Polar Modulation Based Reduction of Communications Energy Consumption

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***Abstract*— Power consumption of the communications infrastructure, particularly that which is LTE-based, is driven by the efficiency of the transmitter. Lower efficiency in the transmitter scales to needs for both larger power supplies and greater resources needed to remove the power dissipated by both the transmitter and its power supply. Improvement in transmitter efficiency therefore leverages, through these other functions, to provide a significant drop of input power draw while maintaining the same quality of service through the network. This corresponds worldwide to more than a million ton reduction of CO2 from electric generation per year at present levels of LTE network buildout.**

Keywords*— *energy efficiency; power amplifiers; long-term evolution; linear amplifier; polar modulation;

I. INTRODUCTION

Analysis of the energy consumed by the mobile communication infrastructure shows that it draws gigawatts of power [1]. Further analysis of the individual components drawing this power shows that the largest consumption occurs in the infrastructure (base station) power amplifier (PA), along with its associated radio transceiver (XCVR) and digital signal processing (DSP) [2]. Meaningful reduction of this power draw therefore requires achieving significant reduction in this power drawn in each base station, though with the further requirement that network service levels are not degraded. This forces recognition that the important metric for base station output signal quality is its modulation accuracy, independent from whether the circuitry implementing that signal is linear or not. This work shows that suppressing transmitter circuit linearity by using switching circuit techniques [3] is successful at maintaining output signal accuracy while improving transmitter operating efficiency for LTE base stations from near 12% to more than 40%.

Standards committees often adopt multi-carrier (MC) signal modulations for communication use. The physical principles established by the Fourier Transform state that the implementing circuitry of MC signals must behave linearly in order to avoid cross modulation among the signal subcarriers. This presently forces class-A transmitter power amplifiers, which by Ohm's Law forces these transmitters into minimum energy efficiency [4]. This increases power draw, which increases greenhouse gas (carbon dioxide) emissions from the generation of the electric power needed to operate these base stations in the communications network infrastructure. A new architecture is needed to simultaneously provide output signal accuracy and greatly improved energy efficiency.

Following this introduction is an evaluation of the typical transmitter architecture and its power flow, including the heatsink function. Limits on power draw when using linear circuitry, and that impact on transmitter energy efficiency are examined. Section III examines the application of switching circuit techniques to these transmitters, and evaluates the improvement in transmitter energy efficiency that results. Reduction of carbon dioxide emissions, along with the reduction of operating costs from electricity alone is examined in Section IV. Conclusions are drawn in Section V.

II. LINEAR TRANSMITTER CHARACTERISTICS

A. Selecting a Template (Heading 2)

Base station transmitters have a top level block diagram and power flow like that shown in Fig. 1. Input power is drawn by the power supply, which converts this source power into the forms needed by the transmitter. This power conversion is not perfectly efficient, resulting in some power dissipation ($P_{D,PS}$), in accordance with the power supply efficiency (η_{PS}), which must be absorbed by the heatsink. The transmitter has its intended communication signal power output (P_{OUT}), and has multiple additional power dissipations, primarily due to the PA efficiency (η_{PA}), and from its internal transceiver and digital signal processing ($P_{D,F}$). These power dissipations all go into the heatsink for removal.

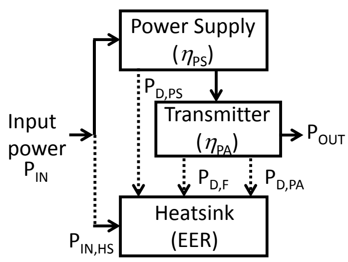

Fig. 1. Power flow in a transmitter includes the power supply. All dissipated power must be absorbed into the heatsink and removed.

The heatsink also draws power when some amount of air conditioning is required to move the dissipated heat away from the transmitter. Air conditioners have a metric called energy-efficiency-ratio (EER; units BTU/W), which has a value of 10 or higher for present high-efficiency units. Combining all of these terms together to determine the transmitter's total input power draw (P_{IN}) gives the result

$$P_{IN} = P_{OUT} + \left(P_{D,PA} + P_{D,F} + P_{D,PS}\right) + P_{IN,HS} \qquad \text{(1a)}$$

$$P_{IN} = \frac{P_{OUT}}{\eta_{PA}}\left(1+\frac{1}{\eta_{PS}}\right) + P_{D,F}\left(1+\frac{1}{\eta_{PS}}\right) + P_{IN,HS} \quad . \qquad \text{(1b)}$$

