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Green Heterogeneous Small-Cell Networks
Toward reducing the CO_2 emissions of mobile communications industry via uplink power control

Muhammad Zeeshan Shakir[1], Hina Tabassum[2], Khalid Qaraqe[1],
Erchin Serpedin[3], Muhammad Ali Imran[4], and Mohamed-Slim Alouini[2]

[1]Electrical and Computer Engineering Dept., Texas A&M University at Qatar, Doha
{muhammad.shakir, khalid.qaraqe}@qatar.tamu.edu

[2] Computer, Electrical and Mathematical Sciences & Engineering Division,
King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia
{hina.tabassum, slim.alouini}@kaust.edu.sa

[3] Electrical and Computer Engineering Dept., Texas A&M University, College Station, TX
serpedin@ece.tamu.edu

[4] Center for Communication Systems Research (CCSR), University of Surrey, Guildford, UK
m.imran@surrey.ac.uk

Abstract

Heterogeneous small-cell networks (HetSNets) are considered as a standard part of the future mobile networks in which multiple low-power, low-cost user deployed base stations complement the existing macrocell infrastructure. This paper proposes an energy efficient deployment of the small-cells where the small-cell base stations are arranged around the edge of the reference macrocell and the deployment is referred to as cell-on-edge (COE) deployment. The proposed deployment ensures an increase in the network capacity, reduction in the co-channel interference and carbon footprint of the mobile operations by employing uplink power control. Moreover, in order to calibrate the reduction in CO_2 emissions, this paper provides daily CO_2 emissions profile for variable traffic loads at different times of the day. Simulation results quantifies the reduction in CO_2 emissions and capacity gains of the proposed COE deployment compared to macro-only networks and typical small-cell deployment strategy in which small cells are randomly deployed within a given macrocell.

Index Terms

Heterogeneous small-cell networks (HetSNets); energy savings; energy consumptions; CO_2 emissions; daily traffic profile and power control.

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I. INTRODUCTION

Wireless networks are rapidly becoming the most popular way of connecting to broadband through home and mobile devices. The resulting customer demand for the ubiquitous network access and wireless services is mainly responsible for the growing energy consumption and consequently the growing carbon footprint of the mobile communications industry [1–3]. Carbon footprint is a key ecological factor which is measured in carbon dioxide equivalent ($\mathrm{CO_2e}$) and is defined as the amount of $\mathrm{CO_2}$ emissions calculated according to the global warming potential (GWP-100) indicator as defined by international panel on climate change (IPCC) [4][1].

The information and communication technology (ICT) sector and the mobile communications industry have been estimated to jointly represent around 2% of global $\mathrm{CO_2}$ emissions and 1.3% of global $\mathrm{CO_2e}$ emissions [5]. Even with the technological advancements of ICT infrastructure, 6% growth rate in $\mathrm{CO_2}$ emissions is expected every year till 2020 [5]. The fundamental factors contributing to the overall global carbon footprint of mobile communications industry includes production, operation, distribution and maintenance of the mobile communications networks, devices and services, the number of mobile subscribers which is 4.5 billions in 2012 and expected to be 7.6 billions till 2020 (which shows a steep growing pattern over the last few years with the proliferation of smart phones, tablet computers, and other smart devices) and mobile data traffic volume which is 45 million TB/year in 2012 and expected to be 623 million TB/year till 2020 [4]. Based on the listed facts and figures, it can be concluded that the ICT sector in general and mobile communications industry in particular has a considerable potential to decrease global carbon footprint especially in developing and emerging economies[2].

To fulfill the escalated customer demands, it is therefore essential to consider paradigm-shifting technologies that ensures to increase the spectral and energy efficiency of upcoming wireless networks. In this regard, recently heterogeneous small-cell network (HetSNet) deployment strategies are gaining significant popularity. HetSNets are envisioned to enable next-generation wireless

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[1] $\mathrm{CO_2e}$ represents a standard unit to measure the impact of each of the different greenhouse gases in terms of the amount of $\mathrm{CO_2}$ that would create the same amount of warming.

[2] Such as China, Hungary, Indonesia, Poland etc. For complete list and grouping follow [6].

networks by offloading traffic from the macrocell network, providing higher data rates, and dedicated capacity to homes and hot spots. HetSNets consist of infrastructures with multiple radio access technologies (RATs) such as femtocells, picocells etc., each having variable capabilities and functions. However, the number and distribution of small-cells across the macrocell area is still a challenging problem that can impact the spectral and energy efficiency of HetSNets [7].

A. Background and Motivation

The population of small-cells is expected to be around 100 million with 500 million mobile users in 2020 [4]. The power consumption of a small-cell today is around 6-10 W, and it can be assumed that a small-cell in 2020 will still consume 5 W. Therefore, the 100 millions small-cells in 2020 may consume 4.4 TWH, i.e., an extra 5% on top of the energy consumption of the existing BS infrastructure. To cope up with this issue, numerous remedies are currently under consideration [1–3, 9] such as (i) improved power amplifier technology which makes the hardware design of a typical BS more energy efficient; (ii) employing power saving protocols such as BS sleeping which enables inactive mode for BSs under low load conditions [10]; (iii) cell size adjustment schemes such as cell-breathing and cell-zooming, where different cells adapt their size depending on the received interference or traffic load conditions[10–13]; (iv) use of renewable energy sources such as solar and wind energy in place of diesel generators may also be useful in reducing the power consumption of BSs, in particular, those at the off-grid sites; and (v) deployment of relays improves the power consumption with reduced complexity[14, 15].

