Envelope Tracking for TD-LTE terminals

White Paper

**TD-LTE pushes TX bandwidth up by 5x and doubles peak power consumption. ET restores the balance, making TD-LTE more energy efficient than FD-LTE, not less.**

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Executive Summary

More than 60 operators have committed to deploy TD-LTE networks, with high profile deployments in China, the US and India, and all major device OEMs have commercially launched TD-LTE compatible devices. A recent market report forecasts TD-LTE subscriptions will reach nearly 1 billion by 2020, with TD-LTE device shipments expected to pass 100 million units in 2014 alone.

Most operators, including China Mobile, are expected to deploy TD-LTE with an asymmetric timeslot allocation of 4:1 (download:upload) to reflect aggregate data traffic across the network. For handset OEMs and chipset vendors, this presents a significant challenge, as handsets are only able to transmit for a fifth of the time.

For a given data throughput, the transmit bandwidth and power has to be five times higher than FD-LTE, increasing transmit power by 7dB. The effect of this is to double the instantaneous current consumed by the RF PA during transmit bursts.

Nujira’s analysis of TD-LTE network drive test statistics shows that 50% of the PA energy consumption is at high power/high bandwidth.

ET is crucial for reducing the peak power consumption, so the most significant power savings from ET can only be achieved by solutions that can support these higher bandwidths in ET mode. Lower performance ET solutions have to fall back to Average Power Tracking (APT) mode at high bandwidths, eliminating the performance advantage of ET and complicating the software development for chipset vendors.

Nujira, the world leader in Envelope Tracking, has characterized several ET PAs with 20 MHz TD-LTE waveforms, using Nujira’s Coolteq.L ETIC, the world’s highest performance ET solution.

Nujira’s fast switching ETIC is able to rapidly transition between a low power standby mode in the downlink (RX) slots, and full power ET mode for the uplink (TX) slots, maximizing the energy savings in TD-LTE mode.

Compared with an equivalent FD-LTE scenario, the peak power consumption doubled, but the average handset power consumption was decreased by 40% when operating in TD-LTE mode.

The benefits of ET are even more relevant to TD-LTE than FD-LTE. But with a fivefold increase in bandwidth, a high performance ETIC is needed to gain full advantage.
What is Envelope Tracking?

Envelope Tracking (ET) is a technique for improving the energy efficiency of RF Power Amplifiers (PAs). The traditional DC:DC converter supplying the PA is replaced by a highly agile ET Power Supply modulator. This dynamically modulates the power supply pin of the RF PA with a high bandwidth, low noise waveform, synchronized to the instantaneous envelope (amplitude) of the signal being transmitted. At any instant in time, the PA is operating in a highly efficient compressed state, where the power supply voltage is just sufficient to enable the PA to transmit the instantaneous output power required, as illustrated in Figure 1.

**ET support is now ubiquitous across new 4G chipsets**

**ET system interface**

To implement an Envelope Tracking system, the chipset designer must add an auxiliary Envelope Generation path to their modem/transceiver chipset, to generate the envelope signal needed to feed the ET power supply modulator. Figure 2 illustrates the system environment in more detail.

The functions required in the modem may be implemented either in digital logic or DSP, and may be integrated into either RF or Baseband ICs. A high speed data processing pipeline takes I/Q data samples from the modem, routes them through a programmable delay line to allow sub-sample time alignment between RF and Envelope paths, calculates the instantaneous amplitude (envelope) of the signal as $\sqrt{I^2+Q^2}$, passes it through a programmable nonlinear Look Up Table (the “Shaping Table”), and then sends the signal to a high-speed D/A converter.

The electrical interface between the modem chipset and the ETIC has been standardized by the MIPI Alliance as “eTrak”, and by the OpenET Alliance.

**The ET shaping table – a software defined PA**

A key feature of Envelope Tracking systems is that the mapping of instantaneous RF signal amplitude to supply voltage is controlled digitally, using a programmable Shaping Table as shown in Figure 2.

The shaping table controls almost all aspects of the PA’s behavior, allowing the system designer to tradeoff efficiency, linearity, RX band noise and EVM in software.

In a traditional fixed supply PA, performance is determined by the analogue characteristics of the device, which are difficult to control across process and temperature. This means the designer must make design-time compromises to support all possible modes. In contrast, ET allows designers to select optimum performance for TD-LTE or FD-LTE operation at run-time.

