



Toward Energy Proportional Networks

Nicolas Montavont², Dareen Shehadeh², Jacques Palicot¹, Xavier Lagrange², Alberto Blanc², Rémi Gribonval⁵, Philippe Mary⁴, Jean-Yves Baudais³, Jean-François Héland⁴, Matthieu Crussière⁴, Yves Louët¹, Christophe Moy¹

1. Centrale Supélec / IETR, {prénom.nom}@centralesupelec.fr
2. Institut Mines Télécom, Télécom Bretagne, IRISA, {prénom.nom}@telecom-bretagne.eu
3. CNRS, IETR, {prénom.nom}@insa-rennes.fr
4. INSA Rennes, IETR, {prénom.nom}@insa-rennes.fr
5. Inria Rennes, IRISA, {prénom.nom}@inria.fr

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Introduction

As in almost all areas of engineering in the past several decades, the design of computer and network systems has been aimed at delivering maximal performance without regarding the energy efficiency (EE) or the effective resource utilization. The only places where this tendency was questioned were on battery-operated devices (such as laptops and smartphones) for which the users accept limited (but reasonable) performance in exchange for longer use periods. Even though the end users make such decisions on a daily basis by checking their own devices, they have no way of minimizing their energy footprint (or conversely, optimize the network resource usage) in the supporting infrastructure. Thus, the current way of dimensioning and operating the infrastructure supporting the user services, such as cellular networks and data centers, is to dimension for peak usage. The problem with this approach is that usage is rarely at its peak, so such overprovisioned systems allow delivering maximal performance, but most of the time they consume high level of energy.

Within the French CominLabs excellence Laboratory framework, the “Toward Energy Proportional Networks” (TEPN) project aims at studying a new telecommunication network paradigm centered on green wireless communications. The main idea of this project consists in adapting the energy consumption of the network to its actual use (in terms of number of served users, or requested bandwidth). An energy proportional network can be designed by taking intelligent decisions (based on various constraints and metrics) in order to (i) consume as low as possible energy for wireless transmission and (ii) adapt the network components to the actual use of the network. This concept can be summarized under the general term of green cognitive network approach. In order to reach this goal, several directions are investigated:

- Study the trade-off between EE and delays that could be introduced by new algorithms in order to drastically reduce the network energy consumption: what if some users could tolerate delays in some of the provided services?
- Define a centralized system which learns the network topology and can take efficient decision on switching on and off different component (carriers, entire base stations (BS), etc)
- Define cross-layer metrics to select which of the network components should operate given a traffic demand. Cross layers metrics concern energy related metrics at all layers of the communication system: electronic, radio interface, MAC protocols, network routing, connection protocol and also the source of energy. These metrics can be viewed as agents that can be integrated in a cognitive procedure.
- Study a new Green Multi-carrier Waveform to efficiently use the High Power Amplifier of the transmitter. Implement some PAPR mitigation method on test bed to illustrate the HPA EE at the BS level

1. TEPN Architecture

We assume a very simplified model of network as presented in Figure 1. It is presented as a tree where the leafs are wireless BS. These BS are the bridge between the wired network (which can be assimilated to the Internet access network) and the wireless clients. This architecture aims at suppressing (as much as possible) the backhaul; i.e., the operator's network between the BS and the Internet. As it is the case in community network, we will consider that most of BS, especially those providing micro cells, are directly connected to the Internet. So the operational cost (in terms of energy and financial) is significantly reduced. Specific functions, such as mobility management or paging would still require an operated network where the network is able to localize a given station in the network.

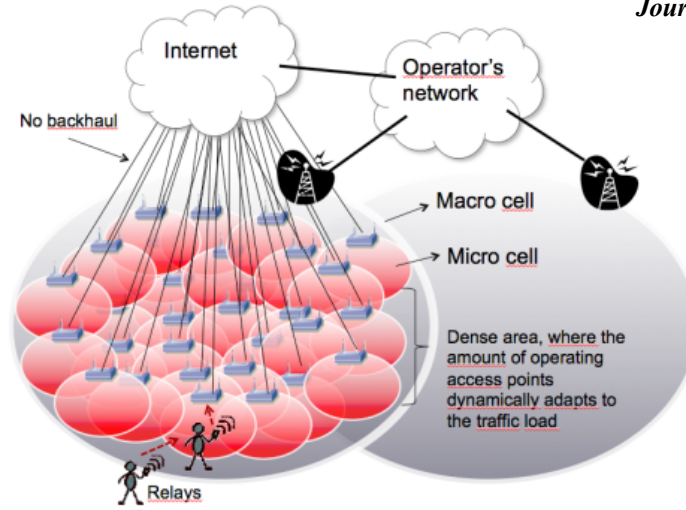


Figure 1: Network Architecture under consideration

2. Network breathing

In order to adapt the energy consumption to the network load, one solution consists in adapting the infrastructure to the traffic demand. This adaptation can be at different level, including physical characteristics of transmission to switching on and off an entire base station. To address this adaptation, we study the theoretical tradeoff between energy EE and spectral efficiency (SE) in large hexagonal-grid wireless cellular networks.