In contrast to the above mentioned energy efficient techniques which are mainly applicable to downlink scenarios, some results of 2010 wireless smart phone customer satisfaction studies from J. D. Power and Associates demonstrate that the iPhone ranked top in all categories except for the battery life (please check [16] and the references cited therein for further details). According to another recent report, up to 60% of the mobile users in China complained that the battery consumption is the greatest hurdle while using 3G services [16]. This fact illustrate that the limited battery life of the mobile users is a fundamental limitation to power-hungry wireless applications [17]. Motivated by the mentioned fact and figures, in this paper we focus on the energy efficiency of uplink heterogeneous network scenarios.

In the context of uplink energy efficiency, several power control (PC) mechanisms are currently under investigation such as closed-loop and open-loop PC, slow and fast PC, and fractional PC [18–20]. In general, the conventional slow open-loop PC compensates for the long term channel variations due to shadowing and the distance of a mobile user from the serving BS, while maintaining the same received target signal to noise ratio (SNR) for every user. The open-loop PC can be implemented at each BS by sending slowly updating PC signaling or each mobile may also derive its own transmission power according to the path loss measurements enabled by the downlink pilots. On the other hand, in closed-loop PC, mobile users can compensate also the fast fading effects by performing frequent measurements and exchanges of control data with its serving BS, which makes the PC less sensitive to errors in the path-loss estimates.

B. Contribution

We propose a deployment in which small-cells are arranged around the edge of the reference macrocell. The deployment is referred to as cell-on-edge (COE) and has been shown to produce significant spectral and energy efficiency gains compared to (i) HetSNets where the small-cells are uniformly distributed across the macrocells, i.e., UDC and (ii) macro-only network (MoNet). The COE deployment improves the energy savings of the HetSNets by enabling PC and ensuring that each mobile user is transmitting with the adaptive power, thereby saving energy and reducing CO_2 emissions of the mobile communication industry. Typically, UDC is considered to be as one of the standard approaches that allow random deployment of the small-cells in the current infrastructure [7, 21–24]. Even though, considering UDC deployment may be more close to realistic deployments, the considered COE deployment excels UDC in the following facts:

- **Energy consumption:** Due to limited battery power constraint and PC mechanisms, mobile users located close to the serving BS are able to achieve their desired targets while minimizing their transmit power. Whereas, the cell-edge users are highly likely to starve and transmit with their maximum powers. In this context, COE deployment allow significant reduction in the transmit power of the cell-edge users while maintaining their target rates.

- **Spectral Efficiency:** As UDC deployment do not restrict the small-cells at the macrocell edges, therefore the small-cell users may cause an under-utilization of the macrocell BS capabilities, i.e., existing infrastructure. As an example, the mobile users close to the macrocell BSs should communicate through macrocell BS as long as the desired link maintains the target rate. However, such mobile users in UDC may get connected through small-cell BSs while forcing several cell-edge users to communicate through macrocell BS with worse channel conditions and maximum transmit power.
- **Interference Reduction:** MoNets and HetSNets with UDC deployment donot completely eliminate the existence of cell-edge mobile users which are highly likely to transmit with their maximum power in order to achieve some throughput gains. Cochannel interference due to such edge mobile users may cause significant degradation in the network performance with aggressive frequency reuse distances.

C. *Paper Organization*

The rest of the paper is organized as follows. Section II presents the two-tier network layout, the channel model, the bandwidth partition, and the channel allocation strategy. In Section III, we present the energy economics of HetSNet and quantifies the energy savings of the COE deployment. Section IV introduces the ecological impact of COE deployment and presents the $\mathrm{CO_2e}$ emissions and reduction in the $\mathrm{CO_2e}$ emissions of the wireless networks. Simulation results and discussions are included where deemed necessary to provide comparative performance analysis of various deployment strategies. Finally, the conclusions are drawn in Section V.

II. HETEROGENEOUS SMALL-CELL NETWORKS

This section introduces the HetSNets layout, bandwidth partition, channel allocation and the energy aware channel propagation model for the proposed COE design of HetSNets.

A. ***Green Network Layout***

We consider a two tier energy aware HetSNets as illustrated in Fig. 1. The first tier comprises of M circular macrocells each of radius $R_m + R_n$ [m] with a BS B_m deployed at the center and equipped with an omni-directional antenna. Each macrocell is assumed to have U_m mobile users uniformly distributed over the region bounded by R_0 and $R_m + R_n$, where R_0 denotes the minimum distance between the macrocell mobile user and its serving BS. The second tier of the HetSNet comprises of N circular small-cells each of radius R_n [m], with low-power low-cost user deployed small-cell BSs B_n located at the center of each small-cell. We consider that the small-cells are distributed around the edge of the reference macrocell. For practical reasons, we calculate the number of small-cells per macrocell as follows:

$$N = \begin{cases} \mu\frac{(R_2^2 - R_1^2)}{R_n^2} = \mu\frac{4R_m}{R_n} & R_m > R_n \\ 0 & R_m \leq R_n, \end{cases}$$

where $R_1 = R_m - R_n$, $R_2 = R_m + R_n$ and the factor $0 < \mu \leq 1$, referred to as the cell population factor (CPF) controls the number of the small-cells per macrocell, i.e.,

$$\mu = \begin{cases} 0 & \text{no active small cells} \\ 1 & \text{maximum number of small-cells per macrocell.} \end{cases}$$

