Energy Efficiency in Heterogeneous Networks

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***Abstract*—An attractive approach to meet increasing traffic demands is to densify existing cellular networks with low power nodes. This creates a heterogeneous network. In this paper we analyse the impact of such a densification on the network energy consumption and the possibilities it offers to enhance the network energy efficiency.**

In a heterogeneous network, the user performance can be significantly improved. This performance increase leads to a shorter transmission time of most data packets, creating longer idle time in the network nodes. In this work, we introduce two node sleep modes operating on a fast and intermediate time scale respectively, in order to exploit short and longer idle periods of the nodes. Our results point out that the total energy consumption of the heterogeneous network featuring the node sleep modes can be maintained at a similar level as the one of the reference network, while the user performance remains superior. At very high traffic load we show that the heterogeneous network can even be more energy-efficient. This means that it is actually possible to increase end-user performance and decrease energy consumption at the same time.

I. Introduction

Introducing low power nodes - later called pico nodes - in a network composed originally of high power nodes - later called macro nodes - creates a so-called Heterogeneous Network (HN). Heterogeneous networks are seen as a promising way to meet the increasing demand for mobile broadband traffic in cellular networks. The new pico nodes complement the macro nodes to provide higher capacity in areas with higher user density. They are assumed to use the same frequency and the same radio access technology (RAT) as the macro nodes. Depending on the demand, a large number of pico nodes might be needed per macro cell to achieve a sufficient capacity increase during busy hours. With the rise in the number of deployed radio access nodes, the energy consumption is expected to be larger in a heterogeneous network compared to current networks with only macro nodes. In this paper we investigate techniques that enable to reduce the energy consumption in a heterogeneous network, while maintaining the same user performance. We also analyse how a heterogeneous network featuring energy efficiency (EE) schemes can have a lower energy consumption than the reference macro network under certain conditions.

Deploying an heterogeneous network under energy efficiency considerations has been studied in [1] and [2]. Both [1] and [2]'s analysis aim at finding out how to deploy macro and pico nodes so as to minimize the energy consumption while ensuring a target system performance. One optimization parameter among others is the distance between two macro sites. Both studies show that an optimized heterogeneous network can be more energy efficient than the optmized macro network, where both optimized networks may have a different inter-site distance. However, in the most likely heterogeneous deployment, the macro network of an operator exists already and pico nodes are added at a later stage to meet increasing capacity requirements. Therefore, in this most likely scenario, the inter-site distance of both networks is given and identical. Our approach targets energy saving in such a scenario with gradual and smooth pico node deployment and is thus complementary to previous work.

The two EE features considered in this paper include micro DTX introduced in [3] and an additional deeper sleep mode for the pico nodes. Both schemes enable to adapt the network to the variations of the traffic demand over the time. Since the new pico nodes do not have the same availability requirements as the macro nodes - they must be primarily active when a user requests high data rate, the pico node sleep mode consists in deactivating the redundant pico nodes at low traffic load. In this paper, the energy consumption of the network is thus evaluated for different traffic loads representing the varying capacity demand over the day.

The paper is outlined as follows. The network model is introduced in section II. Section III describes the two energy efficiency features applied to the network, while section IV provides the simulation assumptions including the power consumption model used for the evaluation. In section V some performance results of the considered EE schemes in a 3GPP Long Term Evolution (LTE) heterogeneous network are provided and analysed, while section VI concludes the paper.

II. Network model

Two network deployments are considered. In the reference deployment N_m macro nodes are providing cellular coverage to a geographical area A. This is the most widely spread deployment nowadays.

The second deployment, the heterogeneous network, consists in adding pico nodes to the reference network. We assume that N_p pico nodes are placed in each macro cell, so that the total number of pico nodes within the area A is given by $N_m N_p$. The heterogeneous network is thus composed of two cell layers, the macro layer and the pico layer.