2.1. EE – SE tradeoff in interference limited networks

The total power consumption of a base station (BS) can be modeled through a linear relation with the transmit power P_t :

$$P_{BS} = aP_t + b$$

where a and b are the power amplifier efficiency and the static power respectively. The power received by a user at distance r_j from the BS, $j > 1$ is

$$P_j = P_t \left(\frac{r_j}{r_0} \right)^{-\alpha} Y_j,$$

r_0 being the close-in reference distance, α the path-loss exponent and Y_j a log-normal (LN) random variable (RV) characterizing shadowing with zero mean and σ as standard deviation in dB. Considering that $j = 1$ is the connected BS, the received power by the user of interest is

$$P_1 = P_t \left(\frac{r_H v}{r_0} \right)^{-\alpha} Y_1,$$

where r_H is the cell radius and $v = r_1/r_H$. Let assume a total available band equal to ω and the system uses a frequency reuse factor K , the Shannon spectral efficiency in bit/s/Hz is

$$\eta_{SE} = \frac{1}{K} \log(1 + \gamma)$$

where γ is the signal to interference plus noise ratio of the user of interest. The average EE can be expressed as

$$\eta_{EE} = \frac{\omega \eta_{SE}}{aP_t + b} = \frac{\omega \eta_{SE}}{a \frac{\left(\frac{r_H v}{r_0} \right)^\alpha \omega}{K} N_0 (2^{K\eta_{SE}} - 1)} + b$$

where $f(v, \alpha) = \sum_{j \geq 2} \left(\frac{r_j}{r_H v} \right)^{-\alpha} \frac{Y_j}{Y_1}$ is the interference to signal ratio (ISR) with shadowing. The analytical expression of $f(v, \alpha)$ is challenging even in the case where no shadowing is considered but a parametric expression of $f(v, \alpha)$ can be found in that case. When shadowing is considered, the EE-SE tradeoff needs to be redefined in a more convenient form. Indeed, SE becomes a random process, so does EE, and due to the slow variations in time of power due to shadowing, they are not ergodic process. The ϵ -SE is the largest rate, R , such that the probability of SE being below R is less than or equal to ϵ . As SE is an increasing function of γ , ϵ -SE can be written as

$$\eta_{SE}^{(\epsilon)} = \sup\{R: F_\gamma(2^{KR} - 1) \leq \epsilon\}$$

with F_γ is the cumulative distribution function (CDF) of the SINR. The outage EE is hence

$$\eta_{EE}^{(\epsilon)} = \frac{\eta_{SE}^{(\epsilon)}}{aP_t + b}$$

After tedious manipulations, an approximation of the CDF of γ can be obtained with a good accuracy and we found that $\gamma \sim LN(\mu_\gamma, \sigma_\gamma)$ where μ_γ and σ_γ are the mean of standard deviation of SINR in dB respectively [1]. Figs. 2 and 3 summarize the results of EE-SE tradeoff without and with shadowing respectively. In Fig. 2, only path loss is considered and it shows the tradeoff between EE and SE for various normalized distances between the user and its connected BS and various frequency reuse factors. It is interesting to remark that the EE-SE tradeoff has a large linear part before a sharp decreasing when η_{SE} is increasing. This large linear part is due to the large amount of energy spent in static power consumption into the BS. On the other hand, since the network is homogeneous (same BS transmit power) and interference limited, SE is converging toward a limit with very small transmit power and resulting in the sharp decrease of EE for further increase of P_t .

The optimal frequency reuse factor in Fig. 2 is 1 for $\nu=0.5$, while it is 3 for $\nu=0.85$. SE is inversely proportional to K and increases for lower K resulting in higher EE for a particular P_t . On the other hand, besides the increased noise power, ISR is also higher for lower K, resulting in decrease of SINR for the given transmit power. The SINR decrease is very significant for $K=1$ than the other values of K when ν is close to 1 preventing this frequency reuse factor to be the best choice. Decrease of SINR also results in lower SE and EE for a particular K as the user moves away from the BS.