The number of mobile users in each small-cell is expressed as $U_n = (U - U_m)/N$, where $U_m = H(R_1^2 - R_0^2)/R_m^2$ and $U = U_m + NU_n$. To be precise, in COE deployment, U_m out of U mobile users are uniformly distributed over the region bounded by R_0 and R_1, whereas the remaining mobile users, i.e., $U - U_m$ are reserved for N small-cells. The bandwidth allocated to a macrocell is reused throughout the macrocell network at a distance $D' = R_u(R_m + R_n)$ [m], where R_u represents the network traffic load. The total bandwidth allocated to the small-cell tier is reused in each of the N small-cells within a given macrocell.

B. Bandwidth Partition and Channel Allocation

We consider the spectrum partition based on the proportion of the number of mobile users in the macrocell and small-cells [25]. The spectrum splitting strategy has been considered to avoid cross-tier interference issues, i.e., the interference between macrocells and small cells. However, this is not a limitation of the presented work as it can be applied to spectrum sharing scenarios as well. Let w_t [Hz] be the total bandwidth of the available spectrum per cell, then the total bandwidth may be divided as $w_t = w_m + w_n$, where $w_m = w_t(U_m/U)$ [Hz] and $w_n = w_t(NU_n/U)$ [Hz] are the amount of the spectrum dedicated to the macrocell and small-cells, respectively, based on the proportion of active mobile users. The macrocell and small cell bandwidth are divided further into subchannels and each subchannel can be allocated to one mobile user at a time and there will not be any mobile user which cannot be serviced by the respective macrocell or small-cell BS. The number of active serviced channels available per macrocell and small-cell can then be given as $N_m = w_m/U_m$ and $N_n = w_n/U_n$, respectively[3]. Each subchannel is allocated to any user randomly without considering the channel conditions, i.e., we consider strictly fair scheduling strategy.

The strict fairness and no opportunistic gains of the random scheduling makes it less attractive for the systems with high spectral efficiency requirements. However, this paper focuses on energy efficient systems with relatively high degree of fairness. In general, PC mechanisms are implicitly designed to balance the received signal power at the BS of interest from all associated users, i.e., the received signal at the BS is indistinguishable. Consequently, all users possesses equal probability of getting scheduled on a given subcarrier. Based on this reason, considering any other scheduling schemes (such as opportunistic schemes) in conjunction with PC (especially fast PC) are expected to provide insignificant performance gains. The opportunistic schemes are more applicable to slow PC mechanisms where partial path loss compensation is performed and an opportunistic selection is performed on the uncompesated path loss of various users.

C. *Energy Aware Channel Propagation Model*

The radio environment of a typical wireless cellular network is described by (i) distance dependent path-loss, (ii) shadowing, and (iii) multi-path fading. In this paper, we only consider path-loss effect since we assume a scenario where an efficient antenna diversity combining system is employed at the BS to eliminate the effects of multipath fading [26]. We consider a two slope path-loss model for macrocell and small-cell networks [26], i.e., the received signal

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[3] In practical cases, the number of active serviced channels available per macrocell and small-cell can be given as $N_m = w_m/\Delta$ and $N_n = w_n/\Delta$, respectively, where Δ can be selected arbitrarily.

power at BS from the mobile user is given as follows:

$$P^{\mathrm{rx}}(r) = P^{\mathrm{tx}} \frac{K}{r^{\alpha}(1 + r/g)^{\beta}}, \tag{1}$$

where P^{rx}[W] denotes the average signal power received at the macrocell/small-cell BS from the desired mobile user which is located at a distance r from the considered BS, α and β are the basic and additional path loss exponents, respectively, $g = \frac{4h_{BS}h_{MU}}{\lambda_c}$ [m] is the breakpoint of a path-loss curve which depends on the BS antenna height h_{BS} [m], the mobile user antenna height h_{MU} [m] and carrier wavelength λ_c, K is the path loss constant. P^{tx} [W] defines the adaptive transmit power of the mobile user according to PC mechanism [27, 28][4] as:

$$P^{\mathrm{tx}} = \min\left(P_{\max}, P_0 \frac{r^{\alpha}(1 + r/g)^{\beta}}{K}\right) \tag{2}$$

where $P_{\max}$[W] denotes the maximum transmit power of the mobile users and P_0 is the cell specific parameter to control the target signal to interference ratio (SINR) at a given sub-channel.

III. ENERGY ECONOMICS OF HETSNETS

In this section, we investigate the relationship of energy economics of HetSNets with the energy consumption and the energy savings of the networks.

