Energy- and Spectral-Efficient Wireless Cellular Networks

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Abstract. The limited spectrum resources and the negative impacts of carbon dioxide emission resulted from inefficient use of wireless technologies have led to the development of green radio. Both the energy and spectral efficiencies should be considered together to meet green radio requirements. In this paper, we investigate the trade-off between energy efficiency and spectral efficiency through different approaches. Cognitive radio is a paradigm-shift technology which is used to increase both the energy and spectral efficiencies. Some efficient spectrum sensing techniques are considered in terms of energy and time consuming. Furthermore, it can be shown that the power control strategies can play a key role in avoiding interference between cognitive and primary users, and hence it can also enhance both the energy and spectral efficiencies. In addition to cognitive radio, a new infrastructure for deploying the cellular base stations which is a heterogeneous infrastructure of macro-, pico-, and femto-cells is proposed to overcome the energy and bandwidth constraints. Further details related to hardware-constraints in a green base station have also been covered.

Keywords: Green radio, energy efficiency, spectral efficiency, cognitive radio, spectrum sensing, transmit power control, heterogeneous networks.

1 Introduction

The continuous rapid growth in wireless applications, devices and demands has led to a rapid growth in energy consumption and spectrum utilization. Due to this growth, both energy and bandwidth resources became so limited for wireless traffic. The limitation of energy resources is represented by the excessive emission of carbon dioxide (CO2) which is the chief greenhouse gas that results from wireless applications and other human activities and causes global warming and climate changes. This gas is accelerating continuously, as shown in Fig. 1, and need to be stabilized [1].

In the field of communications, more than 12,000 new base stations are installed every year to provide services to 300-400 million new subscribers around the world [2]. Many of these stations are driven by inefficient diesel generators which produces

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the carbon footprint. Each base station antenna consumes an average power of 1KW which means 8,800 KWh each year [3]. A network with a medium size normally consists of 12-15,000 cell sites, each can serve two technologies (2G & 3G), and each technology needs around three antennas per technology, which tends to a total energy of 736,000 MWh which can run 168,000 European family houses [3]. Such statistics give a clear indication that the Information and communication technologies (ICT) contribute in the total world's carbon footprint.