The air conditioning input power (if present) depends on the absorbed transmitter power dissipations through

$$P_{IN,HS} = \frac{3.41}{EER}\left(P_{OUT}\left(\frac{1}{\eta_{PA}\eta_{PS}} + \frac{1}{\eta_{PA}} - 1\right) + P_{D,F}\left(\frac{1}{\eta_{PS}} + 1\right)\right) \qquad (2)$$

where $P_{IN,HS}$ is in watts. Results from (1b) are plot in Fig. 2, where the power is normalized to $P_{OUT} = 1$ and the heatsink is assumed to be passive. Power supply efficiency is usually very high, near to $\eta_{PS} = 95\%$. Allowing the PA efficiency to mathematically vary for the sake of analysis, we observe the reciprocal increase of drawn power should the PA efficiency fall below 50%. From [2] it is shown that base station PA efficiency is actually close to 12%. For LTE mobiles the PA efficiency is lower, closer to 9% [5]. Results of this work, described later, show PA efficiency for LTE signals at 47%. The impact of this manifests in lower input power for the same throughput, pointed out in Fig. 2.

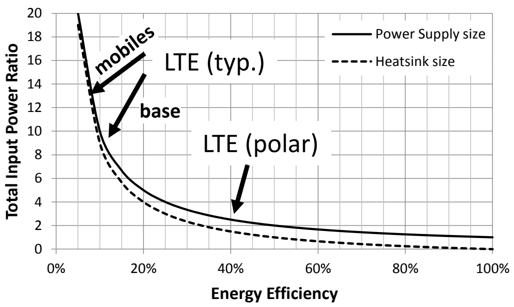

Fig. 2. Power drawn by the transmitter increases reciprocally when the transmitter efficiency is less than 40%. Output signal power is normalized to unity.

Linear PA theory says that a class-A amplifier can have up to 50% efficiency. This result is a consequence of assuming that the resistance of the transistor is zero when it is on, and that it operates as a current source at all output signal voltage values from the supply down to zero. Neither of these assumptions are true in practice. The minimum output voltage needed to have the transistor operate as a current source in a linear amplifier is called its knee voltage (V_k) [6]. The value of V_k subtracts from the supply voltage and limits the maximum extent of the achievable output signal. Additionally, the finite transistor resistance dissipates power which adds to power dissipation and reduces PA efficiency. The result is that any realizable linear PA can never achieve its theoretical efficiency of 50%. The actual limit, which depends on the ratio of V_k to the supply voltage VS is presented in Fig. 3. A very good transistor technology has a ratio V_k/V_S near to 0.1. Less ideal technologies, such as CMOS, have a ratio V_k/V_S above 0.3. The curves in Fig. 3 show that this technology limit bounds achievable linear PA efficiency to no better than 40%, and could be as low as 30% maximum. Similarly the output power capability of such a linear amplifier is reduced. All of this reduces transmitter efficiency and causes input power draw to rise.

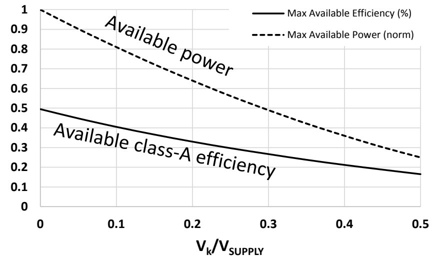

Fig. 3. For any linear amplifier, the existence of transistor knee voltage forces reductions in both available output power and in PA efficiency because the output signal is smaller.

The efficiency values in Fig. 3 apply only to signals that have no envelope variation. If there is any signal envelope variation then the peak envelope power (PEP) exceeds the signal average power by the peak to average power ratio (PAPR). Because the PA output is limited to its PEP value (all amplifiers are peak-power limited), the existence of any signal PAPR forces the output power down. This further reduces PA energy efficiency, in effect putting a ceiling on achievable energy efficiency in any linear PA based on the signal modulation type that is adopted for the application. This effect is predictable and is called the modulation-available energy efficiency (MAEE) [7]. Selected MAEE values for a set of signal modulation types adopted in modern standards is shown in Fig. 4. As expected, as the signal PAPR increases the MAEE value drops. Present and proposed multicarrier (MC) signals have the lowest MAEE values. This is a direct consequence of two things: 1) the high PAPR resulting from how these signals are constructed, and 2) being forced into class-A operation by the Fourier Transform (FT), because the MC signals cannot tolerate the cross-modulation among subcarriers required by the FT when multiple input signals interact with circuit nonlinearities.