The main purpose of deploying pico nodes is to offload traffic from the macro cell. Some of the users that are served by the macro node in the reference network are handed over to the pico nodes in the heterogeneous network. Typically the

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amount of traffic that can be absorbed by a pico node depends on its location within the macro cell, the characteristics of the propagation channel and the traffic distribution over the geographical area [4].

In this section, in order to introduce our idea, we consider a simplified model where each pico node attracts the same portion $0 < \theta < 1$ of the traffic generated in the area A. We assume that some traffic, but not the whole traffic, is served by the pico layer, i.e. $0 < N_m N_p \theta < 1$.

The traffic itself is generated by K users, each downloading a file of size S. So the number of bits conveyed through the macro layer would be $S \cdot K$ in the reference network while it decreases to $S \cdot K \cdot (1 - N_m N_p \theta)$ in an heterogeneous network. In that case the pico layer would carry $S \cdot K \cdot N_m N_p \theta$ bits.

The following analysis focusses on one macro cell and the N_p underlaid pico nodes, so $N_m = 1$.

A. Analysis of the radio node activity time in both networks

Consider $\bar{R}$ being the mean user bitrate in the reference network when each user is scheduled over the whole bandwidth. $\bar{R}$ depends on the user signal to interference ratio (SINR) which in turns depends on the system load. In this simplified model, the system load is a function of the number of simultaneously active users K. At high system load (large K), the interference level increases and $\bar{R}(K)$ reduces.

$\bar{R}'$ and $\bar{R}''$ denote the mean user bitrate in the macro and pico layers of a heterogeneous network, when each user is scheduled over the whole bandwidth. For the specific case of a low system load, the average user throughput in both networks ($\bar{R}$, $\bar{R}'$ and $\bar{R}''$) are typically in the same order of magnitude. The interference level is low and thus the SINR is large for most of users. Therefore the most limiting factor for the throughput at low load is the set of available modulation and coding schemes (MCS).

The heterogeneous network is of particular interest at medium to high system load to reduce the activity time of the radio access nodes. In the reference network the time required for the macro node to serve the traffic, T_0, reaches

$$T_0 = \frac{S \cdot K}{\bar{R}(K)}. \tag{1}$$

In a heterogeneous network the activity time for a macro node (labelled with the subscript m) is given by

$$T_{1,m} = \frac{S \cdot K \cdot (1 - N_p \theta)}{\bar{R}'(K)}, \tag{2}$$

and the activity time of a pico node (labelled with p) by

$$T_{1,p} = \frac{S \cdot K \cdot \theta}{\bar{R}''(K)}.$$

At medium to high load, $\bar{R}''$ is higher than $\bar{R}$, since the users connected to the pico node benefit from better propagation conditions towards their serving node and can transmit with a higher order MCS.

From a macro user perspective, there is a double advantage of having additional low power nodes in the network at high load, as observable in Equation (2). First, the traffic to be served by each node diminishes, since the overall traffic is shared among a larger number of nodes. So, the numerator of Equation (2) is lower than the one of Equation (1). Second, the average user throughput, i.e. the denominator of Equation (2), becomes larger. This is not due to an increase of the useful signal power received by the macro users in the heterogeneous network, since they were served by the same node in the reference network. If the interference created by pico nodes to macro users is neglected due to their much lower transmission power (which is the case in our scenario), $\bar{R}'(K)$ can be approximated to $\bar{R}(K \cdot (1 - N_p \theta))$. This means that due to the lower amount of traffic served by the macro layer, the interference level created by the macro layer reduces and the average throughput increases.

B. Analysis of the energy consumption in both networks

Consider a simplified power model for a radio access node composed of two states: the power consumed during the idle period P_I and the power consumed during the activity time P_A. It is then possible to express and compare in a simple way the power consumption of the reference network E_0 and the one of the heterogeneous network E_1.

