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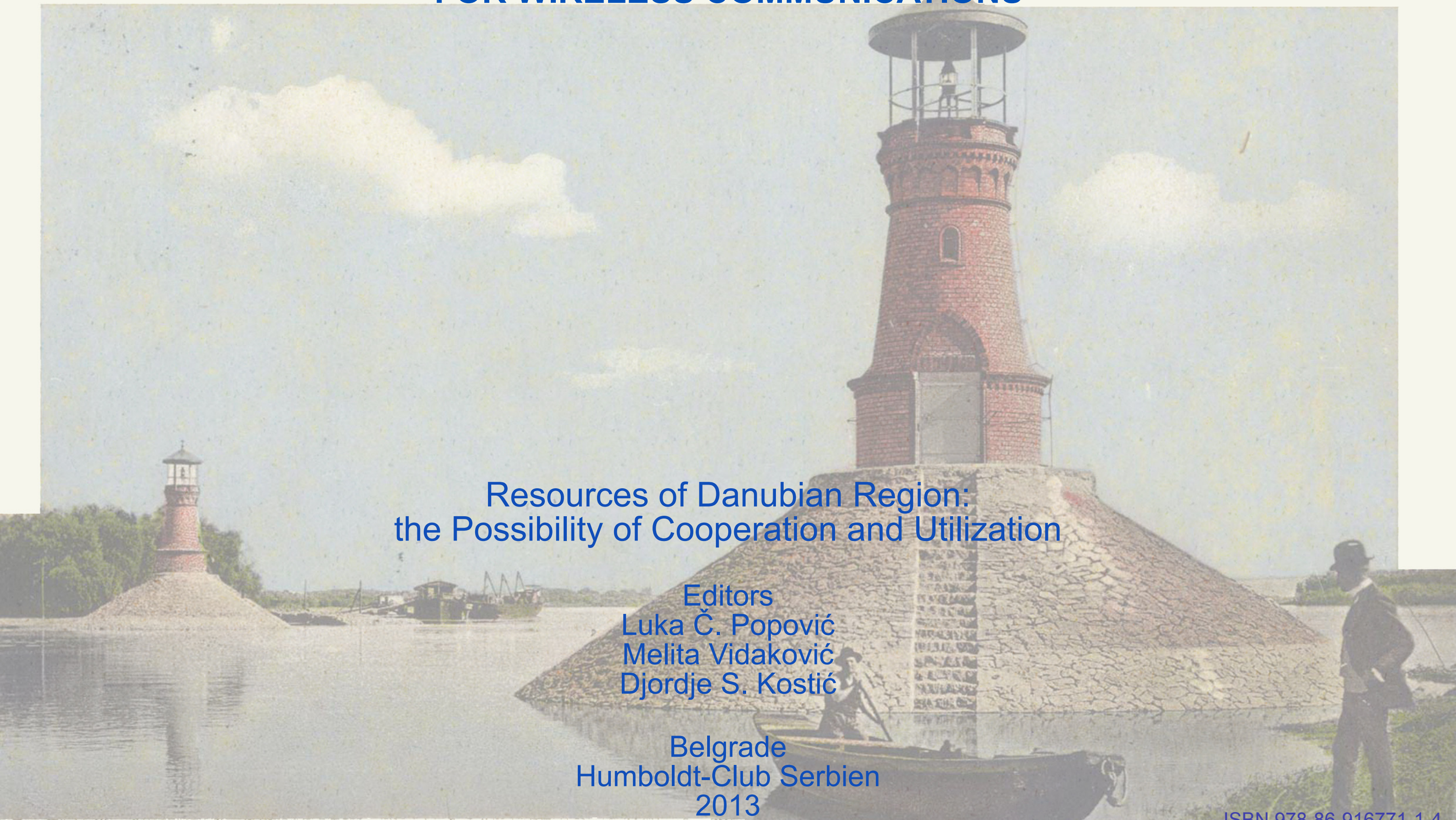
APPROACHES FOR REDUCING POWER CONSUMPTION FOR WIRELESS COMMUNICATIONS



Resources of Danubian Region:
the Possibility of Cooperation and Utilization

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Belgrade
Humboldt-Club Serbien
2013

ISBN 978-86-916771-1-4

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Abstract. Telecommunication infrastructure presents a significant part of the economy of most countries worldwide. For example in the United States, it is about 4% of both the economy and the energy useage. This paper overviews the newest available data for electrical power consumption related to communications, with a focus on cellular wireless infrastructure. An overview of engineering approaches to reduce the power consumption, moving towards „green“ base-stations is presented, with a focus on new techniques for radio-transmitter efficiency improvements in the 2-GHz cellular band.