With ET, PA performance can be optimised for TD-LTE or FD-LTE operation at run-time, simply by selecting a different Shaping Table in software.
FD-LTE transceivers suffer from potential desensitisation of the receiver due to leakage of out-of-band noise from the PA, via the duplex filter. This requires an ET shaping table which compromises on efficiency in order to minimise the noise in the RX band. For most FD-LTE bands, it is noise in the RX band, rather than ACLR or EVM, which limits the performance of the PA.

In TD-LTE operation, where the TX and RX paths are not operated simultaneously, a different shaping table can be loaded which operates the PA deeper into compression, enabling greater energy efficiency, while complying with ACLR and EVM requirements.

Switching between shaping tables can take place in a few microseconds, making it possible to handover between TD-LTE and FD-LTE bands using the same PA chain.
An overview of TD-LTE

In Time Division Duplex LTE, spectrum resources are divided in the time domain between Uplink (handset TX) and Downlink (handset RX), using a 10 ms frame period. The standard defines several subframe configurations with different ratios of Uplink (U) and Downlink (D) bandwidth as shown in Figure 3.

The TD-LTE frame structure also includes a Special subframe (S), which implements a guard band between downlink and uplink. The Special subframe also contains downlink data, and a short amount of uplink data. No guard band is needed between Uplink and Downlink, as the network implements Timing Advance such that Uplink and Downlink are synchronised at the base station. All base stations in the network must also be time-synchronized, to avoid interference between uplink and downlink timeslots in adjacent cells.

Two frame periods are defined, with 5 ms or 10 ms periodicity. Although the 10 ms periods are more efficient, since only one guard period is required per frame, they increase latency.

Most TD-LTE operators, including China Mobile, are expected to deploy TD-LTE with subframe configuration 2. This defines a 5 ms frame with a 4:1 ratio between downlink and uplink, reflecting the typical user data traffic loading, which is highly asymmetric with significantly more download traffic than upload traffic. This has the advantage of maximising overall network capacity, but limits the available uplink capacity and bandwidth to 20% of the channel. For example, a 20 MHz TD-LTE channel only provides the equivalent of 4 MHz in the uplink direction, shared between all users in the cell.

**TD-LTE impact on uplink transmission**

Both TD and FD-LTE networks allocate spectral resources using Resource Blocks (RBs) in both frequency and time. With only 20% of the TD-LTE timeslots available for transmissions from handsets, for a given throughput the network must allocate 5x more RBs to each user in the frequency domain, as illustrated in Figure 4.

In LTE networks, the RF transmission power used is directly proportional to the bandwidth of the transmission, i.e. the number of RBs allocated during the burst. This maintains the same signal-to-noise ratio at the base station by ensuring a constant energy-per-RB.

The 5x increase in instantaneous bandwidth therefore results in a fivefold increase in instantaneous transmit power, a 7 dB increase in RF terms. This significantly increases the peak current consumed by the RF Front End, in particular the RF Power Amplifier.

However, since the RF PA is operating on a lower duty cycle, this does not translate into a corresponding increase in average current consumption.
Handset TX power comparison

To quantify the handset power consumption between FD-LTE and TD-LTE networks, we assumed a scenario with a constant 5 mbps uplink throughput. With a QPSK transmission, this corresponds to 15RBs in the FD-LTE case. We modelled the uplink transmission power for the FD-LTE scenario at 16 dBm average power level.

In the TD-LTE scenario, 75RBs were allocated on 20% of the timeslots. The 5x bandwidth increase gave a corresponding 7 dB increase in transmit power, from 16 dBm to 23 dBm.

In the most common 4:1 configuration, TD-LTE terminals must transmit 5x the bandwidth at 7 dB more power to achieve the equivalent FD-LTE uplink throughput.

![Diagram showing comparison of FD-LTE and TD-LTE (type 2) uplink traffic](image)

Figure 4 - Comparison of FD-LTE and TD-LTE (type 2) uplink traffic

![Diagram showing uplink bandwidth and TX power level assumptions for 5 Mbps throughput](image)

Figure 5 – Uplink bandwidth and TX power level assumptions for 5 Mbps throughput
**TD-LTE drive test statistics**

To validate the theory that TD-LTE pushes up the instantaneous transmit power and bandwidth simultaneously, we analysed drive test data from a 20 MHz TD-LTE network operator, operating over a range of signal strength conditions during both uplink and downlink throughput tests. A non-ET terminal was used, based on a Qualcomm chipset.