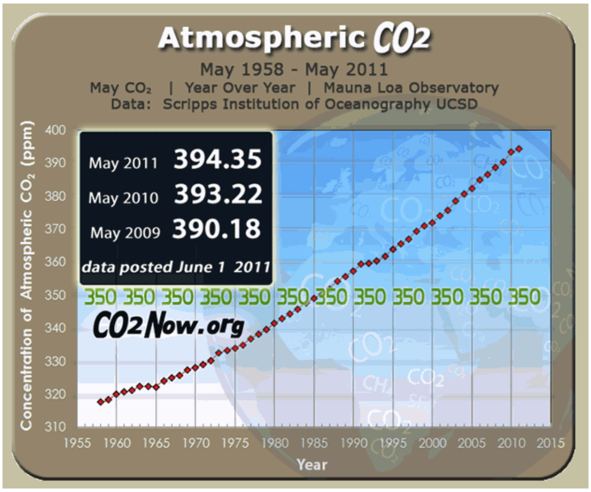


Fig. 1. Concentration of atmospheric CO2

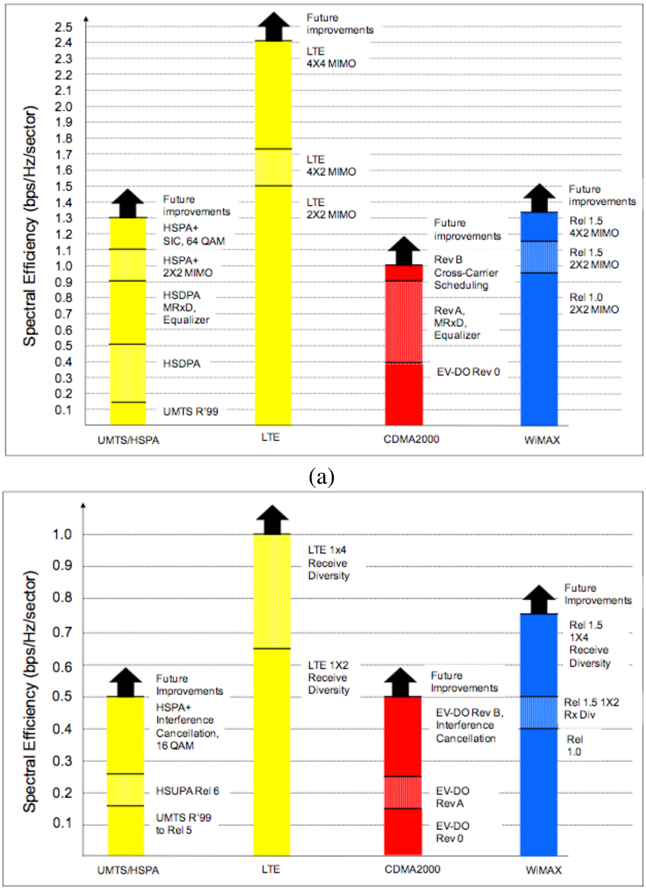
On the other hand, the limitation in bandwidth resources is represented by the fact that the spectrum is not free and it is fixed. Data traffic has increased in the recent years due to the presence of iPhone and other smart software technologies and due to the variety of applications, and it is expected to grow more with the introduction of LTE-A which supports 100Mbps for down-link. In order to achieve such high bit rate, we need to improve the spectral efficiency of the channels.

So far, the improvement in spectral efficiency has been the main interest of the research without much consideration of the energy efficiency metrics. Those two parameters (energy- and spectral-efficiency) should be considered together in order to meet what is known as "Green Radio". In Green radio, both energy efficiency and spectral efficiency need to be maximized. However, they are, sometimes, two conflicting parameters which mean that any increase in spectral efficiency will lead to undesirable increase in power consumption [4]. Therefore, finding a trade-off between the energy- and spectral-efficiency is the goal of this paper. In this paper, we will survey and propose the state-of-the-art the energy- and spectral- efficient technologies that need to be considered in the current and next generation wireless networks.

The rest of the paper is organized as follows. In Section 2, both the energy and spectrum efficiencies are defined and the trade-off between those two parameters is investigated. Section 3 shows the green wireless base stations architecture. Cognitive radio as a promising technology for green radio will be covered in section 4. In Section 5, Heterogeneous network optimization will be suggested to meet a green next generation wireless communication deployment. Finally, the conclusions and recommendations for future work are drawn in section 6.

2 The Trade-Off between Energy and Spectral Efficiencies

The more energy-efficient communication system, the less energy required to achieve the same task. On the other hand, the more bandwidth- (spectral-) efficient communication system, the more bits per second it can transfer through the same channel. The maximization of spectral efficiency is one of the main targets that should be achieved in the next generation networks. Fig. 2 shows a comparison between spectral efficiencies required in different technologies for down-link and up-link transmission.



(a)

(b)

Fig. 2. Spectral efficiency comparison; (a) downlink and (b) uplink

On the contrary, there was no big interest in improving the energy efficiency. Now, green communication is a major challenge and introducing energy-efficient communication systems should be added to the list of major interests of academic and industrial researches. Sometimes, energy and spectral efficiency conflict each other. To formulate this trade-off, the Shannon's capacity equation for point to point communication with AWGN plays the key role [5]:

$$C = B\ log_2\left(1 + \frac{S}{N}\right) \qquad bps\ . \tag{1}$$

where B is the channel bandwidth (Hz), S is the signal power, and N is the noise power which is NoB, where N_o is the power spectral density for AWGN. Therefore:

$$C = B\ log_2\left(1 + \frac{S}{N_oB}\right).$$

The bandwidth (spectral) efficiency (η_B), is the achievable transmission rate per unit bandwidth (bps/Hz):