A. *Energy Consumption of HetSNets*

In general, energy consumption is defined as the power consumption per unit time, i.e., $\text{Energy Savings} = P^{\mathrm{tx}} \times \ \phi(t) \times \text{No. of Days/year}, \quad \text{kWH/year}$, where $\phi(t)$ denotes the number of hours per day a mobile user is active under full load conditions and P^{tx} can be given as in (2). Fig. 2 depicts the energy consumption per user for HetSNets with COE deployment as a function of the small-cell radius. It can be seen clearly that the energy consumption of the COE deployment outperforms the energy consumption of the (i) UDC deployment and (ii) MoNets (compare the solid green curve with the dashed red and the dotted blue curves). The significant

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[4] Mobile users are considered to be able to estimate/compensate their path-loss while adjusting their transmit power accordingly.

improvement is due to the fact that small-cells around the edge of the macrocell ensures a reduction in the edge mobile users of the macrocell which are transmitting with their maximum power[5]. The comparative summary on the performance of HetSNets with COE deployment with respect to the two competitive network deployments is given as follows:

- Comparison with MoNets: energy consumption of the COE deployment outperforms the energy consumption of the MoNets due to (i) the deployment of the small-cells and (ii) reduction in the cell-edge mobile users who are transmitting with their maximum power. As an example, for $R_n = 50$ m, the energy consumption of the COE deployment reduces to 1 kWH per user which offers 68% reduction in energy consumption compared to MoNets.
- Comparison with UDC deployment: energy consumption of the COE deployment outperforms UDC deployment mainly due to the reduction in the edge mobile users who are transmitting with their maximum power, e.g., for $R_n = 50$ m, the COE deployment offers 37% reduction in energy consumption compared to UDC deployment.

*B. **Energy Savings of HetSNets***

The energy savings of the HetSNets can be defined as power savings per unit time such that the power savings per mobile user can be calculated from (2) as $P_{\max} - P_0 \frac{r^\alpha (1+r/g)^\beta}{K}$. Fig. 3 depicts the amount of energy saved by the mobile users which are transmitting with the adaptive power, e.g., the energy savings offered by COE deployment at $R_n = 100$ m is 4 kWH which is more than double the savings that the network can achieve at $R_m = 10$ m and which is 1.9 kWH. In addition, Fig. 3 quantifies the average capacity achieved per user as a function of R_n. It can be observed that the COE deployment remains spectral efficient for medium to higher values of R_n (for more detailed results and discussions see [28]).

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[5] In [28], a threshold distance, R_t has been calculated which is referred to as the distance beyond which the mobile users are required to transmit with the maximum power. As an example, with $\alpha = \beta$, $R_t = 422$ m such that the number of mobile users transmitting with the maximum power increases with the increase in R_m beyond R_t.

C. *Low Carbon Economy*

The economic impact of the energy savings can be calculated in terms of the cost of saved energy. The associated cost can be calculated by assuming 1 kWH $= 10.3$ ¢ as follows[6]:

$$\text{Cost} = \frac{\text{Energy Savings}}{1000 \times 100} \times 10.3, \quad \text{USD/year}. \tag{3}$$

The cost savings corresponding to the energy savings of MoNets with PC is 0.45 billions USD and it is expected to be 0.6 billions USD in 2020. The cost savings are expected to increase further up to 1 billions USD in 2012 and 1.4 billions USD in 2020 for UDC deployment with PC. Finally, the cost corresponding to the energy savings of the COE deployment with PC may reach 1.1 billions USD in 2012 and 1.6 billions USD in 2020. In short, an annual 60% of the cost savings can be achieved in HetSNets compared to MoNets. The economics analysis associated with the energy savings and cost is for the mobile operations only.

IV. ECOLOGICAL IMPACT OF ENERGY EFFICIENT HETSNETS

In this section, we determine the ecological impact of the energy savings of the HetSNets in terms of $\mathrm{CO_2e}$ emissions and reduction in $\mathrm{CO_2e}$ emissions of the networks.

A. $\mathrm{CO_2e}$ ***Emissions and Reduction in*** $\mathrm{CO_2e}$ ***Emissions***

In order to determine the ecological impact of the energy consumption of HetSNets, we calculate the corresponding $\mathrm{CO_2e}$ emissions in mega tonnes [Mtonnes]. The conversion factor for energy consumption to $\mathrm{CO_2e}$ emissions is taken from [29]. Fig. 4 illustrates the uplink $\mathrm{CO_2e}$ emissions for (i) MoNets; (ii) HetSNets with UDC deployment and (iii) HetSNets with COE deployment, where all mobile users are transmitting with their adaptive power to maintain the desired SINR of the link. The $\mathrm{CO_2e}$ emissions of the systems under consideration are compared with the $\mathrm{CO_2e}$ emissions of the MoNets without PC, i.e., the network where the mobile users are transmitting with maximum power and small-cells are inactive. It can be seen clearly that the

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[6] This is average cost per kWH for commercial type of energy use.

CO_2e emissions of the HetSNets reduce significantly in comparison with the MoNets without PC. As an example, the CO_2e emissions of the MoNets without PC in 2016 is approximated as being 19 Mtonnes. The MoNets with PC reduce the estimated CO_2e emissions to 13 Mtonnes (30% reduction). This can be further reduced to 8 Mtonnes (67% reduction) by introducing small-cells in HetSNet with COE deployment. Finally, the significant reduction in CO_2e emissions of the system can be achieved by introducing small-cells around the edge of the macrocells. The proposed HetSNets with COE deployment guarantee to reduce the CO_2e emission to 3.5 Mtonnes (82% reduction). Therefore, the mobile communications industry must act quickly to demonstrate efforts and enforce policies to reduce global carbon footprint emissions.

