Improving the efficiency of base station using Planar magnetic material and AMO architecture

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***Abstract*— Using energy generated with fossil fuel causes global warming due to the greenhouse effect, which threatens our environment. One of the challenges for New Generation Net-works (NGN) is then the reduction of energy consumption, in particular at the BSs (Base Stations) which use about 85% of the total network energy. This paper contributes to the research with a mathematical model that calculates the total power consumption of a BS and enlightens the way to minimize it. First, we analyze the power consumed at every different component of the BS. Then this paper describes new out phasing transmitter architecture in which the supply voltage for each Pa can switch among multiple levels. It is based on a new asymmetric multilevel out phasing (AMO) modulation technique which increases overall efficiency over a much wider output power range than the standard LINC system while maintaining high linearity.**

***Index Terms*—out phasing, LINC, wideband phase modulator, digital predistortion.**

I. INTRODUCTION

Nowadays, telecommunications, mobile Internet and many wireless applications dominate the world of Information and Communication Technology (ICT). In turn, about 2-3% of the world-wide energy consumption is for ICT, which causes about 3% of the total CO2 emissions [1]. Hence, we can understand that ICT is as useful for the human beings, as potentially harmful for our environment. The current threat to the environment could turn into a much more serious threat in the near future, e.g., due to the diffusion of mobile applications for social networks, requiring a better cellular coverage and more capabilities in the core network. The usage cost of mobile services is likely to increase, and, in particular, the energy consumption might grow with the number of BSs and data centers in the network. Hence, as the demand for ICT services rises, higher and higher energy consumption is expected for mobile radio networks.

In order to achieve lower service cost and to preserve the environment, cellular network operators try to deploy various strategies to reduce energy consumption. BSs consume about 85% of the total energy of the network. Their power consumption ranges between ∼ 147 W (Diet BTS 3900E [2]) and 10 kW depending on the size, the coverage area and the technology used [3]. The main axes of finding out efficient ways to reduce the energy consumed are: (i) the optimization of hardware (which is related to hardware producers), (ii) the usage of renewable energy sources and (iii) the smart usage of resources through power saving models and efficient algorithms (which is related to providers).

The primary challenge in RF transmitter design is centered around a design tradeoff between the linearity of the power amplifier (PA) and its efficiency. This tradeoff relates directly to the usefulness of the resulting device: high linearity results in a higher possible data rate and therefore compatibility with complex standards such as WLAN/WiMAX, and high efficiency allows for either longer use or smaller battery size (e.g., in cell phone applications). The general perception that the tradeoff between linearity and efficiency is fundamental tends to produce designs that compromise between the two ideals. The resulting systems may be either linear or efficient, or are designed specifically for a single communications standard and therefore have limited flexibility of use. Meanwhile, consumer demand for both greater transmission rates and smaller devices continues to drive the need for an architecture that is capable of both linearity and efficiency.

We propose the Asymmetric Multilevel Out phasing (AMO) transmitter architecture, described in this paper, as a solution to this linearity-efficiency tradeoff problem. This architecture, shown in Fig. 1, results in significant efficiency improvement over previous methods. Our approach is based on several innovations, including using asymmetric power supplies in a LINC (linear amplification using nonlinear components)-like configuration and an all-digital AMO modulator. Using these techniques, we expect significant improvement over conventional techniques, with a resulting system that is compatible with a wide range of communications standards.

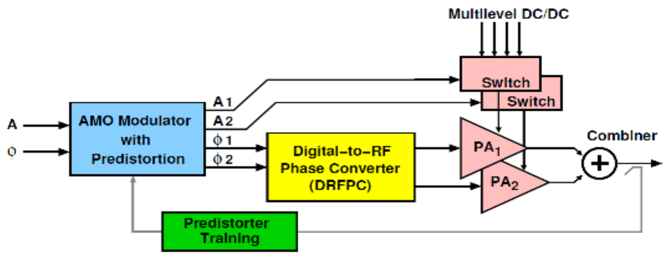

Fig. 1. Asymmetric multilevel outphasing (AMO) architecture

II. POWER SAVING STRATEGIES AND RELATED WORK

Reducing power consumption in a cellular network, and more specifically in a BS, is possible with respect to two main constraints: (i) the minimum required coverage and (ii) the minimum required quality of service (QoS) for all users. Many operators have studied and enforced in their cellular networks new power saving mechanisms based on the inhomogeneous distribution of user traffic over time. The basic mechanism adopted is the introduction of a sleep mode, in which the BS operates at minimal power [4], [5]. When the traffic demand is scarce, most parts of the BS system are switched off and just basic functionalities are in use, like signaling from the switching center in case the system needs to power on (e.g., due to a sudden increase of traffic demand in the area). As outlined by different studies that mostly tackle the sleep mode at mobile user's side, there is a tradeoff between outage of users and energy saving [6]. From the operator's viewpoint, frequent switching to sleep mode may cause denial of service well beyond the operator's commitment to guarantee the availability of its services to the customers. Conversely, as shown later in the work, infrequent or no switching to sleep mode reduces the operator's opportunity to save energy.