$$\eta_B = log_2\left(1 + \frac{S}{BN_o}\right). \tag{2}$$

The energy efficiency (η_E), is the transmission rate per unit energy (bps/W):

$$\eta_E = Blog_2\left(1 + \frac{S}{BN_o}\right)/S\ . \tag{3}$$

Therefore, the relation between spectral efficiency and energy efficiency is shown below [7]:

$$\eta_E = \frac{\eta_B}{(2^{\eta_B}-1)N_o}\ . \tag{4}$$

This relation can be represented by a convex curve shown in Fig. 3.

However, there are many other factors that affect the relation between spectral efficiency and energy efficiency:

- Physical layer transmission: The transmission parameters and strategies, such as modulation order, transmission distance and coding scheme, may also affect the energy and spectral efficiencies. An extensive analysis for the energy-efficient transmission in wireless networks has been achieved in [5].
- Multi-cell/Multi-user systems: the above Shannon equation is for point-to-point communication. In the real wireless network environments many parameters should affect the trade-off such as the inter-cell interference and inter-user interference. i.e., the inter-cell interference degrades both the spectral and energy efficiencies [6].
- The channel state: According to Shannon's equation, using high bandwidth channels can improve the energy efficiency. However, delay spread and frequency selectivity should also be taken into account in trade-off calculation [5].

Hardware energy consumption: circuit power and real practical hardware constraints should be considered in the calculation of this trade-off:

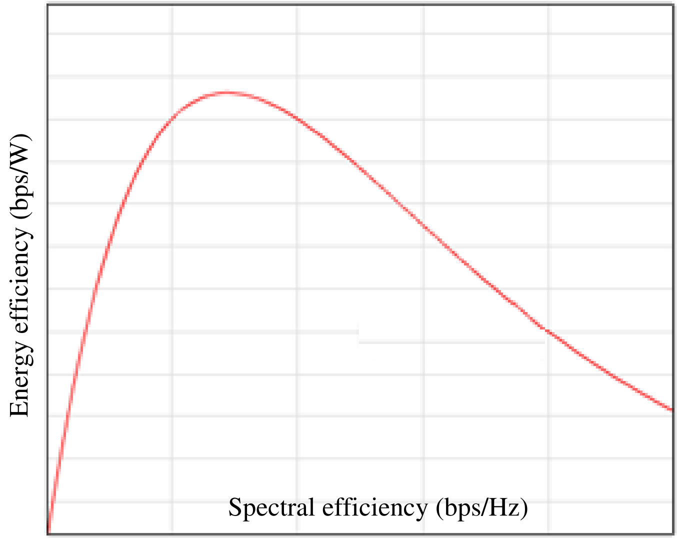


Fig. 3. Energy vs. spectral efficiency in point-to-point communications

3 Green Base Station

Due to the increase in wireless demands and users, the cellular operators had to increase the number of base stations to provide more wireless services to bigger number of users. This growth in number of base stations makes the operators looking seriously for efficient equipments to overcome the energy constraints. The cellular base station consists of several power consuming equipments as shown in Fig. 4. Those equipments consume different amount of power in different technologies as shown in Table 1:

Table 1 shows that the power amplifier is the major source of power consumption in the base station. The more energy-efficient base station, the less heat produced by the equipment, and thus, the less amount of air-conditioning required for cooling. Therefore, the improvement of efficiency of the power amplifier will reduce the power consumption of the main parts in a base station. The energy efficiency of the power amplifier can be improved by using a proper linearization and DSP methods to decrease the required linear area. Besides the power amplifier improvement, there are several approaches that have been proposed in the literature to introduce more energy-efficient base stations. [7, 8] proposed a dynamic planning based on traffic intensity by switching off the underutilized base stations (i.e. during night periods) while maintaining the required quality of service. The results show that the implementation of this approach can save up to 50% of the power consumption. The cooperation between two networks by switching off one of them during low traffic has been investigated in [9] in terms of power saving.