I. Introduction

Telecommunications present a significant part of the economy; in the United States of America it is about 4%, and corresponds to roughly 4% of the energy useage as well. In 2011, the country consumed 97 quadrillion BTUs [1]. In 2008, the total power, in gigawatts (GW) used in telecommunications consisted of radio and television broadcast transmitters, cellular base-station tower equipment, internet, cable television and data centers such as Gogle, and the approximate numbers for the United States are shown in Table I.

Table I. Approximate power useage in the USA for various communications.

Application	AM/FM Radio	TV transmitters	Cellular basestations	Cable TV	Data centers
Power usage	0.03/0.3 GW	3 GW	2 GW	1 GW	10 GW

The number of cellular users and base-stations is increasing rapidly worldwide, as is the number of internet users, therefore increasing the energy demands. The number of Industry is investing $30B/year in the US for capital expenditures related to the wireless cellular infrastructure. This paper discusses and tries to answer the following questions:

- How rapid is the growth of cellular infrastructure?
- How does it impact overall power consumption?
- What are some of the approaches engineers are taking to reduce this power consumption?

II. Growth of Cellular Infrastructure

The estimated subscriber connections since 1985 show an increase from 110,000,000 to 350,000,000 in the past 12 years, indicating the fact that people want to be connected [2]. Figure 1 reproduces the plot from [2] that shows the trends over the past several decades. The inset in the figure shows that cell phones have become prevalent in our lives, and are worn on legs and used everywhere, including bath-tubs, though this is not advisable as water attenuates microwave frequencies heavily, even if the casing is water-proof.

This talk will first present the newest available data for world-wide consumption related to communications, and focus on commercial wireless communications power consumption. More connectivity, as descrbed in Figure 1, means more cell sites that service increased numbers of users and traffic. Figure 2 shows a photo of a typical cell phone tower base station in the inset. The number of sites in the United States installed since 1985 are shown in Figure 2. The increase in cell site numbers from 30000 in 1996 to 0.3 million towers in 2012 implies dramatic increase in power consumption. Since a large fraction of the hardware is related to the radio-electronics industry, the growth in cellular

