applications. As a result, we need to (dynamically) identify scenarios in which the cellular network is able to provide the same (or similar) performance-level while spending significantly less energy.

In order to achieve this goal, we exploit the fact that traffic patterns and link budget are different for uplink (UL) and downlink (DL). Depending on the use case, either DL traffic (e.g. web traffic) or UL traffic (e. g. M2M metering services) dominates. Constraints in the user terminals (UTs), e. g. limited transmit power, imply that the UL determines the coverage area. The common approach to save energy is to turn off base stations (BSs), which affects both UL and DL coverage. In many cases, BSs may not be turned off as otherwise either UL or DL may not be able to provide the required QoS. In this paper, we evaluate the energy-saving potential of existing cellular networks in load conditions below the maximum capacity while guaranteeing a minimum QoS.

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B. Related Work

Chiaraviglio et al. [4] propose to switch off UMTS cell sites in a micro-cell scenario if the traffic load is below a certain threshold. It is assumed that the scenario is interference-limited such that coverage is maintained in low traffic cases even with half of the BSs switched off. A similar approach was investigated in [5] for 3GPP LTE networks while the focus was set on self-organized networking methods in order to guarantee cell coverage. In [6], the coverage problem is solved by re-associating UTs to cells such that BSs may be switched off. Furthermore, a linear dependency between the traffic load of a single HSPA base station and its energy consumption is assumed even though this might not be met in practical systems [7]. All of the previous work does not consider asymmetric traffic requirements and channel conditions in UL and DL which is in the focus of this paper.

C. A New Approach: Asymmetric Traffic Routing

We introduce a novel approach that accounts for the asymmetric traffic demands and channel conditions of UL and DL. It selectively turns off UL and DL at BSs and routes UL and DL traffic through different BSs. Hence, by assigning UL and DL of the same UT to different BSs, we are able to significantly reduce the energy-consumption and are still able to satisfy typical M2M requirements. This paper focuses on M2M communication, which has different requirements than traditional communication towards UTs with an interactive interface. For instance, M2M communication is likely to involve a higher density of terminals with infrequent, very short bursts, low transmit power, and short activity-windows. Even though the focus of this work is to reduce the energy consumption of a cellular network, the approach can also be applied to scenarios with asymmetric traffic demands, e. g. hotspots where a high spatial reuse of DL resources is required and the UL mainly carries signaling information.

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D. Contributions and Outline

This work conducts an extensive system level simulation for M2M traffic based on the IMT-A system and channel model [8]. To our knowledge, such a detailed analysis of M2M communication using a system level model has not been carried out so far. Our approach is evaluated based on two traffic models for high-packet arrival and high user-arrival rate.

The rest of the paper is structured as follows. In Section II, the applied IMT-A system model is presented. The proposed asymmetric UL/DL assignment is described in Section III followed by an explanation of different use cases and their corresponding traffic model in Section IV. A performance evaluation is provided in Section V. Finally, Section VI concludes the paper summarizing our main findings.

II. System Model

The ITU-R defined the requirements and baseline assumptions for IMT-Advanced systems, which are 4G mobile wireless communication systems providing a wide range of access techniques and data rates depending on the respective use cases [9]. Independent groups evaluate different IMT-Advanced candidate technologies based on publicly available and widely accepted guidelines specifying channel models, evaluation scenarios and system simulation procedures [8]. This paper applies these guidelines in order to allow for reproducibility and comparability of our results. The IMT-Advanced channel models are geometry-based stochastic models defining large-scale and small-scale propagation parameters for path-loss, shadowing, cluster and ray distribution, angular spread, and delay spread. Throughout this work, we assume the hexagonal layout with wrap-around suggested in [8].

We investigate two typical metropolitan area scenarios: urban macro-cell (UMa) and urban micro-cell (UMi). The UMa scenario assumes that BSs are mounted well above rooftop level in order to provide continuous coverage in rather large cells. Users move along streets and experience Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions depending on a fixed LOS probability distribution. The UMi scenario focuses on provisioning high throughput in areas with high user densities. Cell sizes are small such that the spatial reuse is increased and the number of users per cell is reduced. Micro-BSs are assumed to be installed below rooftop to increase the isolation between cells. Table I summarizes the most important parameters of both channel models. A detailed description of the models and parameters is given in [8].