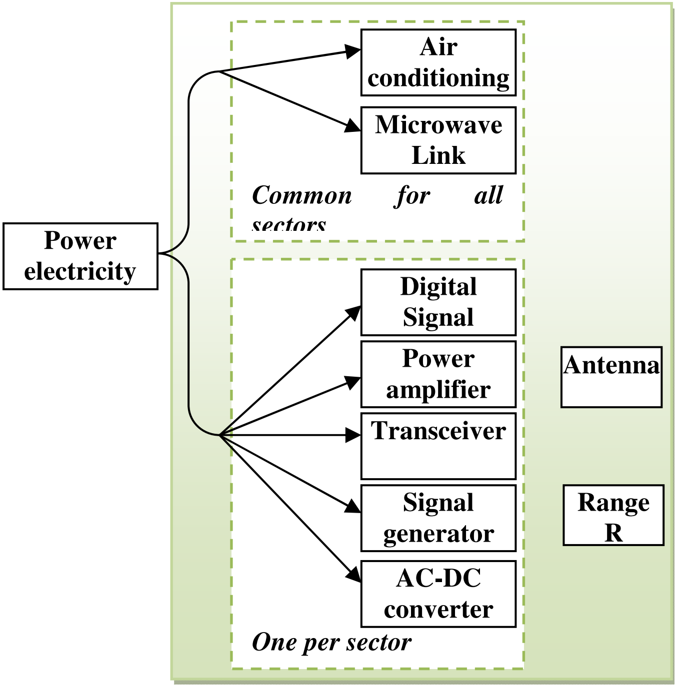


Fig. 4. Power consuming equipments in cellular base station

Table 1. Power consumption of different parts of wireless base stations

Equipment	WiMAX	HSPA	LTE
Digital signal processing	100 W	100 W	100 W
Power amplifier SISO (1x1)	100 W 10% 40dbm	300 W 6.67% 43dbm	350 W 6.3% 43 dbm
Power amplifier MIMO	10.4 W 11.54% 30 dbm	10.4 W 11.54% 30 dbm	10.4 W 11.54% 30 dbm
Transceiver	100 W	100 W	100 W
Signal generator	384 W	384 W	384 W
AC-DC converter	100 W	100 W	100 W
Air conditioning	690 W	690 W	690 W
Microwave link	80 W	80 W	80 W

Also, multiple-input and multiple-output, or MIMO, is considered in the new transmitting systems to improve the system capacity. By improving the spectral efficiency, the transmission duration is reduced which tends to reduction in transmitted power and circuit power consumption. On the other hand, more active components are needed by exploiting MIMO which increase the total power consumption. According to these conflicting facts, the impacts of MIMO techniques on energy efficiency has been addressed in [10, 11] and it was shown that cooperative MIMO transmission and reception can outperform the SISO systems in terms of the energy efficiency, as shown in Fig. 5, when the adaptive modulation is used to control the transmit and circuit energy consumption [10]. However, SISO systems is more energy-efficient than MIMO systems when the latter is not combined with adaptive modulation. Further investigation is required to optimize the MIMO systems for next generation wireless networks in terms of energy efficiency, spectral efficiency and overall complexity.

4 Cognitive Radio

The spectral utilization is one of the most critical problems that face the rapid developments of wireless communications. Previous researches followed some approaches to increase the spectral efficiency at the expense of energy efficiency. Recent researches in cognitive radio technology [4, 12-14] have brought a significant improvement towards green wireless communication. The cognitive radio technique will provide the wireless users with a high bandwidth and allow them to use the unutilized (white) spectrum through dynamic spectrum access techniques [15].