The raw data was then grouped into signal strength ‘bins’ based on the RSRP, the Reference Signal Received Power measured by the handset, which is a good indicator of signal strength.

The results for the top 10 dB of the power control range are shown in Figure 6 as a scatter plot of bandwidth (Y) versus transmit power (X), with the colour of the points reflecting the signal strength, based on the RSRP bins. It can be seen that the data traffic is grouped around three sides of the plot:

- The set of points along the top of the chart show maximum bandwidth uplink transmissions at good signal strength (top left). As signal strength degrades, transmit power is progressively increased until the TX power limit of the terminal is reached, at the top-right corner of the chart. It can be seen that 1 dB of Maximum Power Reduction is being employed by the Qualcomm chipset, limiting TX power to 22 dBm with >18 RBs.

- The set of points along the right of the chart show the transmit bandwidth being progressively reduced as the signal quality degrades. Since the TX power of the handset is limited, decreasing the RB allocation focuses the transmit power into a narrower bandwidth, improving the signal quality at the base station.

![Figure 6 – TD-LTE network drive test statistics - uplink](image-url)
• Finally, the set of points along the bottom of the graph show low bandwidth transmissions at a variety of power levels. The low bandwidth transmissions with good signal quality (bottom left) are generally packet acknowledgements for downlink traffic.

The data shows that in this network, the scheduler chose to allocate high bandwidth data bursts wherever possible, until the transmit power limitations of the handset forced the bandwidth to be reduced. It should of course be noted that this is a single network drive test on a lightly loaded network, but we believe that the principles remain valid across TD-LTE networks.

**TD-LTE PA energy consumption statistics**

Analysing uplink power control statistics without considering the PA energy consumption can give misleading conclusions. Since transmit power is almost always expressed on a logarithmic scale, the PA consumes much more energy at high RF power levels. Based on the statistical distribution across bandwidth and transmit power, we therefore analyzed the energy consumed by the RF PA from the battery as a function of bandwidth, using measurements of LTE PA efficiency made at varying power levels. This produced the analysis shown in Figure 7, which expresses energy consumed by the PA both as a Probability Distribution Function (blue) and a CCDF (red).

It can be seen that around 40% of the energy consumed by the PA is at low bandwidths (5 MHz / 25 RB or less), and around 60% of the energy is consumed at high bandwidths (15 MHz / 75 RB or more).

The conclusion from this analysis is that a high bandwidth 20 MHz-capable ET solution is needed to get the maximum benefits of Envelope Tracking in TD-LTE, and would deliver twice the power savings of a 5 or 10 MHz ET solution.

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**Figure 7 – Statistical distribution of PA energy consumption vs uplink bandwidth**

The TD-LTE drive test data showed that almost 60% of the energy consumed by the RF PA was at bandwidths of 15 MHz or higher.
Modelling handset energy consumption

Based on the 5 Mbps uplink throughput scenario described earlier, we then modelled the overall handset power consumption, broken down into 4 subsystems:

- Application Processor – assumed to be generating the data traffic;
- Modem – running LTE protocol software and digital baseband functions;
- Transceiver – RF upconversion / downconversion;
- RF Power Amplifier – transmitting the required signal.

The Application Processor, Modem and Transceiver power consumption were estimated, based on industry benchmarks. The RF Power Amplifier power consumption was measured, using Nujira’s ET Surface Explorer ETPA characterization system, configured with representative LTE waveforms at the two different power levels.

In the “bursty” TD-LTE case, the power consumption estimates for the AP, Modem and Transceiver power consumption were modelled to increase during the uplink (TX) slots, to take into account the increased instantaneous data rate relative to the FD-LTE scenario.

During the TD-LTE downlink (RX) slots, the Modem and AP power consumption estimates were reduced, rather than zeroed, to take into account the background tasks of application-layer & MAC-layer buffering of the traffic.

The RF PA power consumption was measured assuming a 4 dB front-end loss, at 16 dBm and 23 dBm antenna power.