Parameter	UMa	UMi
BS antenna height	25 m, above rooftop	10 m, below rooftop
BS Max Tx power	46 dBm	41 dBm
MS Max Tx power	24 dBm	24 dBm
SF std. dev. (dB)	$\sigma_{\text{LoS}} = 4$ $\sigma_{\text{NLoS}} = 6$	$\sigma_{\text{LoS}} = 3$ $\sigma_{\text{NLoS}} = 4$
Delay distribution	exponential	
AoD and AoA dist.	wrapped Gaussian	

TABLE I

Main channel model parameters

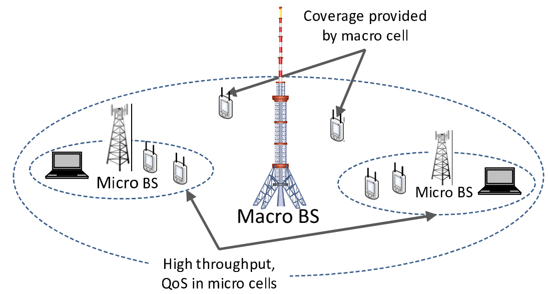

Fig. 1. Macro/micro overlay deployment concept

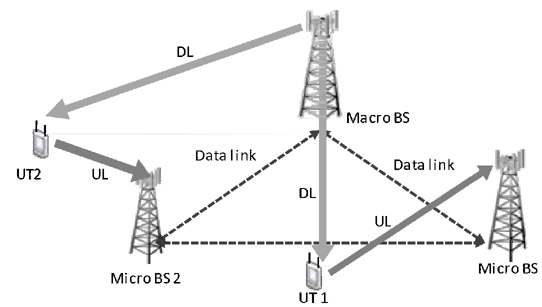

Fig. 2. Asymmetric assignment of uplink and downlink in cellular networks

Both, UMa and UMi scenario target different applications, e.g. high throughput for indoor-terminals in the case of UMi and high coverage for UTs not associated to micro cells or having low QoS requirements in the case of UMa [10]. In order to guarantee both continuous coverage and high data throughput, operators may overlay the deployment of macro- and micro-BSs as illustrated in Fig. 1. We further assume that BSs are inter-connected, which is a common assumption for example in LTE networks (using the X2 interface).

III. Asymmetric Node Assignment

An advantage of overlay deployments is the possibility to switch off micro-BSs for the purpose of energy saving in situations with low or no traffic load, e. g. at night [5]. Hence, during those low-traffic periods macro-BSs would provide service to the area which is otherwise covered by micro-BSs. However, many terminals, e.g. M2M devices, are deployed indoors and therefore experience high path-loss towards macro-BSs. Hence, the necessary service UL quality may not be guaranteed, and, in order to ensure a minimum QoS also to indoor users, micro-BSs cannot be completely switched off.

In macro-cellular deployments, the limiting link is the UL while during low-traffic periods in micro-cellular deployments an unnecessarily strong DL is supported and therefore energy-saving potentials are not exploited. One way to counteract this problem is to assign a UT to different BSs in UL and DL. As illustrated in Fig. 2, a UT could be served by a micro-BS in the UL while the same UT is served by a macro-BS in the DL. If applied to all UTs, micro-BSs can turn off the DL-module and macro-BSs can turn off the UL-module in order to save energy. Therefore, the UL-bottleneck in a network using only macro-BSs can be avoided while the energy-saving benefits are still preserved. In addition, also the energy-consumption at the UTs is reduced as the transmit power is lower and the active time-period is shorter than in a system using only macro-BSs. Hence, this approach is capable of jointly reducing the energy-consumption on the network and terminal side. We study these benefits in Section V and refer to this network operation as *asymmetric assignment*.