In order to achieve efficient utilization of the spectrum, the unlicensed cognitive radio user (secondary user) can adapt its transmission and reception parameters to avoid interference with the primary user, and thus, it gives a significant enhancement

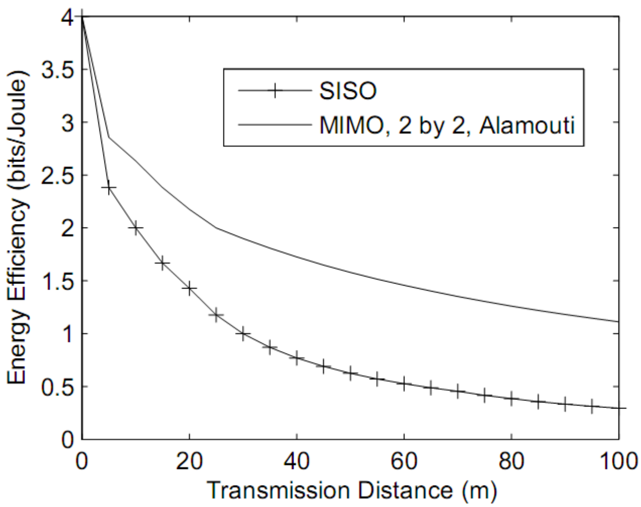


Fig. 5. Comparing energy efficiency of MIMO and SISO

to green wireless networks. In [12], an energy optimization framework shown in Fig. 6 has been proposed to adjust parameters (e.g., modulation, radiated power and coding) and components characteristics (e.g. power amplifier) using cognitive radio.

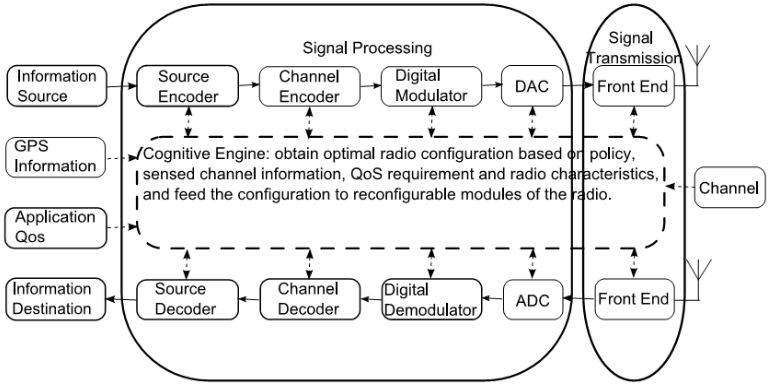


Fig. 6. Cognitive radio energy optimization framework

According to [12], Fig. 7 shows the simulation of this framework using cognitive transmission over adaptive modulation along with power amplifier radiated power and it shows a significant energy saving up to 75%. However, the energy saving becomes less significant as the distance increases.

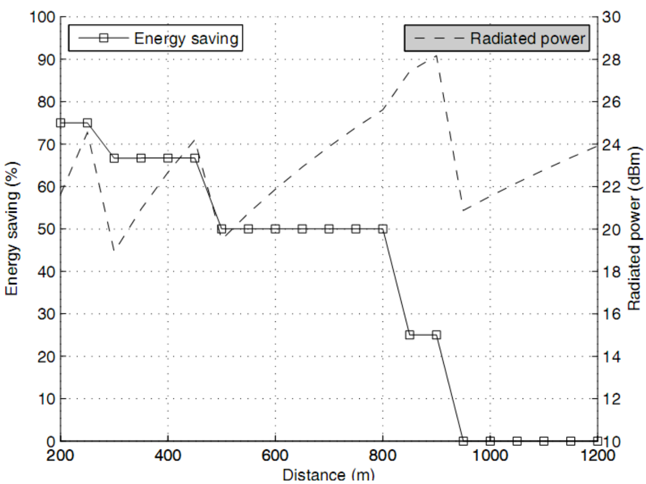


Fig. 7. Energy saving with cognitive transmission

The cognitive radio is a paradigm-shift technology that let the user interact intelligently with the environment through what is known as cognition cycle. This cycle consists mainly of four consecutive steps as shown in Fig. 8.