Calculation of CO_2e emissions is based on the source of energy generation. In order to generalize our results, we summarize the CO_2e emissions corresponding to the several other sources of energy generation in Table I[7]. List of the selected countries corresponding to the respective source of energy generation is also included. As an example, today, the CO_2e emissions of HetSNets with COE deployment is 0.84 Mtonnes (73% reduction in comparison with MoNets and 44% reduction in comparison with HetSNets with UDC deployment) and is expected to be being 1.8 Mtonnes in 2020 (74% reduction in comparison with MoNets and 43% reduction in comparison with HetSNets with UDC deployment). Moreover, this can also be observed that the contribution of natural gas (as a source of energy generation) toward CO_2e emissions is significantly low compared to the other two competitive sources of energy generation which is the reason that natural gas is being considered as a potential source of clean energy generation. The CO_2e emissions of the wireless networks corresponding to different sources of energy generation will provide guidelines to the rapidly developing countries and emerging economies to select an appropriate environment friendly source of energy generation for ICT and mobile communications industry and thereby reduce the carbon footprint emissions of the mobile communications industry further.

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[7] Simulation parameters used to generate the table: $P_{\max} = 1$ W; $\alpha = \beta = 2$; $R_m = 300$ m; $R_n = 50$ m; P_0=0.8 μW; $\mu = 2$; $K = 1$, $g = 300$ m; for small-cell network and $g = 600$ m for macrocell network.

B. ***Daily*** $\mathrm{CO_2e}$ ***Emissions Profile***

The daily $\mathrm{CO_2e}$ emissions profile quantifies the amount of $\mathrm{CO_2e}$ emissions corresponding to the various mobile traffic loads i.e., $\%$ of the active mobile users at different times of the day. Fig. 5 depicts the daily $\mathrm{CO_2e}$ emissions profile for the European country corresponding to the daily mobile traffic loads profile introduced in [4]. It can be seen clearly that the $\mathrm{CO_2e}$ emissions of MoNets without PC is significantly higher during peak times of the day. Moreover, the $\mathrm{CO_2e}$ emissions of the HetSNets with COE deployment improve significantly during the peak time of the day compared to other two competitive network deployments (MoNets with PC and HetSNets with UDC deployment). As an example, the maximum number of active users is 16% at 9 pm. The corresponding daily $\mathrm{CO_2e}$ emissions of MoNets without PC is estimated as 142 Mtonnes which is reduced to 120 Mtonnes with PC. Moreover, UDC deployment contributes 60 Mtonnes to daily $\mathrm{CO_2e}$ emissions and finally HetSNet with COE deployment reduces the daily $\mathrm{CO_2e}$ emissions to 47.5 Mtonnes. Therefore, the daily $\mathrm{CO_2e}$ emissions profile clearly shows how the proposed HetSNet with COE deployment improves the energy savings and thereby establishes green HetSNets by contributing less amount of $\mathrm{CO_2e}$ emissions to the environment.

V. CONCLUSIONS

In this paper, we investigated the energy consumption and energy savings of the two tier HetSNets, where the small-cells are arranged in such a fashion that they guarantee significant energy savings and thereby establishing "green" HetSNets. It has been shown that the significant energy savings can be achieved by (i) deploying small-cells around the edge of the macrocells and (ii) employing power control in the uplink where each mobile user is transmitting with adaptive power. It has been shown further that the $\mathrm{CO_2e}$ emissions of the COE deployment is reduced upto 82% in comparison with the $\mathrm{CO_2e}$ emissions of the MoNets without employing power control. Therefore, the reduction in $\mathrm{CO_2e}$ emissions is considered as a cornerstone in designing and planning of environment friendly wireless networks.

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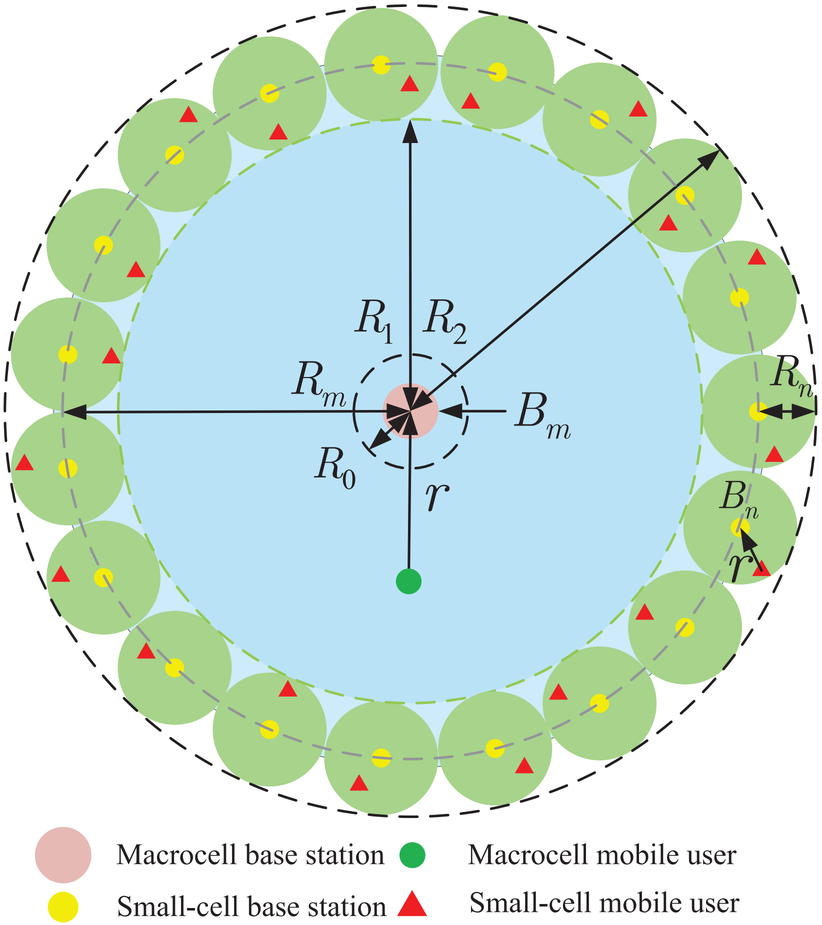