In order to implement an asymmetric assignment of UL and DL, we need to distinguish between logical and physical BSs. Conventional cellular networks manage each physical BS as an own logical entity, while in the asymmetric assignment a logical BS assigned to a UT might consist of different physical BSs, e. g., one for UL and one for DL. This differentiation of logical and physical BSs needs not to be revealed to UTs, which can still address one (logical) BS while the core network takes care of the correct assignment of physical BSs.

An implementation of the asymmetric assignment involves changes on the physical and medium-access layer. However, most of these changes can be transparent to UTs and be applied only to the BS and inter-BS communication. Regarding the site selection process, let each UL-BS be assigned to a DL-BS in order to form a logical BS. Each UL-BS forwards the received connection requests as well as the channel quality indicator (CQI) to the assigned DL-BS, which then selects the UL-BS serving each UT. This implies that we can implement the proposed asymmetric assignment by only forwarding signaling and controlling information between UL-BSs and DL-BSs. Alternatively, UL-BSs could quantize their received signal and forward it to the DL-BS. However, this implementation requires significantly more backhaul. Power control at UTs is affected as micro-BSs usually have a lower path loss towards a particular UT than macro-BSs. Hence, using a distributed power control by sending CQI values from UL-BSs to DL-BSs, we can obtain further energy-saving benefits at the UT.

IV. Use Cases

The benefits of the introduced deployment and user assignment approaches are demonstrated for two different traffic models, each reflecting a different application scenario.

A. High-Rate User Arrival Model

The first model represents a scenario in which each terminal has one single file to be delivered. Such a scenario might appear in metering applications, where nodes regularly execute measurement tasks and aggregate information over a long period of time. Another example are event-triggered terminals, which deliver specific measurements after receiving a certain trigger event, e. g. pictures from a surveillance-camera after a motion-sensor has been activated. We model these scenarios using a Poisson arrival process of nodes which aim on transmitting one single file to the assigned BS. The Poisson arrival process reflects the case of sporadically active terminals that request a connection to their BS once enough data has been aggregated and the data buffer has been filled.

Each UT delivers a single file modeled by a typical FTP stream [11]. The size of each file is distributed according to a truncated log-normal distribution with mean $\mu = 0.9385$ and standard deviation $\sigma = 2.0899$ (the applicability of this distribution has been shown in [11]). Furthermore, each file has at minimum $0.5\,\mathrm{kbyte}$ and at maximum $500\,\mathrm{kbyte}$.

In our analysis of this scenario, we are particularly interested in the maximum node-arrival rate, which is supported by the system. Future cellular networks are expected to serve a tremendous number of M2M nodes using the same air interface as mobile terminals. Hence, the number of resources for M2M-communication is very limited and must be efficiently used to avoid blocking mobile terminal services. Furthermore, we study the average time a terminal needs to deliver its file, which is a good indicator of a terminal's energy consumption.

B. High-Rate Packet Arrival Model

The second traffic model represents scenarios where terminals regularly need to deliver information through a mobile network. A relevant example would be a health care data monitoring system for elder people in order to identify any degradation of health status at an early stage. Further examples are regular road state information about traffic density and industry production monitoring systems.

This high-rate packet-arrival model applies a Poisson arrival process to the packet generation of terminals. A fixed packet-size is considered since most of these applications regularly transmit the same amount of information. More specifically, we assume that 210 users are uniformly distributed over the system area. Exactly $10\,\mathrm{users}$ are connected to each BS in the case of UMa, as defined in [8], and at most $10\,\mathrm{users}$ are assigned to each BS in the case of UMi and asymmetric assignment. The packet size taken as representative for some of the uses cases is $1024\,\mathrm{bytes}$.

V. Performance Evaluation

This section discusses numerical results for the previously introduced asymmetric assignment as well as for networks deploying either macro-BSs or micro-BSs.