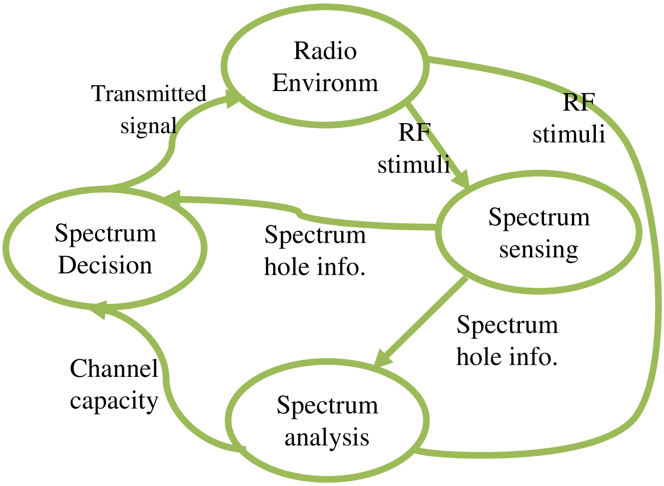


Fig. 8. Cognition cycle

First, the cognitive radio technique will let the unlicensed users to determine which portion of the spectrum is currently not used (spectrum holes) and detect the existence of the primary licensed users, (spectrum sensing) [16]. Those unlicensed users should keep monitoring the spectrum continuously and therefore, they will still active. Due to this pivot role, the spectrum sensing is considered as one of the most time and energy consuming part of the cognitive radio device. Previous work concentrated on the time overhead of the spectrum sensing [17, 18]. In [16], an optimal sensing duration has been designed to maximize the throughput using the energy detection scheme. [17] studied the trade-off between the spectrum usage time and the energy efficiency of the spectrum sensing. Recently, and due to the green communications trends, the energy consumption of the spectrum sensing becomes one of the most challenges that face the academic researches nowadays. J. Wei and X. Zhang proposed an energy-efficient spectrum sensing technique using cluster-and-forward based Distributed Spectrum Sensing (DSS) [19]. This technique has shown a significant decrement in the total energy consumption while maintaining high sensing accuracy. A further improvement to the energy efficiency of the spectrum sensing has been proposed by [20]. The researchers proposed a Time-Division Energy-Efficient (TDEE) sensing technique that well balanced the trade-off between spectral efficiency and energy consumption by investigating heterogeneous and homogeneous networks. Although there was a good investigation for the efficient spectrum sensing, the green cognitive radio still need more interest to study the trade-off between all the spectrum sensing parameters which are: energy efficiency, spectral efficiency, sensing time and accuracy. However, the complexity of spectrum sensing can be reduced by exploiting some artificial intelligent techniques [14].

After sensing the spectrum, the cognitive radio user has to select the best available channel to meet the quality of service requirement over all available spectrum bands (spectrum management) [21]. Then, it allows the secondary user to access this channel along with the other users (spectrum sharing).

For cognitive radio, the introduced solutions for spectrum sharing can be classified into three phases: i.e., according to their architecture, spectrum allocation behavior, and spectrum access technique [22]. Upon the information available from the spectrum sensor, the cognitive radio user varies its transmitted power to maximize its performance. This operation is called "Transmit Power Control (TPC)". TPC can play an important role in terms of green radio optimization by improving power efficiency. In order to increase the spectral efficiency, higher power levels should be allocated to more fading channels and low levels to better ones and therefore the interference will be minimized. Previous work in power control showed a big interest on maximizing the spectral efficiency, e.g., [23] proposed an optimal power control over different fading channels to maximize the ergodic capacity of the secondary user taking into account the primary user protection. By considering that the secondary user can share the licensed spectrum with the primary user as long as its interference power to the primary user still below a specific threshold level, [24] investigates the capacity gain offered by this spectrum sharing approach in Rayleigh fading environments, and derived an optimal power allocation scheme from the outage and ergodic capacities points of view. However, we can improve the power efficiency by using power truncation such that the secondary user can transmit in good channel conditions and abstain from transmission otherwise [25]. In such cases, bad channel conditions will cause long time delays which improve the power efficiency due to power truncation but, on the other hand, will minimize the spectral efficiency. Therefore, a trade-off between a spectral efficiency and power efficiency has been investigated in [25] as shown in Fig. 9. This figure shows the energy efficiency and goodput versus peak power in case of power truncation. Here, we can see that, at low level of peak power, the goodput is increasing as the peak power decreases. Further decreasing in peak power will result in goodput reduction while the energy efficiency is still increasing.