As reference time interval we consider T_0, the average activity time of a node in the reference network. So the energy consumed during that time interval is $E_0 = P_{A,m} \cdot T_0$. Since T_0 is larger than $T_{1,m}$ and $T_{1,p}$, the energy consumption to operate a heterogeneous network over T_0 is given by

$$\begin{aligned} E_1 = \ & P_{A,m} \cdot T_{1,m} + P_{I,m} \cdot (T_0 - T_{1,m}) \\ & + N_p \cdot P_{A,p} \cdot T_{1,p} + N_p \cdot P_{I,p} \cdot (T_0 - T_{1,p}), \end{aligned} \tag{3}$$

which consists of the energy consumed by the macro node (first line of Equation (3)) and the energy consumed by the N_p pico nodes (second line of Equation (3)).

Equation (3) can be rewritten as a function of E_0

$$\begin{aligned} E_1 = \ & E_0 \cdot \ \left(\tfrac{T_{1,m}}{T_0} + \tfrac{P_{I,m}}{P_{A,m}}(1 - \tfrac{T_{1,m}}{T_0}) + N_p \cdot \tfrac{P_{I,p}}{P_{A,m}} \right. \\ & \left. + N_p \cdot \tfrac{T_{1,p}}{T_0} \tfrac{1}{P_{A,m}}(P_{A,p} - P_{I,p})\right). \end{aligned} \tag{4}$$

Current base stations that do not have any energy efficiency features have a relatively high power consumption in idle mode. Considering values from [5] in Equation (4), i.e. $P_{I,m} \approx 0.5 \cdot P_{A,m}$ and $P_{I,p} \approx P_{A,p} \approx \frac{1}{3} \cdot P_{A,m}$, the contribution of the pico nodes to the overall network energy consumption can be approximated to $N_p \cdot \frac{P_{I,p}}{P_{A,m}} = N_p \cdot \frac{1}{3}$. It is thus not dependent of the amount of traffic carried by the pico layer. In this particular example, from at least three pico nodes per macro cell, E_1 becomes larger than E_0, independently of the decrease of the macro layer activity time. This illustrates that introducing many pico nodes without EE in the network goes together with a rise in the network energy consumption.

In order to build an energy efficient heterogeneous network our idea is to consider two sleep mode techniques. One is a light sleep mode which is applicable to both macro and pico nodes, the other is a deeper sleep mode conceivable mainly for the redundant pico nodes. The details of each sleep mode are described in section III. With these sleep modes, components of a radio access node are switched off in idle time, i.e. when the node is not transmitting any user data nor broadcasting any signalling information. Consequently, the power consumption in idle time with sleep mode techniques can reduce significantly, i.e. $P_{I,m} << P_{A,m}$ and $P_{I,p} << P_{A,p} < P_{A,m}$.

With a much lower $P_{I,p}$, the power consumption rise in a heterogeneous network is under control and a larger number of pico nodes $N_p = \left\lceil \frac{P_{A,m}}{P_{I,p}} \right\rceil$ can be deployed before $E_1 > E_0$ always applies.

For the sleep modes to have a significant impact in the overall network power consumption, the activity time of radio access nodes, especially the one of the macro nodes, should decrease. To get a lower $T_{1,m}$, the traffic offload from the macro layer to the pico layer, $N_p\theta$, plays an important role. As seen in the previous section, it has a double positive impact on the lowering of $T_{1,m}$. However, there is a trade-off in increasing $N_p\theta$. The drawback of a large N_P was discussed previously, and furthermore a larger θ decreases $T_{1,m}$ but increases $T_{1,p}$.

But it is possible to observe $E_1 < E_0$ at high traffic load when T_0 is large and the traffic offload provides much lower $T_{1,m}$ and $T_{1,p}$. As an example, $E_1 = \frac{11}{15} \cdot E_0$ in a heterogeneous network with three pico nodes per macro cell, if the activity time of the macro and pico nodes can be reduced to $\frac{1}{10} \cdot T_0$, and assuming $P_{I,m} = P_{A,p} = \frac{1}{3} \cdot P_{A,m}$ and $P_{I,p} = \frac{1}{10} \cdot P_{A,m}$.