A. Simulation Setup

Our results are obtained using a system level simulator (SLS), which has been calibrated against the channel models defined by IMT-Advanced [8]. In the case of UMa we deploy one central site with one tier of macro-BSs using wrap-around and inter-site distance $d_{\mathrm{is,uma}} = 500\,\mathrm{m}$. In the case of UMi we deploy three tiers of micro-BSs with one central site and inter-site distance $d_{\mathrm{is,umi}} = 200\,\mathrm{m}$ in order to simulate the same area in both cases. For the asymmetric assignment we apply an overlay of both deployments where only micro-BSs serve the UL and only macro-BSs serve the DL.

The assignment to BSs is done based on the path-loss experienced between UTs and BSs. Depending on the assigned BSs and whether it is a macro-BS or micro-BS, the UMa or UMi channel model is applied [8]. The frame structure is implemented according to the IEEE 802.16m standard [12]

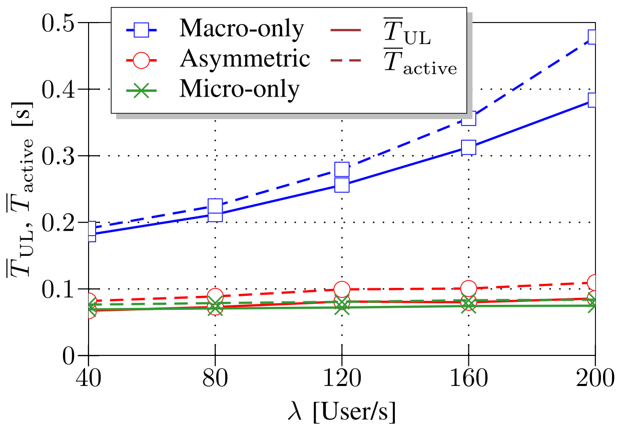

Fig. 3. Average uplink-time $\overline{T}_{\mathrm{UL}}$ (solid lines) and active-time $\overline{T}_{\mathrm{active}}$ (dashed lines) depending on the average user arrival rate λ

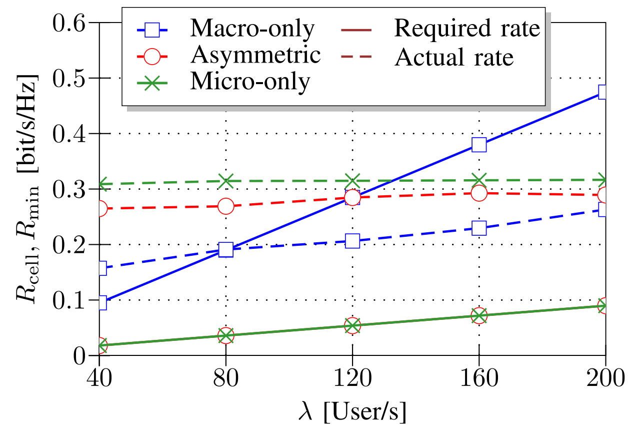

Fig. 4. Required (solid lines) cell normalized cell data rate in uplink according to Little's law and actual normalized cell data rate (dashed lines)

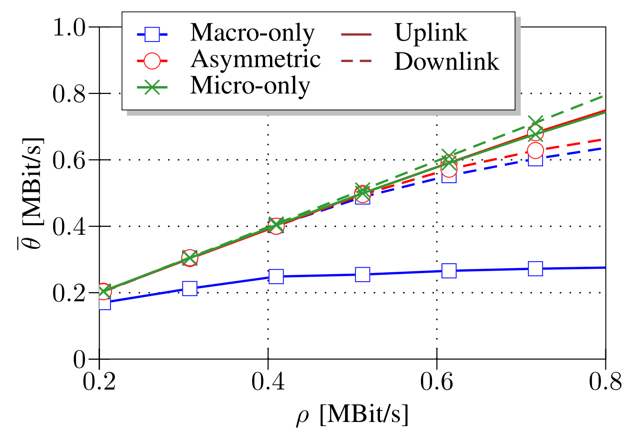

Fig. 5. Average throughput $\overline{\theta}$ in uplink (solid lines) and DL (dashed lines) depending on the required average load per user ρ

operating in TDD and using $10\,\mathrm{MHz}$ bandwidth. We further employ a proportional fair scheduler operating at frequency reuse 3. The scheduling utility is chosen as the ratio of expected throughput and weighted average throughput achieved so far. BSs use four antennas and UTs use one antenna while at maximum two UTs are served on one resource block.