As shown in Figure 8, the peak power consumption during TD-LTE uplink bursts was around 2x the FD-LTE consumption, but the average power consumption across the whole frame was reduced from 1500 mW to 880 mW, a saving of around 40%.

This reduction was due partly to the increased energy efficiency of the RF PA when operating at high power, and partly due to the reduction in overhead from the LTE modem and application processor, which can be shut down during the RX slots instead of having to operate continuously at lower bandwidths.

This saving in average power consumption also translates into a thermal benefit, due to the corresponding reduction in waste heat generated by the components.

![Figure 8 – Handset energy consumption model, FD-LTE vs TD-LTE](image)
ET measurements with TD-LTE waveforms

To use Envelope Tracking with a TD-LTE system imposes several challenging requirements on the ETIC implementation:

- Fast transitions from Active ET to standby mode and vice-versa;
- Low power consumption in standby mode during the RX timeslots;
- High ET-mode bandwidth, due to the limited duty cycle available for uplink transmissions;
- High efficiency at high ET bandwidths, needed to maximize the power savings from ET;
- High output power, due to the statistical increase in TX power and the desire to avoid Maximum Power Reduction waivers.

Nujira’s NCT-L1300 ETIC meets all these requirements, and can operate in ET mode at the full 20 MHz bandwidth required for TD-LTE, typically delivering in excess of 28 dBm at the PA output.

Measuring ET solutions in TD-LTE scenarios is more complicated than FD-LTE measurements, due to the need to generate time-aligned MIPI RF Front End (RFFE) control sequences to change the operating mode of ETIC and RFPA synchronously with the burst structure of the RF and Envelope waveforms.

Nujira’s Coolteq.t Flexible Development System can generate time-aligned RF, Envelope, and RFFE signals to test the ETIC+PA in a truly dynamic TD-LTE environment, as shown in Figure 9.

Using the MIPI RFFE interface to switch the PA and NCT-L1300 ETIC to Low Power Standby mode at the end of the burst reduces the quiescent current consumption to a few microamps during the downlink (RX) slots of the TD-LTE frame. Just before the start of the uplink transmissions at the end of the Special Subframe, the MIPI RFFE interface is used to restore the ETIC to full power ET mode.

Measurement of the EVM of the signal in burst and continuous modes showed no impact on EVM from the burst-mode operation. The power consumption of the PA+ETIC was reduced by around 30% in the ET bursts, compared to APT operation.

Figure 9 – Oscilloscope plots of TD-LTE ETPA, showing ET supply voltage (blue) and ETIC/PA MIPI RFFE serial control bus (purple). The right-hand waveform is zoomed in to show the end of one TD-LTE uplink burst, with the transition to low power standby mode.
Conclusions

With TD-LTE networks being deployed in an asymmetric configuration for improved network efficiency, uplink capacity and throughput are getting squeezed in comparison to FD-LTE networks, compromising the user experience for data uploads.

The most commonly deployed TD-LTE networks will tend to push up instantaneous transmit power by 7 dB, and transmit bandwidth by a factor of 5 compared to FD-LTE networks.

The corresponding increase in peak current consumption, which can be double that of FD-LTE, makes the case for adding Envelope Tracking even more compelling, with ET typically reducing the peak current consumption of the RF PA by 30%.

Modelling the overall handset power consumption showed that the TD-LTE configuration was more energy efficient for a given throughput than an FD-LTE implementation, although the peak power consumption was doubled.

The high bandwidth of TD-LTE transmissions makes low bandwidth ET (or fast-tracking APT) solutions unattractive, with drive test statistics suggesting that low bandwidth solutions can only address less than half of the potential energy savings of ET.

In addition to high efficiency at high bandwidth, ETICs for TD-LTE must also support rapid mode switching between ET and low power standby, to minimize power consumption during the RX timeslots of the TD-LTE frame.

Nujira’s NCT-L1300 ETIC can transition seamlessly between FD-LTE and TD-LTE modes with zero overhead, and supports ET even at the highest 20 MHz bandwidths.

In TD-LTE terminals, high bandwidth ET solutions offer double the energy savings.

![Figure 10 – Comparison of TD-LTE peak and average power consumption with equivalent FD-LTE terminal](image-url)