III. Energy efficiency schemes

A radio access node, i.e. a base station, is composed of different components: power amplifier (PA), radio frequency (RF) transceiver, the base band (BB) unit and finally the power supply (DC) and cooling (CO). Basically in current base stations, all components contribute to the overall power consumption of the node even during the idle time when there is no data nor signalling transmission to perform, as shown in Fig. 1 [5]. The two energy efficiency features considered here are based on the deactivation of certain base station components during the idle time of a BS. Thus, a lower power consumption in idle mode can be achieved. This puts however new requirements on the hardware of a BS that may not be met by current BSs but could be taken into account when designing future base stations.

Macro and pico nodes have different roles in the network and therefore shall meet different requirements concerning their availability. Consequently different kinds of sleep mode can be applied to them.

Macro nodes provide the basic coverage meaning they must be always reachable by potential users. For that purpose, even if there is no active user in a macro cell and no data transmission is scheduled, the macro node still needs to broadcast regularly cell-specific signalling information and monitor the uplink to identify if a user wants to establish a connection. A sleep mode based on the complete shut down of a macro base station is thus hardly conceivable. Even if several RATs are implemented at a macro node, the radio components

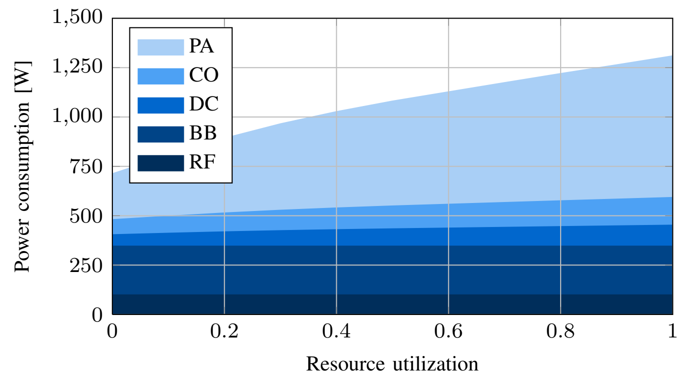

Fig. 1. Power consumption breakdown of a 3-sector macro BS

related to at least one RAT should remain active so as to supply mobile communication coverage.

Pico nodes are redundant nodes deployed to help the macro node handle high traffic demand at certain points in time. A larger variety of sleep mode mechanisms are hence applicable to pico nodes.

A. Micro DTX

Micro Discontinuous Transmission (DTX) is a sleep mode technique, introduced in [6] and [3], and which is suitable for an Orthogonal frequency-division multiplexing (OFDM) based system such as LTE. The idea is to deactivate the power amplifier of a LTE base station (BS) during empty OFDM symbols. In LTE an OFDM symbol with a normal cyclic prefix length lasts 71.4μs. So, the micro DTX assumes a quick reactivation of the power amplifier in the order of less than one OFDM symbol according to [6], [3].

The main advantage of this technique is to exploit very short idle periods of the BS. These are expected to occur more often in the future as there will be an increased amount of traffic generated by means of regular small packets, e.g. social networking type of traffic.

To enable a quick return to the normal operation mode, the cell should remain visible to the legacy users. Therefore the cell-specific signaling still need to be transmitted in certain OFDM symbols even when there is no data transmission. In particular the cell-specific reference symbols (CRS) which are transmitted regularly limit the time where micro DTX can be applied. Basically, a BS can go to the micro DTX mode and reduces its power consumption only between two CRS transmissions. For LTE, the highest possible micro DTX ratio would be of 10/14, since from the 14 OFDM symbols that compose each normal subframe, 4 OFDM symbols contain CRS in case of a transmission with up to two antenna ports.