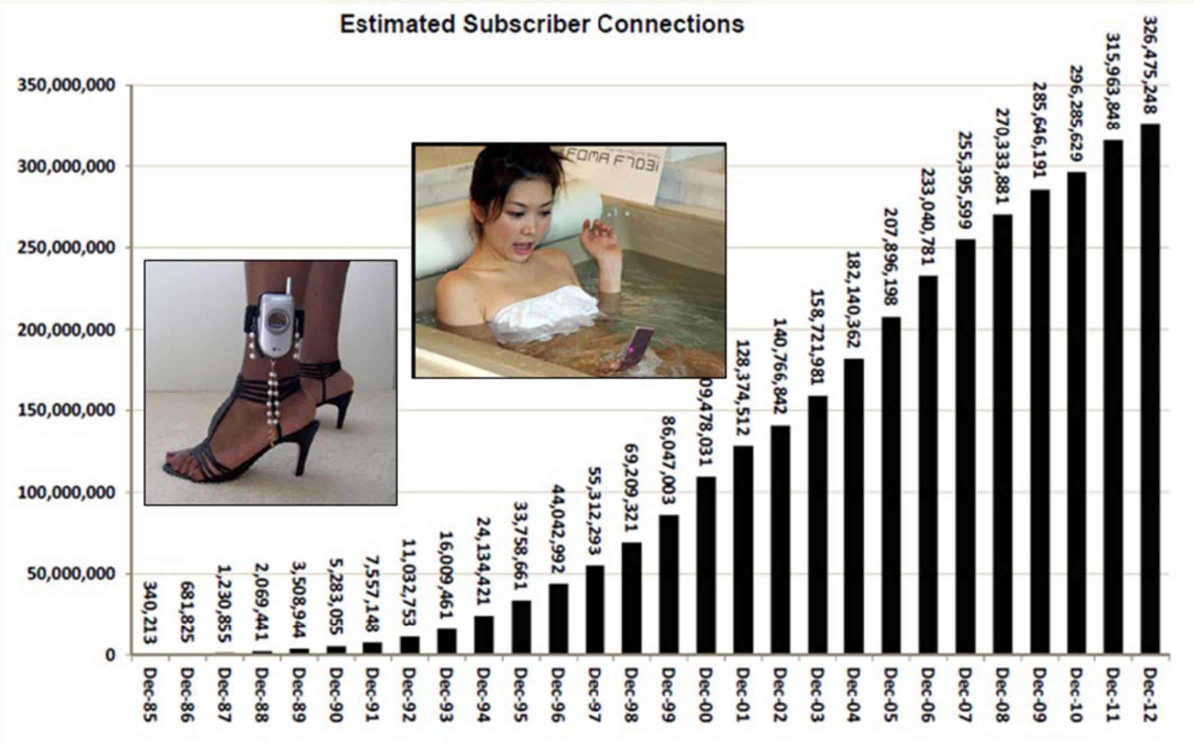


Figure 1. Data taken from [2] shows the dramatic increase in estimated cellular wireless subscriber connectionssince December 1985. The increase is exponential until about 2008, and is showing some saturation in the past 4 years.

infrastructure is accompanied by growth in the radio-engineering sector of the electronics industry. The total market is expected to grow to US$1.9B, and the cellular infrastructure is expected to be a US$1.2B market, as illustrated in Figure 3.

The power consumption of each cell site is related to the data rates per user. Personal computer, tablet, and smartphone users demand an average data rate of 2 Mb/s, 1 Mb/s, and 250 kb/s, respectively. These rates represent a range from high-definition video streaming with a display resolutions of 1280 × 720

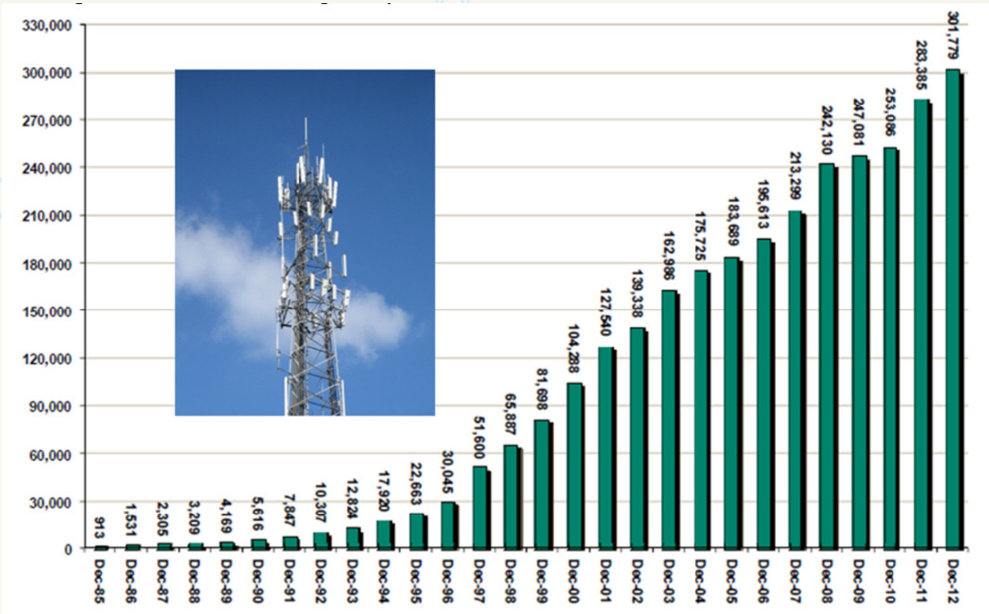


Figure 2. Data taken from [2] shows the number of cell sites in the United States installed since 1985. The increase in cell site numbers from 30000 in 1996 to 0.3 million towers in 2012 implies dramatic increase in power consumption.