Figure 1. Graphical illustration of the two tier heterogeneous network where a macrocell is surrounded by N small-cells around the edge such that the mobile users are transmitting with the adaptive power.

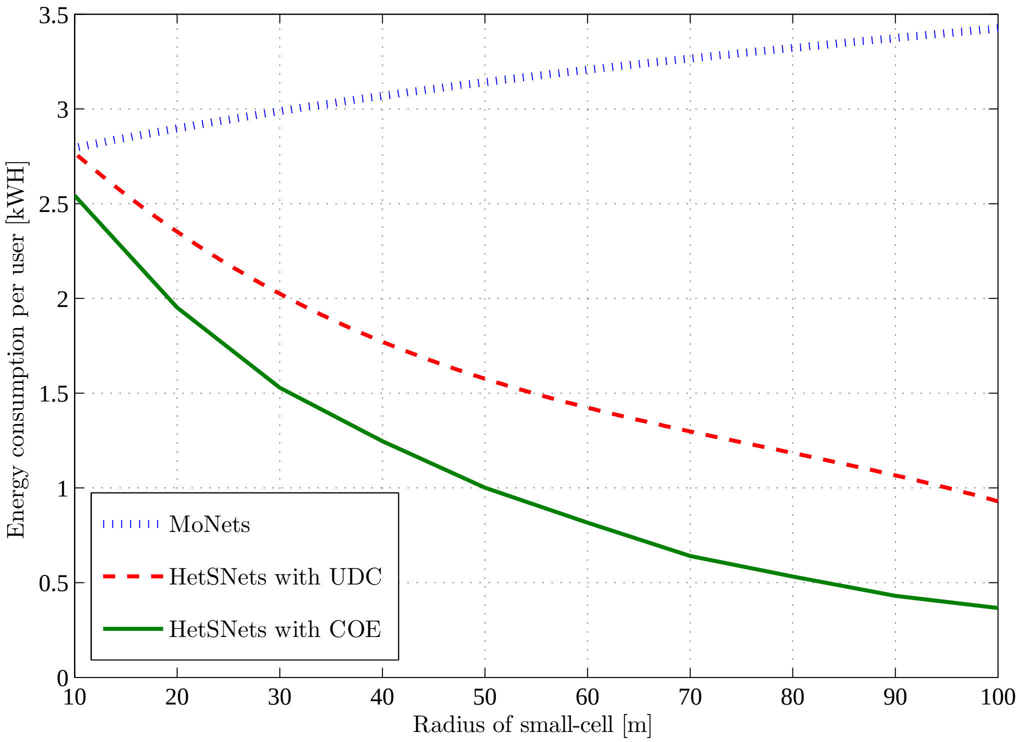

Figure 2. Energy consumption per user as a function of the small-cell radius for (i) Macro-only networks (MoNets); (ii) HetSNet with cell-on-edge (COE) deployment and (iii) HetSNet with uniformly distributed small-cells (UDC). Simulation parameters used: $\alpha = \beta = 2$; $R_m = 300$ m; P_0=0.8 μW; $\mu = 2$; $g = 300$ m for small-cell network and $g = 600$ m for macrocell network.