B. Pico node sleep mode

In addition to the micro DTX, the pico nodes introduced in a heterogeneous network can be subject to a deeper sleep mode technique, in which not only the PA but also the RF and BB components of a pico node are deactivated. The inactive state here is assumed to last in the order of a few hundred milliseconds.

When applying this mode the control signaling can not be transmitted by the pico node anymore, and therefore the pico cell becomes invisible to the user. So all remaining users must be handed over to another cell before entering the sleep mode. This kind of deep sleep mode is possible for a pico node in a heterogeneous network, as the overlaid macro cell that provides the basic coverage can take care of remaining users.

Several implementations of the pico node sleep mode are possible depending on the criteria used to trigger the reactivation, and also on the level of integration of the pico nodes into the macro network. For instance one could think of a pico node sleep mode in which an uplink (UL) signal strength sensor remains active and triggers the pico node reactivation when the measured UL signal strength exceeds a threshold. This indicates the presence of a user in the surroundings of the pico node.

In this paper we consider a heterogeneous network in which the pico nodes are able to tightly cooperate with the overlaid macro node. A good connection between the macro and its pico nodes is thus required. But such a setup offers a more flexible pico node reactivation that can be based on more elaborate criterion. In the following the macro node controls the activation and deactivation of its underlaid pico nodes and takes its decision based on the traffic load in the different cell layers. This enables to react quickly to the traffic demand variation and avoids the re-activation of pico nodes for users that would not benefit from a higher available bitrate, e.g. VoIP users. Moreover, compared to the pico node activation based on uplink signal measurement, the present scheme does not require long measurement filtering before triggering the activation.

As shown in Fig. 2, the macro node regularly checks the traffic load level in its cell. If the traffic load exceeds a certain threshold, all pico nodes under its control are activated. An activation delay of 100ms is assumed here. Note that a macro node equipment is serving all sectors (or cells) of a site. Here we assume that the macro node activates the pico nodes located in the macro sector where the load is increasing. After triggering the pico node activation, the macro node requests all users to measure the signals from neighboring cells. This may result in a handover of some users towards the pico nodes. The activated pico nodes regularly monitor the served traffic. If the traffic load remains low after a certain delay, δ_{active}, these pico nodes autonomously go back to sleep, see Fig. 3.

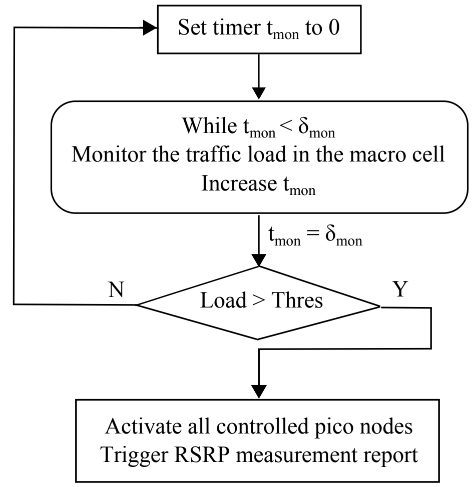

Fig. 2. Traffic load based activation of pico nodes by the macro node

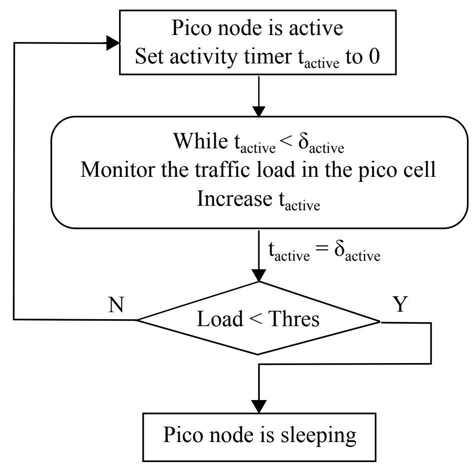

Fig. 3. Traffic load based deactivation of pico nodes

IV. Simulation assumptions

For this study, the micro DTX mode and pico node sleep mode were implemented in a dynamic multi-cell radio network simulator modeling OFDM transmission.