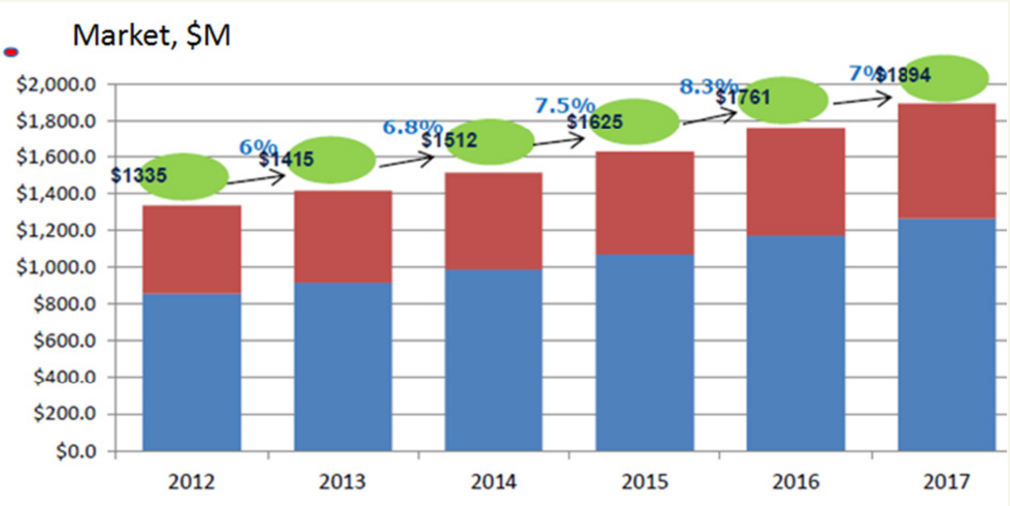


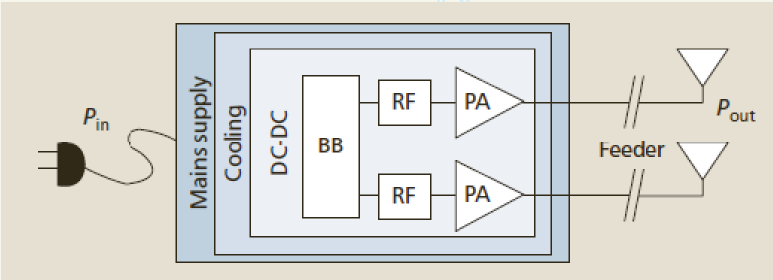
Figure 3. Data taken from [3] showing the projected increase in cellar infrastructure in the next few years.

pixels (720p HD) to intensive web browsing, which accumulates to a data volume of 900 Mbytes/h and 112.5 Mbytes/h, respectively. Ordinary users demand 1/8 of the respective heavy user rates. When the data rates increase, the bandwidth of the radio-link increases, thus increasing the power consumption. In the next section, the parts of a typical base-station and the fraction of the total power consumption that they contribute is discussed.

III. Base-station Hardware Power Consumption

A base-station consists of multiple transceivers (TRXs), each of which serves one transmit antenna element. The antennas are pointed in different directions (referred to as "sectors") in order to cover space omnidirectionally in the horizontal plane. A TRX consists at a high level of a power amplifier (PA), a radio frequency (RF) small-signal TRX module, and a baseband mixed-signal (analog and digital) unit including a receiver (uplink) and transmitter (downlink) section, digital signal processing circuits, a DC-DC power supply, an active cooling system, and an AC-DC unit (mains supply) for connection to the electrical power grid. This is illustrated in Figure 4.

The influence of the antenna type on the power efficiency is modeled by a certain amount of loss, including the feed cable, bandpass filters which are designed for a specific band that is licensed by the provider, duplexers, and matching components. The feed loss is typically about 3dB (or, half of the



Typical base-station	Power amplifier	Air conditioning	Analog and digital signal processing	Power supply loss
% power consumption	50-80%	10-40%	5-15%	5-15%
Approximate power	1200W	300W	200W	100W

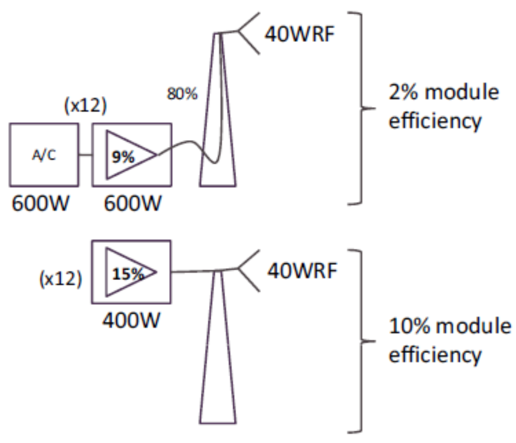
Figure 4. (top) Block diagram of a base-station front end unit with antennas, power amplifiers (PAs), radio-frequency transceivers (RF), base-band processing (BB), DC-DC converters for supplying power to the various parts (DC), air-conditioning required to cool the electronics and main power supply connected to the grid. (bottom) Table showing approximate power consumption by different parts of the base-station.