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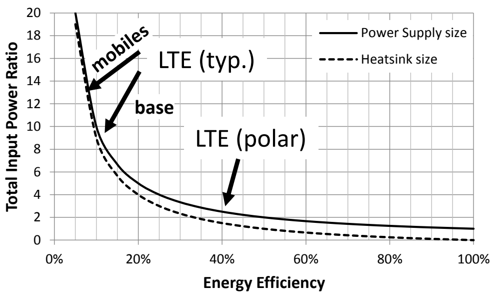

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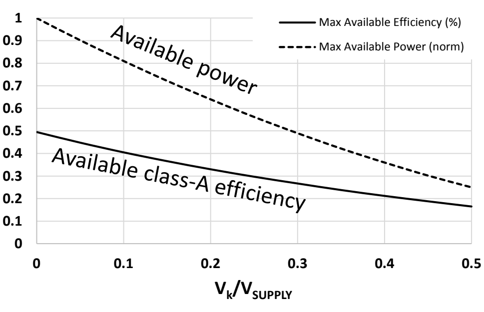

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III. Tripling Energy Efficiency

Improving PA efficiency requires reducing transistor power dissipation, corresponding to having the load line intersect power dissipation contours of lesser value. One possibility is illustrated in Fig. 6 using LTE waveforms. At maximum output power the LTE signal must completely fit along the load line bounded by transistor cutoff and the knee voltage (intersection of the load line with the knee profile). At lesser output power, the smaller output signal spends nearly all of its time close to the center of the load line, near the maximum power dissipation of the amplifier. One option is to shift the supply voltage down when the output power required is reduced. As shown here, this shifted load line intersects power dissipation contours that have significantly lower values than those intersected at full voltage. This technique is called average power tracking (APT). This helps, yet efficiency can be further improved.

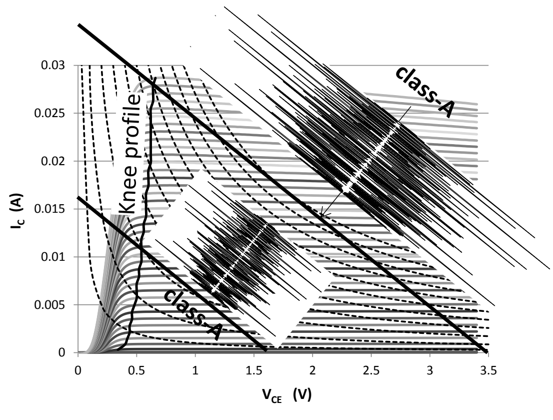
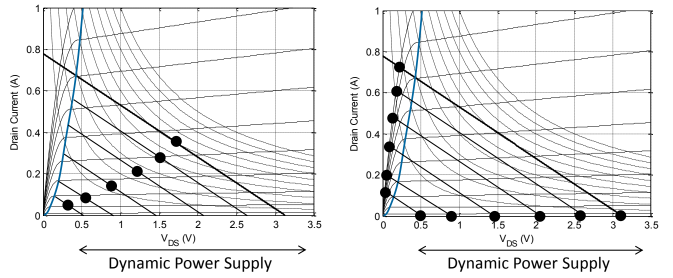


Fig. 6. As LTE signal power requirement decreases, using lower supply voltage and a correspondingly changed bias does dramatically drop transistor power dissipation.

One option is to use envelope tracking (ET) as shown in Fig. 6a. Both the supply voltage, and the transistor bias, are dynamically varied in accordance with the signal envelope in real-time. The PA remains linear at all times, which is very important for MC signals. Values of the power dissipation contours continue to drop when the signal envelope is small, as it mostly is for high PAPR signals.



a b

Fig. 7. Energy efficiency improvement using dynamic power supply transmitter techniques: a) envelope tracking; b) direct polar modulation. Operating the RF transistor as a switch intersects the lowest value contours of constant power dissipation, directly maximizing efficiency by eliminating circuit linearity.

Power dissipation drops, and efficiency improves, when the operating point is moved from the middle of the load line to its end points. This is shown in Fig. 6b. These points represent switching action of the PA transistor, because the transistor (ideally) spends no time transitioning between these end points. Though as long as the transistor is fast enough, generally meaning that its transition frequency f_T is 50 times higher than the desired operating frequency [8] then this ideality can be safely adopted. Without any circuit linearity remaining this approach shifts from linear operation to polar modulation [9].