An important characteristic of cellular networks, that is widely exploited to save energy through sleep mode-like operation, is the day-night behavior of the users. In fact, day activity is predominant: in the morning users are moving from residential areas to office areas while in the evening, they follow the opposite direction, leading to an aggregation of users in both areas and demanding a large capacity for both. However, when people aggregate at office areas, residential areas have light traffic needs and vice versa. During the night, both kinds of areas might experience low traffic demand. Hence, BSs with tunable capacity have been deployed, with the possibility to turn off most of the radio systems when the traffic demand is consistently low. The use of efficient software to switch off the BSs or to switch into sleep mode is a good saving technique taking advantage of the day-night behavior [7]. Most specifically, NSN [4] and NEC [8] have developed software for monitoring the traffic and automatically turning off BSs in Self Organized Networks (SONs).

On the way to green cellular networking, operators have also defined other green strategies that involve: (i) selection of strategic places for deploying their network and their BSs [11], (ii) the upgrade to eco-friendly hardware, and (iii) the adoption of renewable power sources.

First, the deployment of the BSs over an area is very important for network operators. Depending on urban or rural environments with dense or light traffic the coverage strategy is different: many small BSs or a few large BSs to cover the area of interest using a single or multiple sectors per cell and one or multiple antennas (MIMO). The better the BS spatial distribution is, the less the number of BSs needed to satisfy the required coverage level and capacity, which turns into less total power consumption and less energy spent per bit [12]. Second, regarding hardware, the goal is the increased efficiency of the various BS components (rectifier, signal processing circuit, PA, feeder and cooling system). Enhancements in all parts of the BS yield a total power reduction of about 80-85% [1], [13]. Third, the adoption of renewable power sources, such as solar panels and wind generators, could play a significant role in future BSs. However, reduction of the need for fossil fuels and for connection to the electrical grid is practically possible only if BS consumption is reduced to a few hundreds of Watts [2]. Because this solution seems difficult in most cases and it has huge CAPEX (capital expenses) the use of a hybrid BS (combination of solar and diesel power generators) seems very attractive in the short term, since it obtains a reduction up to60% in energy consumption and up to 35% in CAPEX [14].

III. CONVENTIONAL APPROACHES

Communication standards that support high data rates such as WLAN/WiMAX employ variable-envelope modulation, and so linear amplification is required. One approach is to use an inefficient but highly linear PA. However, there are two main types of transmitter architectures that enable the use of more efficient but nonlinear switching-mode PAs: (1) polar, and (2) outphasing, or LINC. The fundamental idea of polar architectures, shown in Fig. 2(a), is to divide the signal to be amplified into amplitude and phase components. The phase components used as the input to a nonlinear, high-efficiency switching PA, while the amplitude component drives the power supply of the PA to create a varying envelope signal. While this improves the PA efficiency, it also requires the use of an efficient power converter. Because power converter efficiency degrades dramatically as bandwidth increases, it is very difficult to achieve high efficiency for high data-rate communicationstandards.Thisisexacerbatedbythe5-10x bandwidth expansion that occurs during the conversion from Cartesian to polar coordinates [1]. Thus this method is only practical for low-bandwidth systems. Outphasing [2], and specifically the LINC architecture, introduced by Cox in [3],is shown in Fig. 2(b).It is based on the idea that an arbitrary input signal can be divided into two constant-amplitude, phase-modulated signals that can each be non-linearly amplified and then passively recombined as a vector sum to produce an output signal that is a linearly amplified version of the input. The LINC strategy eliminates the high-bandwidth power converter of the basic polar architecture, using outphasing to realize amplitude variation. However, the efficiency of the power combining is high only over a small range of output powers. To avoid signal distortion and preserve switching amplifier efficiency, an isolating combiner such as a Wilkinson combiner must be used. Isolating combiners achieve 100% efficiency only at maximum output power. When the inputs are outphased to vary the amplitude, power is wasted as heat in the isolation resistor [4]. The overall efficiency is therefore inversely proportional to the peak-to-average power ratio (PAPR), limiting the benefits of this technique in high data-rate communication standards such as WiMAX, in which the PAPR is high.