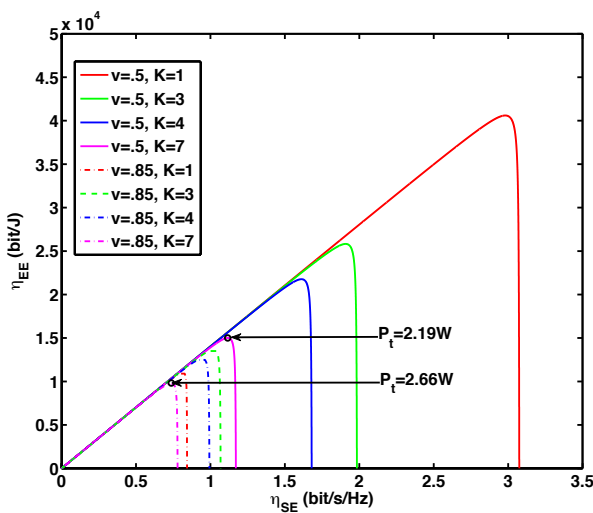


Figure 2 : EE-SE tradeoff according to normalized distances and various frequency reuse factors.

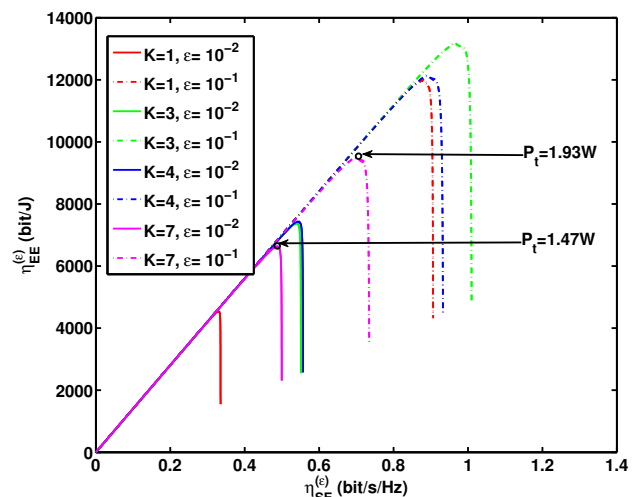


Figure 3: $\epsilon - SE - EE$ tradeoff for various frequency reuse factors and outage probabilities and $\nu=0.5$.

Fig. 3 illustrates ϵ -EE-SE tradeoff when $\sigma = 5$ dB. For a particular P_t and K, $\eta_{SE}^{(\epsilon)}$ increases as ϵ increases leading to higher values of $\eta_{EE}^{(\epsilon)}$. However, high ϵ causes lot of outage which is not necessarily desirable, but the value can be set according to the QoS to meet. From Fig. 3, it can also be observed that $K=3$ allows the highest EE and SE when $\nu=0.5$ due to the significant SINR decrease in shadowing environment when $K=1$. If the user moves further from the BS, eventually $K=4$ and $K=7$ are observed to achieve the best performance, but are not plotted here due to the lack of space.

On the other hand, we developed a centralized framework that gathers base station information (location, RSSI, bandwidth, etc) and run various algorithms to optimize the network deployment by turning on and off BS. We use a smart system to discover the BS topology, by taking advantage of the large number of mobile clients. Once learnt, the network topology is used to determine which BS are redundant, and which BS can be switched off in period of low traffic demand. Through network simulations in ns-3, we observed that in average traffic demand, delaying some users can save a large amount of energy.

2.2. AP switching ON/OFF in Dense WLANs

According to recent studies, the number of APs in urban areas has increased 14 times in one decade [5]. This proliferation of APs resulted in a high density and high energy consuming WiFi Networks. Moreover, APs are kept powered on all the time even when they are not being used such as at night causing unnecessary energy consumption. In order to reduce this wasted energy, a promising approach was proposed to dynamically adapt the number of active APs according the user traffic demand. This approach is based on switching off the APs that are not in use (have no users associated with) and keeping only some APs sufficient to provide service and connectivity to existing users.

In our work [4], we investigated the potentials of this approach and evaluated the redundancy of APs in dense WLANs. We studied the feasibility of reducing the number of active APs in a real urban environment. Through war-walking, we collected real measurements in the city center of Rennes using the application Wi2Me [6]. These measurements contain information about all the APs discovered during the war-walking including BSSID, SSID, channel number, signal level, supported security protocols, link data-rate, GPS coordinates of the mobile terminal and a timestamp. Then after analyzing and processing the raw data we obtain the *Coverage Matrix*, which represents the detected APs and their coverage (Figure 4).

Finally, we applied two algorithms called the *Greedy* algorithm and the *Continuous* algorithm, to select the Minimal Set of APs, i.e. we select the least number of APs that provide the same coverage for the investigated area as the original detected set of APs.

Our results show that it is possible to use only around 6.5% of the existing APs in order to provide the same coverage for users. Hence, the potential of energy saving obtained by switching off the non selected APs could reach 94%.