The traditional problem with polar modulated transmitters is that they have difficulty generating low and zero envelope values. The work in [3] demonstrates that polar modulation technology is progressing in this area, and it is now improved such that high quality LTE signal generation is achieved.

Demonstration of this LTE signal quality using polar modulation is shown in Fig. 8. No spectral regrowth is seen near the signal due to amplifier compression, even though the PA transistor is operating as a switch. Margin to the specified transmit mask is excellent for these LTE signals. Switch-based RF power using direct polar modulation is now a viable option for implementing LTE transmitters.

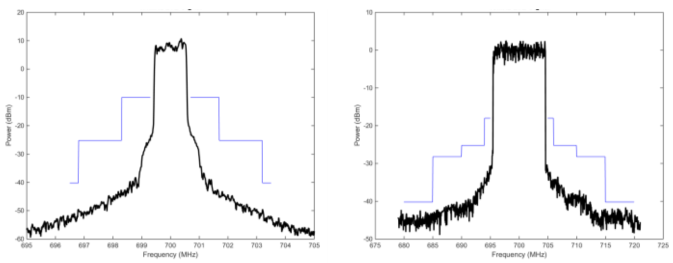


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Fig. 8. Output signal accuracy meeting specifications is achieved with the switch-based polar transmitter: a) LTE at 1.4 MHz bandwidth; b) LTE at 10 MHz bandwidth.

The impact on transmitter energy efficiency is seen in Fig. 9. Measured LTE transmit efficiency is 41% (filled circle), up from the prior reported 12% (open circle). This efficiency improvement has a direct consequence and several leveraged consequences, all of interest to the goal of reducing energy draw. First, the PA efficiency improvement reduces the PA power dissipation with no change in the output signal power or characteristics. This then directly reduces the PA power draw as described in Fig. 1.

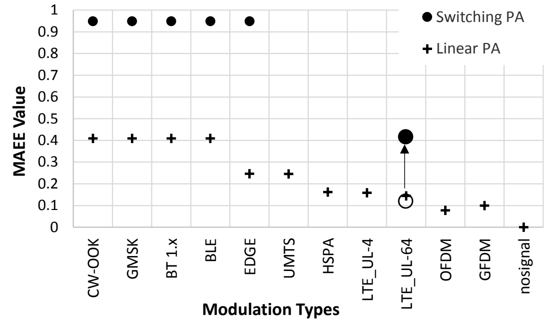
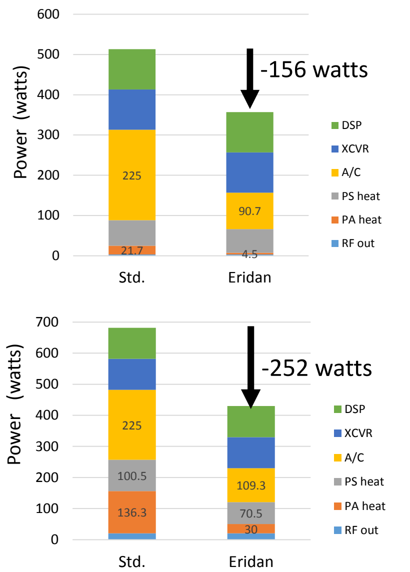


Fig. 9. Applying polar transmitter technology to the LTE signal directly increases transmitter efficiency from 12% to 41%.

IV. Environmental and Economic Impacts

Reduced PA power draw is leveraged two ways. First, the draw from the transmitter power supply is reduced accordingly, along with a proportional reduction in the power dissipated by the supply. Second, this reduced dissipated power from the PA and the supply reduces the load into the heatsink, so any heat pump or air conditioner does not need as much heat moving capacity, reducing its part of the input power draw. These differences are evident in the bar charts in Fig. 10. Additionally, in this work no effort is made to reduce the power consumption in the XCVR and DSP blocks. This goal is left to future work.



a

b

Fig. 10. Adopting a polar LTE transmitter reduces overall power draw for infrastructure transmitters: a) -156 watts each for 3 watt metrocells; and b) -252 watts each for 20 watt microcells

For the 3-watt RF output metrocells, the input power reduction from each transmitter (per sector) is 156 watts, as shown in Fig. 10a. Greatest reduction is seen in the PA and in the air conditioning, followed by the power supply. Thus, by improving the PA efficiency, this improvement leverages into reduced power draw by other parts of the transmitter. Considering a worldwide installation of 6 million such metrocell transmitters, the total power reduction provides an energy saving of more than 8 billion kilowatt-hours each year, equivalent to the output of 10 generating stations of 100 megawatts each running continuously. Depending on the fuel mix used to generate this electricity, this means that between 5 and 9 million tons of CO_2 will not be released into the atmosphere worldwide, annually. This will add up to even greater energy savings over the 20 year lifetime of a typical metrocell.