power is lost in the feed cable), unless the PA is placed on top of tower, which increases maintenance cost. From the table in Figure 4 it can be seen that 50-80% of the total power consumption in a base-station can be attributed to the microwave (radio-frequency) power amplifier. In order to improve linearity (signal fidelity) and efficiency, typically pre-distortion is performed digitally in the BB block of Figure 4 [6], in combination with Doherty type PAs [5], which reduces the amount of air-conditioning required and thus reduces the energy bill. The required extra feedback for pre-distortion and additional signal processing [6] are necessary in larger base-stations. In smaller base-stations (lower power), such advanced PA architectures are omitted, at the expense of an increased operating back-off; the fact that the PA accounts for a smaller percentage of the total base-station power consumption justifies a lower PA efficiency.

Consider an example cell-phone base station, which typically radiates about 50-100W around 2GHz in each sector. Due to bandwidth limitations, increasingly complex modulation schemes are used, which demand high linearity of the transmitter. This is especially difficult to accomplish if the transmitter needs to be efficient, and typical cell-phone output-stage power amplifier efficiencies are about 10%. In older base-stations, the power amplifier efficiency was less than 10%, resulting in a module efficiency of about 2%. This means that for every 100W of radiated power, 5kW of power is required from the grid. In newer base-stations, the PA is more efficient, on the order of 15-20%, resulting in an overall module efficiency of great than 10%, or 1kW of power consumed for every 100W radiated power. It can be seen that even such a small increase in efficiency of the PA results in a five-fold reduction in power consumption of the module, but is still expensive in terms of power usage.

Older base-stations are still prevalent, since their lifetimes are fairly long. Therefore, an example of a 40-W microwave transmitter module which is 9% efficient is meaningully illustrative: this requires 600W of prime module power due to the 80% efficient cable from the tower to the utility room, and the heat losses in the transmitter. In addition, 600W of active cooling are required per module, and for a 12-module base-station, this implies about 14kW of power consumption.

Since higher efficiency power amplifiers do not exist on the market, research and development is needed to improve efficiency of microwave power amplifiers [7]. If the power amplifier can be made 45% efficient, while keeping its linearity, the cooling energy requirement will also go down, reducing the total consumption to 2.4kW, or a factor of seven, as illustrated in Figure 5. In the next section, engineering challenges and solutions for achieving efficiency increases will be described and examples given.



RFPA Efficiency	Module Prime Power	Site Prime Power
9%	1200W	14.4kW
15%	400W	4.8kW
45%	200W	2.4kW

Figure 5. Example approximate power consumption of a 9% efficient 40-W radio-frequency PA module (older design), a 15% efficiency PA (current designs) and a future 45% efficient PA. The difference in prime power consumption is almost a factor of seven.

IV. High-Efficiency Power Amplifiers for Wireless Communications

The main challenges in a wireless communications power amplifier come from the new types of signal modulaton techniques that are used in order to increase channel capacity and allow large number of users for paid bandwidth. Figure 6 shows the polar plot and time-domain plot of a typical cell-phone signal with W-CDMA moduation [8]. The signal is modulated in both amplitude and phase (frequency), and the signal amplitude varies dramatically over time, and the changes from low to high amplitudes happen extremely quickly. These two properties, referred to as high peak-to-average ratio (PAR) and large bandwidth, impose severe difficulties on efficient operation of the microwave power amplifier [7]. This can be seen from a qualitative plot of the efficiency versus output power of a PA shown in Figure 7 [8]. At higher output power levels, the efficiency is high, but these large-amplitude signals do not happen often in time, as described by the probability density function of the amplitude, also shown in the plot. Therefore, the PA is usually operating at lower amplitudes, where it is much less efficient. Several approaches are used to improve the efficiency for high PAR signals: the Doherty type amplifier, currently used in many base-stations; outphasing or LINC amplifiers; and supply-modulated amplifiers [7]. These are described below along with some examples of demonstrated efficiencies.