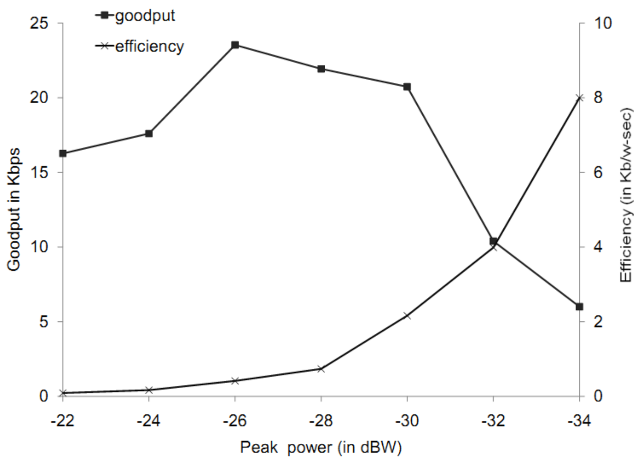


Fig. 9. Goodput & efficiency vs. P_{peak} at $I_{max} = 2\times10^{-12}$W and SNR=12dB

When the primary user has been detected, the cognitive radio user should leave the channel and access other unutilized channel (Spectrum mobility). Spectrum mobility presents a new type of handoff in next generation networks which is known as spectrum handoff. The purpose of spectrum mobility is to ensure a smooth and quick transition between different operational modes [15].

5 Heterogeneous Networks

Current wireless cellular networks are homogeneous networks that are deployed using a macro-centric planned process. In such deployment, all macro base stations have similar parameters, e.g., backhaul connectivity to the data network, antenna patterns, power levels, and receiver noise floor [26]. With the growing of wireless traffic demands, more flexible deployment architecture is needed to overcome capacity, and link budget limitations and to maintain user satisfaction. Therefore, the heterogeneous network is the alternative deployment that brings the network closer to the user. The heterogeneous network consists of a high power macro base station, several low power pico, femto, and/or relay base stations. Although the major target of heterogeneous network deployment is to improve capacity, it has a significant potential to improve the energy efficiency. [27] studied the power consumption of combined macro- and femto-cells architecture and found that the overall power consumption can be reduced depending on the uptake of femto-cell usage. Different femtocell capacities have been used in the simulation made by [27] as shown in Fig. 10.

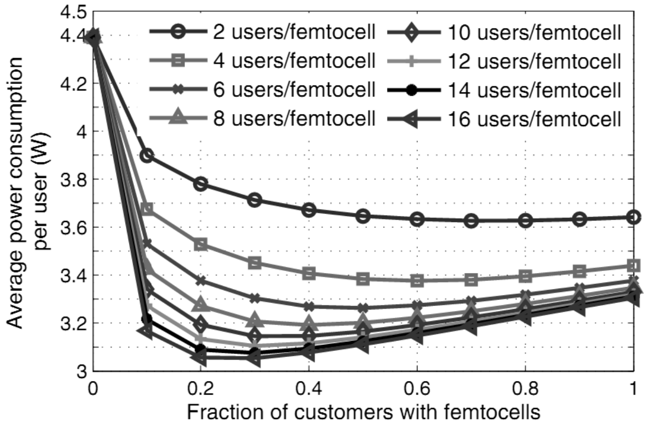


Fig. 10. Power consumption per user for different levels of femtocell support

It is clear from the figure that more power can be saved as the capacity of femtocell increases. This result can be explained from two points of view. First, the smaller the capacity of femtocell the more users need to connect with macrocell, and therefore, the more power required to perform this long connection. Second, the more users served by one active femtocell, the more other femtocells can be switched to sleep mode, and therefore, the more power can be saved. Also, a combination of pico- and macro-cells architecture has been investigated by [28] and a simulation has been made to show that such deployment can reduce the energy consumption for high data rate user demands as shown in Fig. 11.