III. BASE STATION MODEL

We will use the following notation. For a device X, the power consumed by X is denoted PX and its efficiency is denoted ηX. The notation PX in and PX out refers to the input and output power of the device X. NA denotes the number of sectors in a BS. Fig. 1 illustrates the BS structure and the power flow. The basic components are: the rectifier, the baseband digital signal processing circuit, the PA, the feeder, the antenna and the cooling system. Next, we analyze each part of the BS and we present a mathematical model for the total power consumption.

A. Energy consumption of BS components

1) Rectifier: The rectifier transforms the signal from AC to DC. The efficiency of the rectifier is about 92% for a conventional rectifier and about 97% for the case of latest products, for amperage loads between 40-90% [18]. For lower amperage loads, there are controller schemes that monitor the amperage load in order to turn off (or standby) a subset of amplifiers, so the average amperage load will increase among the rest of the amplifiers, achieving maximum efficiency [19]. The power consumption of the rectifier (dissipated as heat that needs to be removed, e.g., by the cooling system) relates with its output power (PR out) and its efficiency (ηR). It is given by:

$$PR = PR\ out \cdot (1 - \eta R)/ \eta R. \quad (1)$$

2) Baseband Digital Signal Processing Circuit: The Base- band Digital Signal Processing Circuit is considered as having constant power consumption [13]. Its approximate power consumption is PSP = 150 W for conventional BSs and PSP = 110 W for nowadays BSs. This power is dissipated as heat and has to be removed, e.g., by the cooling system. 3) Power Amplifier (PA): An amplifier is any device that magnifies the amplitude of a signal. In radio-frequency (RF) PAs, such as the one used in cellular BSs and broadcast transmitters, a very important parameter is the efficiency which is given by ηPA = PP A out PP A in . Traditional PAs have an efficiency of about 15%. The excessive energy is transformed into heat. Specialist design techniques are used to improve efficiency, such as Digital Pre-Distortion (DPD), Doherty and Envelope Tracking (ET) which can lift the efficiency up to 60% (cf., e.g., [1] and references therein). The PA could be in four possible states: switching state, transmitting state, turned off state and idle state. During switching state, the PA commutes from active to inactive and vice versa. The probability of being in switching state π0 is given by the time needed to start up, plus the time needed to switch off on average (e.g., 65 μs and 25 μs respectively [20]), over the total average period T between two consecutive switch-ons of the PA, π0 = Tsw/T. In transmitting state, the PA is active and boosts the signal to be transmitted over the BS air interface. The probability of being in transmitting state, π1, is given by the average number of bits per packet, S, over the average transmission rate, R, times the average number of packets per second, λ. This probability is π1 = λ · S/R, and represents the load of the system. The PA is in turned off state when its circuitry is inactive and no signal can be amplified. The probability of being in turned off state, π2, is given by the average time Toff of being turned off over the total average cycle duration T. Thus, π2 = Toff/T. In idle state, the PA is active but not transmitting. The probability of being in idle state is π3 = Tidle/T. The average power consumption for each state is Psw, PTx, Poff, Pidle, for switching, transmission, turned off and idle powers respectively. To sum up, these are the average power consumptions computed over each cycle T, where each cycle T is representative of the total process. The resulting model for PA's consumption is

$$PPA\ in = \pi 0Psw+\pi 1PTx+\pi 2Poff+\pi 3P$$

4) Feeder: The feeder is the cabling system connecting the BS to the antenna. In conventional BSs, antennas and equipments are a few meters apart, and connected through a coaxial cable. The signal attenuation of such a feeder is typically about 3 dB. Nowadays, Remote Radio Heads (RRH) technology is used instead: a very small cabinet holds the BS radio frequency devices very close to antennas, and it is connected to the (possibly remote) baseband signal processing equipment by means of optical fibers. Its efficiency is:

$$\eta F = Pout/ PPA\ out, \quad (3)$$

and approaches 1 when using RRH, and 0.5 when using coaxial cabling. The power dissipated due to efficiencies lower than 1 is transformed into heat. 5) Cooling System: In electronic equipment and circuits, power dissipation is generally a stated condition. Electronics also have specific margins of operative temperature and in order to keep the temperature of most components of the BS within specified design limits we need to cool the sites. Air conditioners (A/C) are often the choice for radio sites. Like stated in, such cooling requires as much power as one third of the heat power generated inside the BS, i.e., one extra Watt is required to dissipate three Watts of heat. In addition, other cooling techniques such as free ventilation, forced-air cooling and heat exchangers have been proposed in order to save energy either for economic reasons, for energy independence of the BS, or to save battery life in off-electric- grid operated BSs. Furthermore, NSN concludes that BSs with a total power consumption less than 500 W (excluding the output power of the BS, Pout) do not use A/C system. Thus, we model the power consumption at the A/C system as:

PAC =[(PR in − 500 – Pout)/3 , (4)

where, the notation [X]+ = max[X,0] is used.

III. PROPOSED APPROACH

AMO Modulation Fundamentally, AMO modulation decomposes a com- plex vector, which represents a baseband constellation point, into two vector ssuch that the sum of the two vectors constructs the original complex vector with the minimum outphasing angle, as illustrated in Fig. 3. The two vectors are the baseband representation of the two PA outputs. As compared to the multilevel LINC (ML-LINC) technique [5], by making independent changes in the supply voltage for each of the two PAs, the AMO technique results in smaller outphasing angles so that higher efficiency can be achieved even in relatively high-PAPR standards. Mathematically, AMO modulation can be defined with a polar representation of a baseband signal,

C(t) = ri(t) + jrq(t) = A(t)ejθ(t). (1)

In order to have linear PA output, C(t) is predistorted into

P(t) = Ap(t)ejθp(t) (2)

by a polar lookup table (LUT). P(t) is decomposed into two parts as

P(t) = W(V1(t)ejφ1(t),V2(t)ejφ2(t)) (3)

where W represents Wilkinson power combining and

φ1(t) = θp(t) + cos−1 ((V1(t)2 + 4Ap(t)2 − V2(t)2)/4V1(t)Ap(t))

,φ2(t) = θp(t) − cos−1 ((V2(t)2 + 4Ap(t)2 − V1(t)2)/4V2(t)Ap(t)).

B. Multi-standard Efficiency Optimization

As we use AMO to minimize loss in the Wilkinson combiner, we have to determine the optimal value of each level rk (these are the maximum output amplitudes for each of the different supply voltage levels when both PAs are driven by the same supply). Note that this simplifies to the standard Wilkinson efficiency when rk = rj. The total average efficiency can be computed if the amplitude PDF p(A) of the signal is known (see Fig. 4 and Fig. 5 for the PDFs of HSUPA and WLAN signals, respectively). This is done by dividing the PDF into several regions separated by the rk (and their combinations), integrating the PDF curve to find the efficiency in each region, and summing the result. For N different supply voltages, there are N 2 combinations of supply voltages for the two PAs. However, the combiner efficiency decreases as the difference between two levels increases. Also, the efficiency improvements small when the difference between the two levels is large. Therefore, in our system we restrict the combinations to be adjacent supply levels (i.e., rk and rk+1).

IV. AMO ARCHITECTURE

The AMO architecture, which consists of 1) predistorter for linearizing the combined nonlinearity from DRFPC (digital-to-RF phase converter)/Switch/PA, 2) AMO modulator, and 3) amplitude switch and RF PA. The AMO modulator first determines the combination of the two PA supply voltages based on a peak amplitude within a time interval. The AMO mapper decomposes the predistorted amplitude and phase into two pairs of amplitude and phase commands. The AMO mapper is implemented with a first order approximation of (3). The time delay mismatch between the amplitude and phase paths is maintained to within less than 1ns by a time aligner between the AMO mapper and the amplitude switch.

The DRFPC, which is based on the direct-digital RF modulator [6], performs phase modulation by embedding the phase component of the AMO mapper output into an RF carrier. The DRFPC consists of an array of current steering switches as in the direct-digital RF modulator. The DRFPC brings a significant transmitter power efficiency boost particularly for low output power levels for two reasons. First, the analog matching requirement in the current steering switches is relaxed because the static phase errors in the DRFPC output, which result from analog mismatch, can be corrected by the predistorter. Second, as compared to traditional IQ modulators, the DRFPC does not need baseband active filters for DAC output shaping.

The PA supply modulator, which consists of a fast switching network driven by the AMO modulator. For maximum efficiency, the PAs are switching-mode amplifiers (e.g., class-E, class-F, class-E/F, etc.).

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