Invented many decades ago, Doherty power amplifiers make use of a main amplifier which operates at lower amplitudes and a peaking amplifier for higher powers, connected via a special impedance transformation network. At low output power levels the main amplifier operates linearly and the peaking amplifier is inactive, dissipating no power. As power increases the main amplifier becomes compressed and operates efficiently as the peaking amplifier turns on. A variety of permutations have evolved from

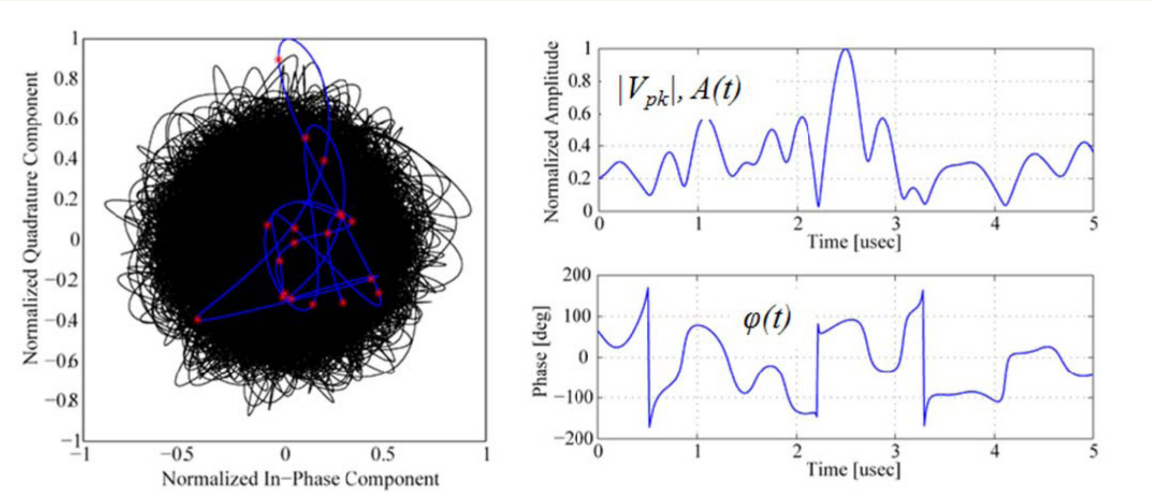


Figure 6. Polar plot (left) and time-domain plot of amplitude and phase (right) of a W-CDMA cell-phone signal shows very large swings in amplitude which happen extremely quickly.

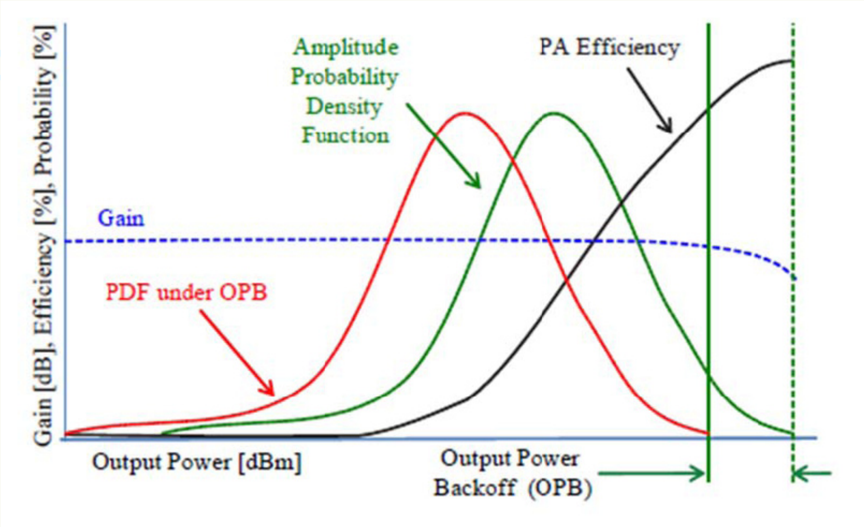


Figure 7. Typical PA efficiency and gain behavior over output power. Probability density functions for a high-PAR signal at two average output power levels are overlaid.

this basic concept varying the size and number of peaking amplifiers. These techniques improve efficiency at reduced output power levels and, therefore, average efficiency of high-PAR modulated signals. These PAs have achieved up to 40% efficiency at 2.14GHz with 60W of average power. This performance is an increase of 15% over a standard PA with the same device. Though very significant in terms of efficiency enhancement, the Doherty solution is not without disadvantages. Linearity is necessarily degraded and requires the use of DPD linearization. Though not always active, both amplifiers are always driven with RF input power, reducing gain by at least 3dB, or two times. Furthermore, the output transformation network has bandwidth typically less than 10%.