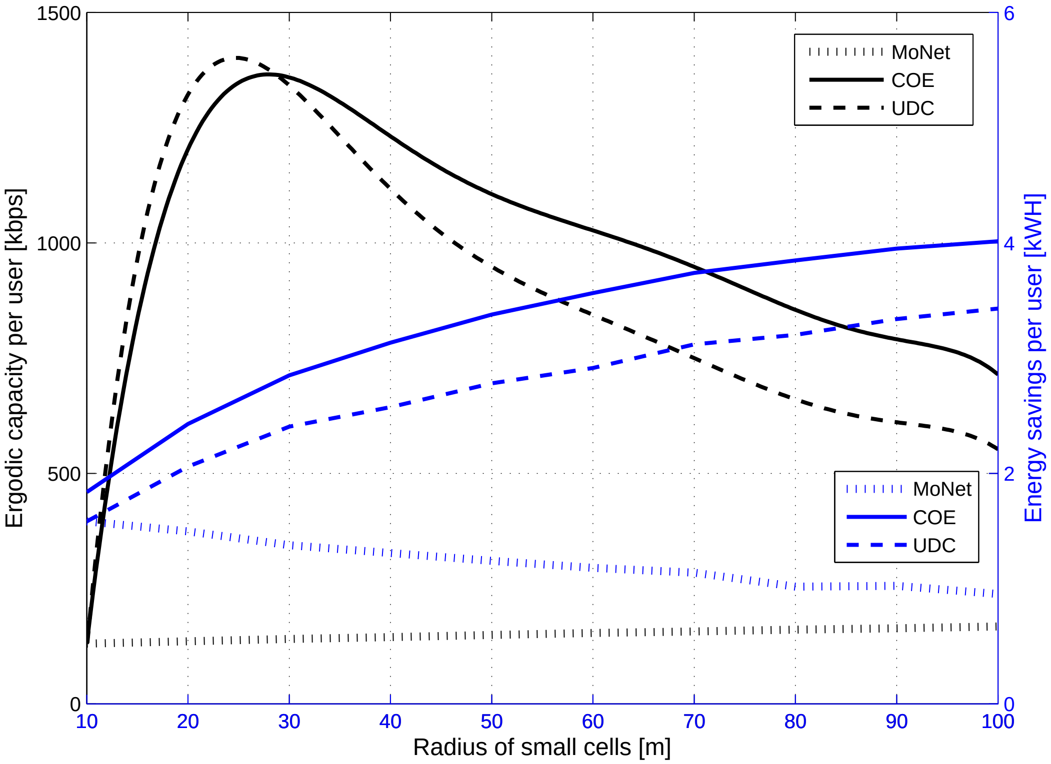

Figure 3. Energy savings per user as a function of the small-cell radius for (i) Macro-only networks (MoNets); (ii) HetSNet with cell-on-edge (COE) deployment and (iii) HetSNet with uniformly distributed small-cells (UDC). Simulation parameters used: $P_{\max} = 1$ W; $\alpha = \beta = 2$; $R_m = 300$ m; P_0=0.8 μW; $\mu = 2$; $g = 300$ m for small-cell network and $g = 600$ m for macrocell network.

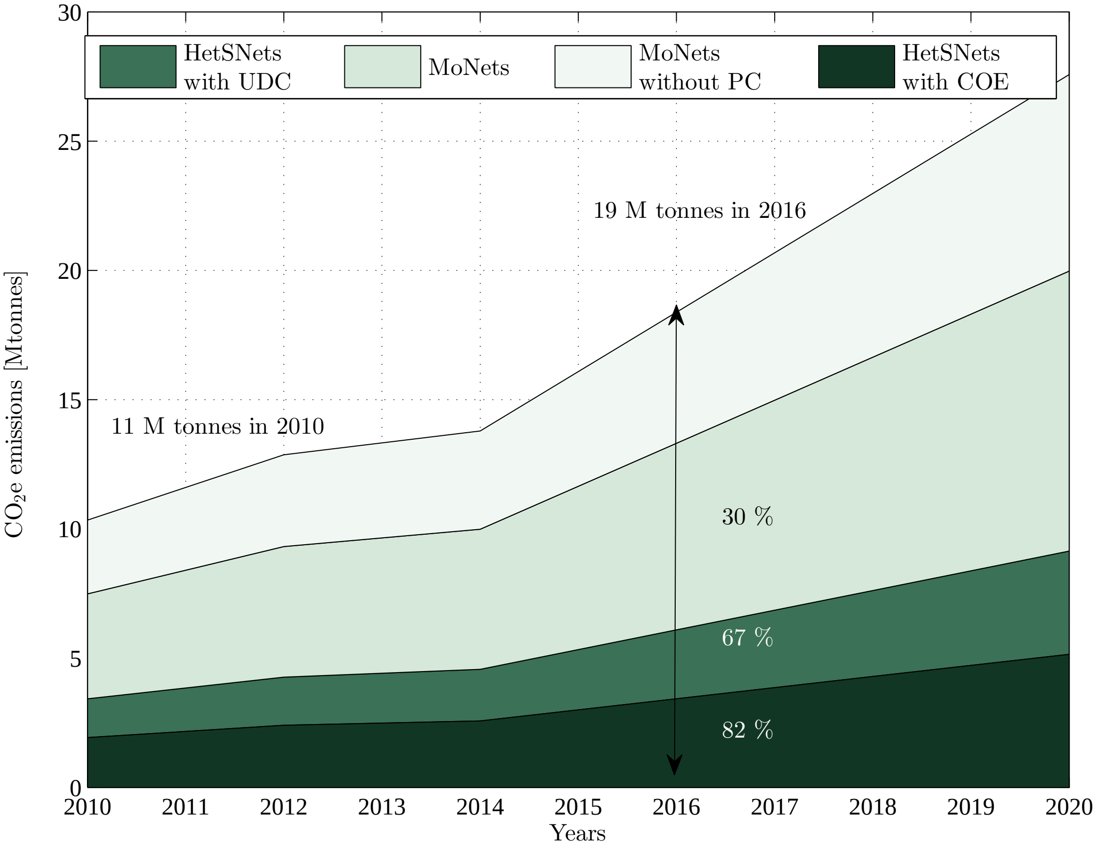

Figure 4. Uplink CO$_2$e emissions for (i) Macro-only networks (MoNets) without power control; (ii) Macro-only networks (MoNets) with power control; (iii) HetSNet with cell-on-edge (COE) deployment and (iv) HetSNet with uniformly distributed small-cells (UDC). Simulation parameters used: $P_{\max} = 1$ W; $\alpha = \beta = 2$; $R_m = 300$ m; $R_n = 50$ m; P_0=0.8 μW; $\mu = 2$; $g = 300$ m for small-cell network and $g = 600$ m for macrocell network. Conversion factor used: 1 kWH = 0.5246 kg CO$_2$e emissions which represents the energy used at the point of final consumption.