B. System Performance

We start our system performance study by evaluating the time $T_{\mathrm{active}}(i)$ that a UT i is active in order to receive the assigned file in the DL and to transmit its file in the UL. The average over all UTs is given by $\overline{T}_{\mathrm{active}}$. We further consider the time $T_{\mathrm{UL}}(i) \leq T_{\mathrm{active}}(i)$ in which a UT is active in the UL. $\overline{T}_{\mathrm{active}}$ is particularly important to evaluate the static energy consumption, which is the minimum required energy of an active UT and independent of the transmission-status. By contrast, $\overline{T}_{\mathrm{UL}}$ qualifies the flexible energy-consumption depending on the number of frames in which the UT must transmit. We further compare the average UL-throughput $\theta_{\mathrm{UL}}(i)$ and DL-throughput $\theta_{\mathrm{DL}}(i)$ of each UT i averaged over all active frames, considering finite buffers at UT and BS.

C. High-Rate User Arrival Model

At first we discuss the performance for the previously introduced high-rate user arrival model, where each UT transmits one single file. Numerical results were obtained after a simulation of 1000 superframes, i. e., overall $20\,\mathrm{s}$.

Consider Fig. 3 which shows the uplink-time $\overline{T}_{\mathrm{UL}}$ (solid lines) and active-time $\overline{T}_{\mathrm{active}}$ (dashed lines) for different user arrival rates λ. It shows that using only micro-BSs or an asymmetric assignment implies that UTs require significantly less time to finish their tasks, compared to the macro-cell scenario. More specifically, for $\lambda = 80\,\mathrm{user/s}$ the active-time $\overline{T}_{\mathrm{active}}$ is reduced by more than 50% compared to using only macro-BSs, which, assuming a linear dependence, would translate to 50% lower energy consumption at the terminals.

Next, we evaluate the ability of the individual assignment approaches to handle the required load. Fig. 4 shows for uplink transmission the actually achieved normalized cell data rate R_{cell} (dashed lines) as well as the required normalized cell data rate R_{min} (solid lines) according to Little's law [13]. By contrast to asymmetric and micro-only assignment, the macro-only assignment cannot satisfy the demand of UTs for $\lambda > 80$ because $R_{\mathrm{cell}} < R_{\mathrm{min}}$. DL data rates are not shown for the sake of brevity. However, in the DL all three approaches satisfy the required data rates. This demonstrates that macro-BS deployments primarily face a bottleneck in the UL, which can be avoided using the asymmetric UL/DL assignment.

D. High-Rate Packet Arrival Model

Fig. 5 shows the achieved average throughput in UL (solid lines) and DL (dashed lines) depending on the packet arrival rate $\lambda = [25, ...100](packets/s)$. The results are shown depending on the required average load ρ per user given by the product of packet arrival rate λ and packet size $(1024\,\mathrm{byte})$. In order to guarantee a stable system the achieved average throughput per user must not be lower than the required average load per user, represented by a bisecting line. We can immediately see that the macro-only mode is not able to cope with the required load in the UL, and in the DL only for loads below $0.6\,\mathrm{MBit/s}$. By contrast to UMa, a micro-only and the