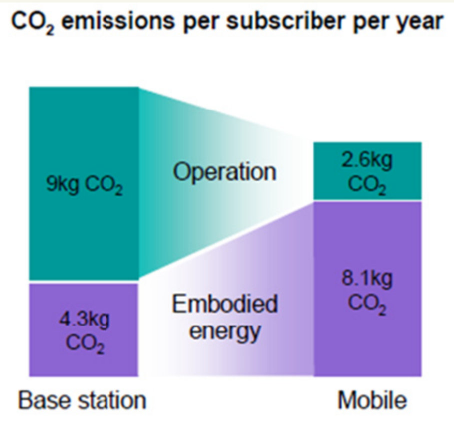
Chiriex, outphasing, and LINC architectures (discussed in detail in [7]) also utilize two high-efficiency PAs to maintain high efficiency over a range of output power levels. The input to both PAs is a constant envelope signal, maintaining high efficiency compressed operation continuously. Peak power is achieved by feeding both PAs with an identical signal. A phase offset of equal magnitude and opposite sign can be applied to the input signal of each PA resulting in out-of-phase output power combining, and consequently reduced output amplitude.

Supply modulation techniques all involve variation of the PA drain supply voltage with desired output power. Reduced drain supply voltage changes the PA operating point and consequently reduces output power capability. Gain compression, and thus efficient operation, occurs at reduced output power. This fundamental idea has been implemented in the literature in many ways and with varying terminology. Envelope Elimination and Restoration (EER) was originally conceived in 1952 by Kahn. An amplitude detector is used to determine the RF input modulation amplitude, and a drain supply modulator applies a linearly related PA drain supply voltage. A limiter at the PA input eliminates envelope variation, applying a constant input power level to the PA. Gain changes with drain supply variation and imposes amplitude modulation on the PA output signal. Other approaches which include some input signal amplitude modulation have also been used and are a topic of current research as well as development in industry. These approaches have demonstrated over 50% total transmitter efficiency, which is a dramatic increase from the prevalent 9% used in base-stations today.

V. Discussion and Conclusions

In summary, the total power consumption of wireless communications infrastructure has been steadily growing over the past few decades and is projected to continue to grow in the future. Most of the power is consumed by the high-power base-station, and within each base-station, most 50-80% of the power is consumed by the radio-frequency power amplifier. The PA efficiency is reduced when efficient modulation schemes are used for the signal. Since the radio spectrum efficiency is important both as a resource and financially, the modulation schemes are becoming increasingly difficult for the radio transmitter to amplify without consuming large amounts of power. Research and development has led to more complicated transmitter architectures in order to improve efficiency for complex signals: Doherty, outphasing and supply modulation.

Overall, handsets, or mobile units, are a small part of the total energy consumption, because they radiate a lot less power, typically below 0.5W, compared to a base-station which radiates 100W or more per sector. Therefore, the main reason for improving efficiency of a handset power amplifier is battery life. To illustrate this point, consider the fact that chargers account for 5W or about 0.01kWh/d/p in Germany (less than 0.01%) [10]. Another contributor to power consumption is the "embodied" energy, which is that other than operation energy required to maintain the equipment even when there is no traffic. This can be a significant part of the total power use, especially in the mobile device where the overall transmitted power is much lower than in a base station [9]. This is illustrated in Figure 8 qualitatively, including trends for related CO_2 emissions.



Base station	Mobile
Digital, RF hardware	Digital, RF hardware
Feed lines, antennas	Plastic housing
Tower	Charger
Climate control	Installation
Installation	Delivery
Delivery	Reclamation
Reclamation	Packaging
Packaging	(Transportation)

Figure 8. Operational and embodied energy for a base station and mobile unit for cellular wireless communications [9]. The embodied energy is a relatively larger portion of the total energy consumption of a mobile unit because the operational energy is significantly lower than in the base-station case (<1W of radiated power, compared to >100W).

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