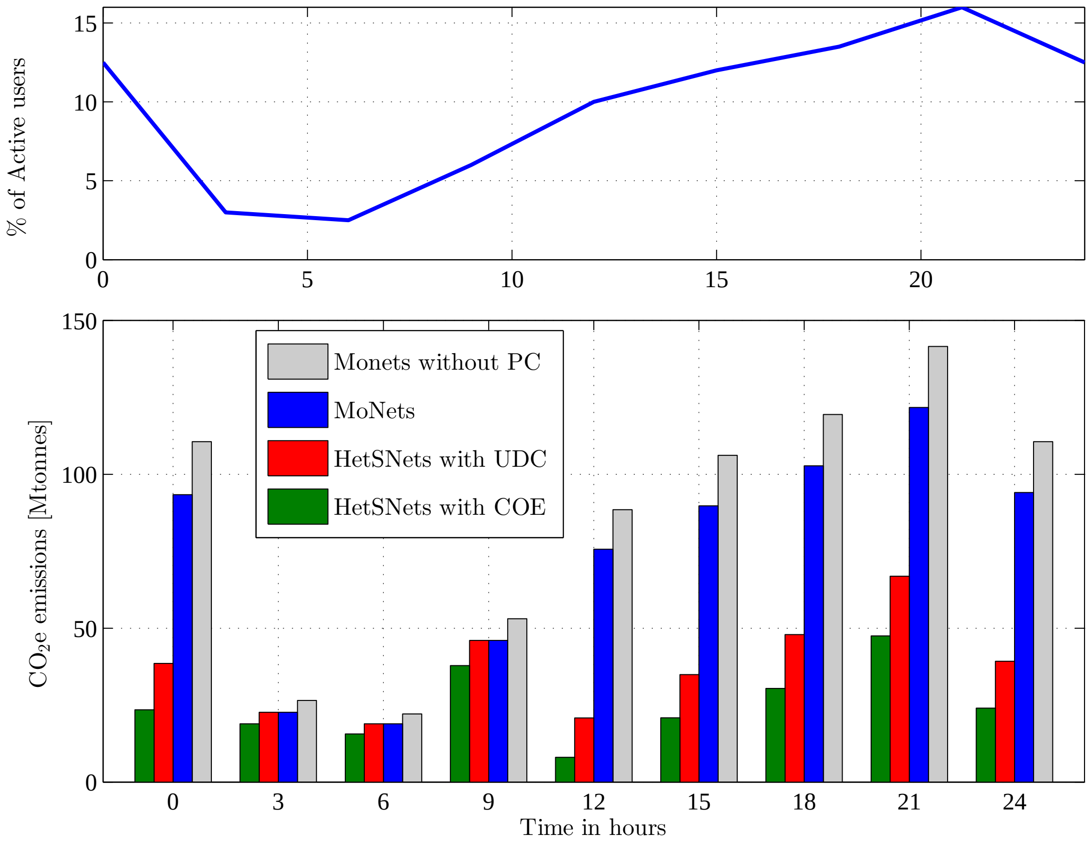

Figure 5. Daily CO$_2$e emissions profile corresponding to various traffic loads at different times of the day in a typical European country for (i) Macro-only networks (MoNets) without power control; (ii) Macro-only networks (MoNets) with power control; (iii) HetSNet with cell-on-edge (COE) deployment and (iv) HetSNet with uniformly distributed small-cells (UDC). Simulation parameters used: $P_{\max} = 1$ W; $\alpha = \beta = 2$; $R_m = 300$ m; $R_n = 50$ m; P_0=0.8 μW; $\mu = 2$; $g = 300$ m for small-cell network and $g = 600$ m for macrocell network. Conversion factor used: 1 kWH = 0.5246 kg CO$_2$e emissions.

Table I

CO$_2$e EMISSIONS FOR DIFFERENT SOURCES OF ENERGY GENERATION.

Fuel	KgCO$_2$ per unit	List of selected countries with source of energy generation	CO$_2$ emissions Mtonnes					
			MoNeT		HetSNet-UDC		HetSNet-COE	
			2012	2020	2012	2020	2012	2020
Natural Gas	0.1838	USA, Russia, Japan, Turkey, UK, Saudi Arabia	3.2654	7.0072	1.495	3.2037	0.8419	1.8044
Gas Oil	0.2785	Japan, Mexico, USA, Saudi Arabia, Indonesia	3.9758	10.6017	2.2653	4.8544	1.2757	2.734
Coal	0.3325	China, USA, UK Australia, Japan, Russia	4.7466	12.6573	2.1734	5.7956	1.2239	3.2642