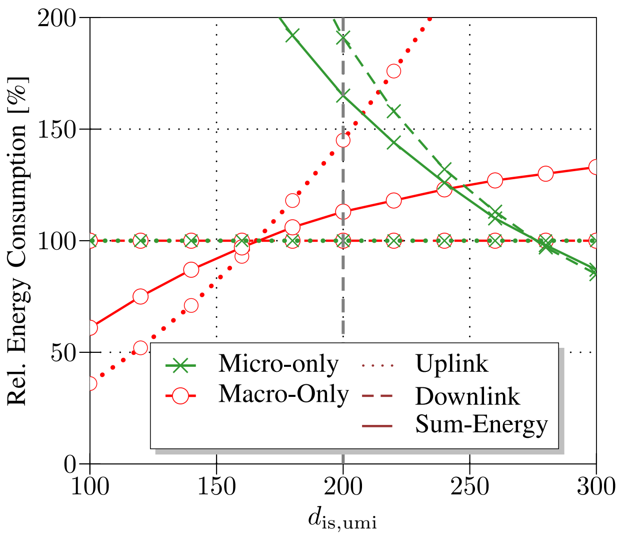

Fig. 6. Energy consumption relative to the asymmetric assignment in uplink (dotted lines), downlink (dashed lines), and sum of both (solid lines)

asymmetric assignment achieve sufficient UL rates for up to $\rho \approx 0.6\,\mathrm{Mbit/s}$ and in the case of micro-only assignment also the DL rates suffice for the simulated packet arrival rates. These results show that for high UL and moderate DL load, the asymmetric assignment achieves sufficient performance figures compared to the macro-only assignment. The best performance is provided by the micro-only assignment at the cost of a higher energy consumption as shown in the next part.

E. Network Energy Savings

The energy-saving potential is emphasized with an exemplary energy budget. We apply the model given in [7], where an energy model has been proposed, which separates the flexible energy-consumption depending on the transmit-power and the static energy-consumption depending on signal processing, power loss, battery backup and other factors. We use the macro-BS and micro-BS model of [7] (using the UMTS1 configuration) and assume that micro-BSs require air conditioning due to the high transmit-power of $41\,\mathrm{dBm}$. Figure 6 shows the relative energy-consumption using only micro-BSs and using only macro-BSs compared to a network using our proposed asymmetric assignment depending on the inter-site distance of micro-BSs, $d_{\text{is,umi}}$.

For very short distances, the macro-cellular deployment is more energy-efficient as the static energy in UL/DL dominate in the case of micro-cellular deployments. However, the asymmetric assignment already outperforms the macro-cellular model for $d_{\text{is,umi}} \gtrapprox 170\,\mathrm{m}$. By contrast, the micro-cellular model only provides energy-saving benefits for $d_{\text{is,umi}} \gtrapprox 240\,\mathrm{m}$. Only for very large values of inter-site distance of about $d_{\text{is,umi}} \gtrapprox 280\,\mathrm{m}$ a micro-only assignment is more energy-efficient than the asymmetric assignment. For higher inter-site distance the performance also drops and the demand for high data rates cannot be satisfied anymore. In the case of $d_{\text{is,umi}} = 200\,\mathrm{m}$, which is the suggested value by IMT-Advanced, the asymmetric assignment is about 15% more energy-efficient than the macro-cellular assignment and about 60% more energy-efficient than the micro-cellular assignment.

VI. Summary and Conclusions

Property / Deployment	Macro-only	Micro-only	Asymmetric
UL Throughput	Low	High	High
DL Throughput	Medium	High	Medium
UL Energy Consump.	Medium	Low	Low
DL Energy Consump.	Low	High	Low

TABLE II
SUMMARY OF PERFORMANCE EVALUATION RESULTS

This paper discussed an asymmetric UL/DL assignment scheme where UL and DL of a UT is served by different BSs. We evaluated the approach according to the IMT-Advanced [8] system level methodology for mobile systems. Compared to other approaches such as [5], our approach requires much less complexity as no dynamic redefinition of cells is required. By contrast to related work such as [5], [6] we show that not only BSs can reduce their energy-consumption but also UTs due to a shorter active-time and lower UL transmit-power.

Our key results are summarized in Table II. The asymmetric assignment approach is more energy-efficient than pure macro-cellular and micro-cellular deployments (15% and 60%, respectively), and the asymmetric approach achieves this considerable energy saving with a maximum system throughput similar to the micro-cellular deployment and thus, significantly higher than a pure macro-only deployment.

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