The simulated 10 MHz LTE network consists of seven sites with three macro cells per site and an inter-site distance of 500 m. For the heterogeneous network three pico nodes are randomly placed per macro cell area, a minimum distance of 100m to the macro node is however guaranteed. So, overall there are 21 cells in the reference network and 84 cells in the heterogeneous network. As commonly used for HN performance evaluation by 3GPP, the heterogeneous network configuration 4b of [7] has been followed to build user clusters. There is a probability of 0.67 that users are dropped within a hotspot of 40 m radius around one of the pico nodes. The same user distribution is used in the reference macro network also. The maximum transmit power of macro nodes reaches 46 dBm while it is 30 dBm for pico nodes. A conventional cell selection based on downlink received power is applied. All cells operate at a carrier frequency of 2 GHz. The ITU Urban Macro propagation model [8] is used to characterize the channel between a macro node and a user, while the Urban Micro channel model is used for the pico nodes.

A Round Robin scheduler allocates evenly resources to the active users. Traffic is generated using the FTP based traffic model as described in [7]. Users are created according to a Poisson process, they transfer a file of 500 kByte over TCP and disappear from the system. Several user arrival rates were simulated to obtain results for the different traffic loads characterizing the daily traffic variation as proposed in [5] and shown in Fig. 4. In the chosen scenario the peak traffic demand per area and operator reaches 92 Mbps/km^2.

TABLE I
POWER MODEL PARAMETERS

Node type	P_{max} [W]	P_0 [W]	Δ_p	P_μ [W]	P_s [W]
Macro sector	40	237	4.83	150	-
Pico node	1	106	6.35	62	10

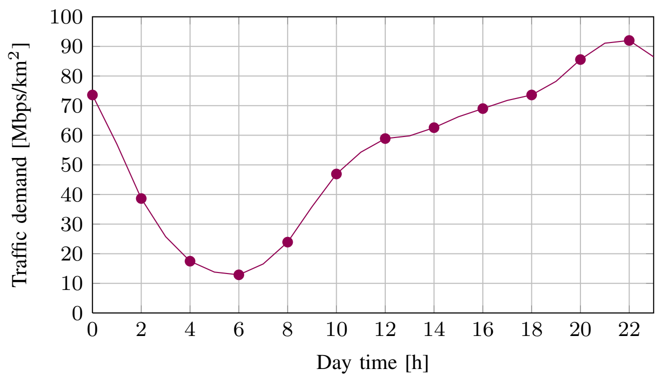

Fig. 4. Traffic demand variation over the day

The activation and deactivation thresholds for the pico node sleep mode were set to 3 Mbit/s and 100 kbit/s resp., while $\delta_{active} = \delta_{mon}$=1 s.

A. Power consumption model

To evaluate and compare the power consumption of the reference network and the heterogeneous network, the power model developed by the european project EARTH for year 2010 state-of-the-art base stations has been used [5]. Note that a micro node in EARTH corresponds to a pico node here.

In the EARTH model, the power consumption consists of a fixed part that is consumed in idle mode and a variable part based on the traffic load served by the base station. The output RF power P_{out} scales with the number of frequency resources scheduled at the given time. If all frequency resources are scheduled at a certain time, P_{out} reaches the maximum power P_{max}. This power model is an approximation of the measured power consumption of a BS transceiver [5] as depicted in Fig. 1 for a macro BS that handles three sectors.

The modelled power consumption P_{in} of a node is expressed as

$$P_{in} = \begin{cases} P_0 + \Delta_p \cdot P_{out} & \text{if } 0 \leq P_{out} \leq P_{max} \\ P_\mu & \text{if } P_{out} = 0 \text{ and micro DTX on} \\ P_s & \text{if } P_{out} = 0 \text{ and sleep mode on} \end{cases}$$

The power model parameters are given in Table I. The values for the micro DTX mode were obtained from [9]. For the pico node sleep mode, a remaining power consumption of 10W is assumed at the pico node. This is aligned with [10].