In the mentioned work, the researchers build their results upon the power consumption measurements. Other metrics like Energy Consumption Gain (ECG) and Energy Consumption Ratio (ECR) have been identified to quantify energy consumption performance in small cell size deployment [29]. Further verifications for power saving can be achieved by measuring the energy efficiency of such networks. In [30], the overall average cell energy efficiency with unit of bits per Joule has been derived for heterogeneous cellular deployment to as follows:

$$E_{e,cell} = \frac{R_{Ma}+\sum_{n=1}^{N} R_{pi,n}}{P_{Ma}+\sum_{n=1}^{N} P_{pi,n}}. \tag{5}$$

Where R_{ma} and $R_{pi,n}$ denotes the average data rate provided by macro and *nth* pico cells respectively. P_{Ma}, and $P_{pi,n}$ represents the power consumed by macro and nth pico stations respectively.

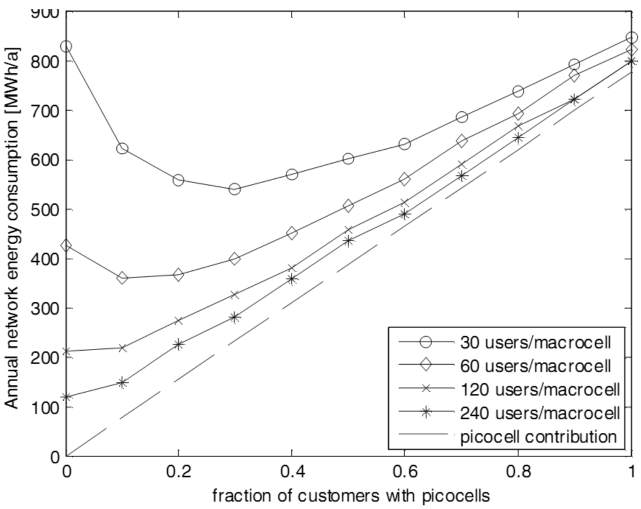


Fig. 11. Power consumption per user for different levels of femtocell support

In addition to the energy efficiency, [30] studied the effect of cell size on the energy efficiency performance by introducing another important metric which is: Area Energy Efficiency (AEE). Further improvement in terms of energy efficiency can be added to the heterogeneous cellular networks by considering low power sleep mode solution when a cell is not used [31]. Further green techniques, projects, and metrics have been surveyed and summarized in [32].

6 Conclusions

In this paper, the relation between energy efficiency and spectral efficiency is investigated under several approaches and constraints. Several approaches, such as cognitive radio and heterogeneous network, are discussed in term of energy and spectral efficiency optimization to meet green radio requirements. In cognitive radio, we show that it can improve the energy efficiency in spite of that its major role is to maximize spectral efficiency. Designing an efficient spectrum sensing algorithm in terms of energy, time and accuracy is one of our interests for future work. Also, heterogeneous wireless network can be used to maximize both the spectral and energy efficiency. Sleep-mode strategy and cell-size reduction are the main techniques used with deployment of heterogeneous network. In addition to that, green base station architecture is proposed to enhance the energy efficiency of energy consuming parts of the base station (e.g. power amplifier). And multiple antennas (MIMO) can be used to maximize the capacity and further investigation needed to optimize the design of MIMO transmitters and receivers in terms of energy efficiency, spectral efficiency and overall complexity.

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