The environmental impact from implementing this technology for the larger 20-watt output microcell is more significant. Looking at Fig. 10b, the top-level power draw reduction is 252 watts per microcell transmitter. Again, considering a worldwide installed base of 6 million microcells, the net power savings here is more than 13 billion kilowatt-hours each year. Again, depending on the fuel mix used to generate this electricity, adopting this technology means that between 8 and 14 million tons of CO_2 will not be released into the atmosphere worldwide, annually. Considering the 20+ year lifetime of microcells, this adds up to a considerable savings of greenhouse gas emissions.

Beyond this environmental benefit, the direct cost of the electricity that is no longer used has a considerable immediate economic impact. Looking at Fig. 11, the operating expense (OpEx) reduction recognized from adopting polar modulation in LTE base stations is material to business. Here the operating expense reduction is evaluated across various costs for electricity. In locations where the cost of electricity is low, such as areas where hydro power is plentiful (e.g. Quebec) the annual OpEx reduction per base station is between \$100 and \$200. However in locations where cellular infrastructure is powered by local Diesel generators because the electric power grid does not extend there, the OpEx savings are much greater. In these areas the annual OpEx reduction can be as much as \$500 per transmitter. With the restricted coverage area of these moderate power base stations, the total annual power expense reduction reaches into millions of dollars.

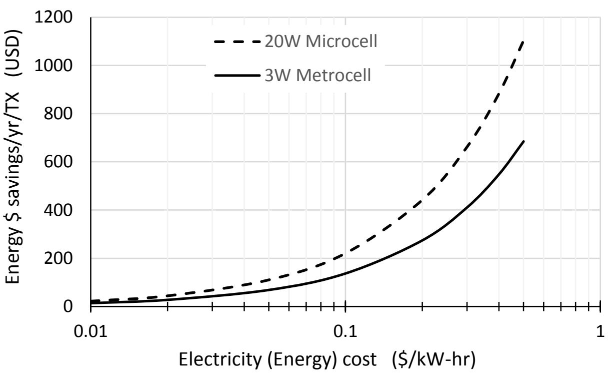


Fig. 11. Annual expense reduction for each transmitter depends on the local cost of electricity

V. Conclusion

Linear circuitry is expensive, whether to develop in the first place, or to acquire and to operate across years in the field. While linear technology is well understood and widespread, any practical alternative that presents itself must be paid attention to.

Since the standards committees have adopted MC signal modulations for cellular communication use, the Fourier Transform states that the implementing circuitry must behave linearly in order to avoid cross modulation among the various signal subcarriers. Using linear circuitry forces class-A transmitter operation, which by the further principles of Ohm's Law force these transmitters into a condition of minimum energy efficiency. This is not good for desired low operating expense. Neither is it good for reduction of greenhouse gas (carbon dioxide) emissions from the generation of the necessary electric power needed to operate these base stations in the communications network infrastructure. Combining the physical constraints of Ohm's Law and the Fourier Transform for these signals, energy efficiency for any LTE implementation using linear circuitry is bounded to 12% (~1/8). Having 7 out of every 8 electrons drawn from the supply convert directly to heat and not make useful output signal is a major problem.

An alternative exists, where switching techniques can be adopted instead of using linear circuitry. This approach recognizes that the most important metric of any transmitter is to have the output signal be accurate to specification requirements. This is not the same as requiring linear circuitry. These are different, and this difference can be usefully exploited.

Switching techniques for RF transmitters operate fundamentally with polar modulation, since the linearity necessary for quadrature modulation is no longer available. By Ohm's Law, these transmitters have significantly higher energy efficiency that that possible from linear circuitry implementations. This efficiency improvement is significant, and has important consequences to overall network operation with respect to both direct operating expense and also considering the generation and release of greenhouse gasses resulting from the generation of the necessary electricity to operate the communication network.

Polar modulation is now maturing with respect to the multicarrier signals adopted by standards committees. Originally considered impossible, this is no longer true. Energy efficiency benefits are now realizable using these techniques, which are material and meaningful to environmental goals of slowing climate change by reducing the release of carbon dioxide into Earth's atmosphere.

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