V. SIMULATION RESULTS

The average user performance is depicted in Fig. 5 for the different network deployments. At low traffic demand, the average user bitrate in both deployments, macro and heterogeneous networks, is similar. At such low loads, few users are active and the resources available in the macro network are sufficient to provide high user data rate. The throughput limiting factors here are first the set of available

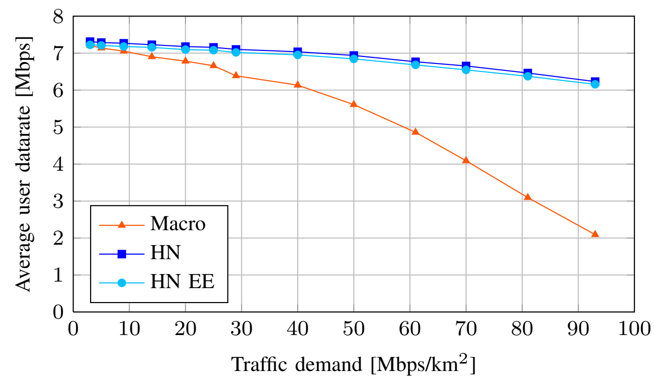

Fig. 5. Average user throughput versus area traffic demand

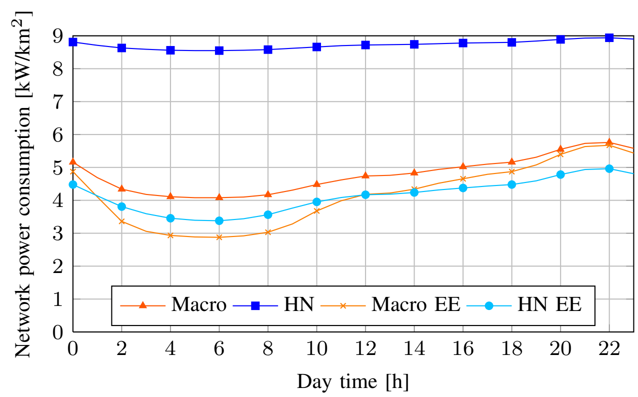

Fig. 6. Network power consumption variation over the day

MCS as already mentioned in section II-A and second the TCP slowstart in particular for transmission of small files.

When the traffic demand in the system increases, the resources available at the macro network must be shared among more users resulting in a longer download time for each user. Moreover, since users are active longer, the interference level in the system rises, which also contributes to the decrease of the user bitrate. In this case, introducing pico nodes is beneficial since it relaxes the constraint of limited network resources. As discussed in section II-A, in a heterogeneous network, the high traffic demand is served over the resources available at the macro and pico layers. Consequently, at the same medium to high traffic demand level, the average user bitrate can be significantly improved in a heterogeneous network compared to the macro network as seen in Fig. 5.

Moreover, it can be observed that the sleep mode features do not affect much the user performance in heterogeneous networks. The same level of user bitrate can be maintained as without the EE features.

Fig. 4 illustrates the traffic variation over the day as measured in [5], while the corresponding power consumption in the whole network can be seen in Fig. 6. The relation between the power consumption needed to run a macro network and the traffic load variation can be observed. In the busy hours the network power consumption reaches a maximum while it decreases in the early morning hours. The fixed component of the power consumption which is related to the P_0 of the power model is predominant though. The situation is even more extreme for the heterogeneous network, since the measured power consumption is almost constant over the day. P_0 of the macro and pico nodes is there also the main contributor of the overall power consumption, independently of the traffic load at a time of the day. This was also analyzed based on a simplified power model in section II-B. Introducing 3 pico nodes per macro cell provides thus an excellent improvement of the end user experience but increases the average daily power consumption by 83% in the considered scenario.