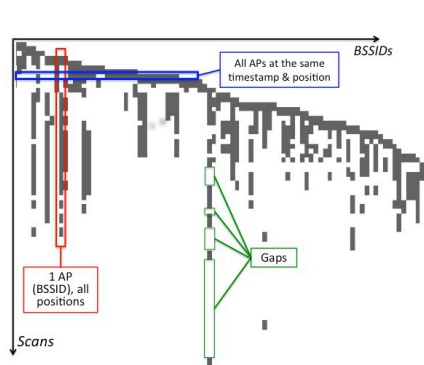


Figure 4: APs' Coverage Matrix

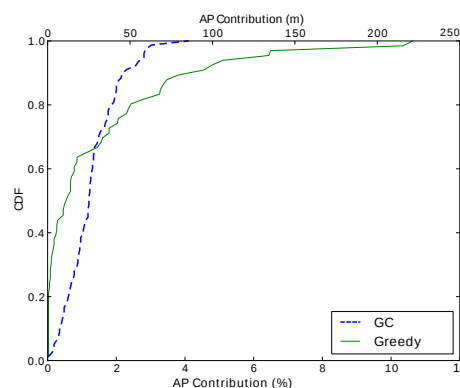


Figure 5: CDF of APs Contribution to Total Coverage (in percentage and in meters)

In continuity to this work, now we are studying how switching APs on and off in real time, in a synchronized manner. We are investigating the possible solutions and evaluating their performance in terms of the time needed to complete the wake up, the energy consumed, and the changes, if any, required in the mobile terminals.

On the other hand, and in the frame of a centralized system, we are developing a communication protocol based on 802.11k that permits to a centralized controller to communicate with the APs, order them to collect measurements and report them to it, and accordingly take the appropriate decision to switch off the unnecessary APs.

3. Design and implementation of new signal waveforms and processing

At the transmitter level, high power amplifier (HPA) is one of the most energy consuming equipment (as in BS). The high consumption of the HPA (mainly due to the very low efficiency) added with the cooling consumption result in consumption greater than 50% of the overall base station consumption. Decreasing this consumption contributes not only to goals for sustainable development, but also to the profitability of the telecommunication industry. To reach this objective we may process at the signal level. It is possible to decrease the peak-to-average power ratio (PAPR) of classical multi-carriers waveform or to define a new waveform which exhibits a very low PAPR.

3.1. PAPR decreasing techniques

In the literature, two main approaches are usually advocated to solve the problems of the PAPR and the non-linearity of the PA. The first one is to carry out PAPR reduction methods consisting in reducing the dynamics of the signal by means of dedicated signal processing, such as clipping, coding, Selected Mapping (SLM) and Tone Reservation (TR). The second approach which can be used in a complementary way with the former is to make use of linearization techniques that tries to compensate for the non-linearity of the PA (Digital Pre-Distortion, Linear Amplification with Non-linear Component method and Feedback). Hence, an efficient implementation of a communication system in which the PAPR of the signals plays an important role should embed a PAPR reduction technique followed by a linearization process. We propose a smart solution that would control the PAPR reduction and linearization stages in a flexible way according to some predefined parameters so that they become adaptive and self-configurable.

3.2 New Waveform design

The objective of this study is to define a new multicarrier waveform keeping the advantages of OFDM signals, mainly the good performances w.r.t. the multipath channels. The main idea is based on a new orthogonal basis to build the multicarrier signal. A possible interesting solution is also submitted to this conference.

4. Decision Making for Green Cognitive Networks (GCN)

In order to make appropriate decisions (the best decision to reach greener behavior in our project), cognitive radio equipment relies on information gathered from the environment in order to adapt itself in the best possible way to its changes. In a context of high uncertainty and unknown environment, as often expected in a Cognitive Radio context, reinforcement learning is a promising solution for intelligent decision making. Dynamic spectrum access is a main topic of cognitive radio which has motivated the use of learning policies such as UCB (Upper Confidence Bound) to solve a MAB-based problem (Multi-Armed Bandit) with the goal to learn about frequency opportunities in the environment. TEPN extends this approach while combining an energy-efficiency perspective with previous solution tackling spectrum scarcity. QoS-UCB algorithm is proposed by TEPN as a new solution based on both channel quality information and availability. Paper [3- is also submitted to these URSI Scientific Days on that topic.

5. Conclusion

In this paper, we showed the approaches followed by the TEPN project to make the energy consumption of a network proportional to its load. By studying the trade-off between energy efficiency and spectral efficiency, we are able to establish theoretical bound of the problem. Then we worked on three solutions: switching on and off APs in order to make the network breath depending on the user traffic, design of new waveform and finally defining new decision making algorithm to use cognitive radio. Next we want to use the intelligent decision making algorithm in defining AP-user links to not only minimize the number of APs that are active, but also to better tune the radio to find the best compromise between the coverage and the bandwidth.

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