When the micro DTX functionality is implemented in the radio access nodes, the correlation between the traffic load and the power consumption in a macro network becomes more visible. The contribution of the fixed part reduces to P_μ when the traffic is low, while P_{max} is consumed during peak hours. By contrast, the variation of the power consumption for the heterogeneous network with EE features is moderate over the day. Since there is less served traffic per node compared to the reference network, the fixed component of the power consumption remains predominant all day long.

In Fig. 6 it can be seen that the power consumption of the heterogeneous network with both EE features is actually lower than the power consumption of a macro-only network during busy hours. This comes from the better load sharing among nodes and the exploitation of short and longer idle times with micro DTX and pico node sleep mode. This trend can clearly be seen in Fig. 7, where the power consumption of different network layouts is represented against the traffic demand. At low traffic load the heterogeneous network requires more power due to the fixed power consumption of the additional pico nodes. Then, when the traffic load increases, heterogeneous network becomes more energy efficient than the macro network when sleep mode functionalities are available.

Fig. 7 also emphasizes the importance of the achieved traffic offloading by the pico layer. If the pico nodes are ideally placed in the center of user hotspots, 50% of the traffic demand is served by a pico node, i.e. $N_m N_p \theta = 0.5$, in this scenario. For all traffic loads larger than 56 Mbps/km^2 the heterogeneous network consumes less power than the reference network. However, it is not straight forward to deploy pico nodes in the hotspot center. The location of hotspots may not be known accurately or due to various real life constraints the pico node can not be installed in the ideal location. Fig. 7 also shows the power consumption of a heterogeneous network when pico nodes are located 20 m away from the hotspot center. Due to the pico misplacement, only 39% of the traffic can be served by the pico layer. Consequently, the power consumption curves for this heterogeneous network configuration and for the reference network cross at a later stage corresponding to a traffic demand of 61 Mbps/km^2.

VI. Conclusion

Reducing operating expenditures while meeting both internal and external demands on reduced carbon footprint is a challenging task for operators. By 2016, densely populated urban areas representing 1% of the Earth's total land area are set to generate around 60% of the total mobile traffic.

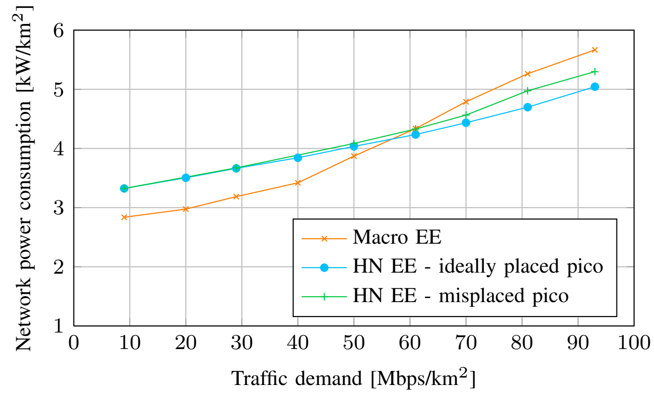

Fig. 7. Network power consumption versus area traffic demand

In this paper we show how an operator can use densification in such areas to address a need for additional capacity while at the same time maintaining the energy consumption to a reasonable level. Our results point out that heterogeneous deployment, where additional low power nodes are introduced in an existing network, can be an energy efficient solution. By serving the users from a nearby pico node, energy is saved in the macro node. If micro DTX is used in all nodes (macros and picos) and if the pico nodes are put in a deep sleep mode when they are not carrying any user traffic, then a significant reduction of the network energy consumption can be achieved.

In this study we have assumed that the macro node is responsible for activating the pico nodes inside its coverage area. The results show that the increased user throughput provided by the network densification also provides more time for nodes to sleep. By introducing the energy efficiency features studied in this paper (pico sleep and micro DTX) when upgrading to a denser heterogenous network we can increase user performance and reduce energy cost during peak hours, both at the same time.

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