SDR RADIO SUBSYSTEMS USING POLAR MODULATION

Earl McCune (Tropian Inc., Cupertino, CA, USA; earl.mccune@tropian.com)

ABSTRACT

Although simple in principle, actually building a general radio subsystem for a software-defined radio product has proven elusive. Implementation difficulties have arisen mainly from noise figure, circuit nonlinearity effects, and power dissipation. To jointly address these three issues an approach that uses polar coordinates as the signal processing basis instead of rectangular (I&Q) coordinates is investigated. A completely different radio architecture results, which has no requirement for RF circuit linearity. The noise floor of these polar radios appears to be dominated by VCO phase noise, and not traditional noise figure effects, when well designed. Further, running the RF circuitry in switch-mode improves power dissipation compared to backed-off linear approaches. Preliminary results are presented which imply good application generality, particularly for the various cellular radio standards used around the world.

1. INTRODUCTION

Whether for global roaming or staying on a single consolidated operator's network of multiple system types, mobile terminals must operate in multiple modes to maintain coverage. Such mobiles necessarily have an increased complexity over single-mode devices, which is economically undesirable for many reasons. Problems are especially exacerbated for mobiles that must operate both full duplex for CDMA systems, and half duplex for time division (GSM or TDMA) systems. Conventional transmitter architectures for constant envelope half-duplex signals (e.g. GSM/GPRS) generally have little in common with conventional transmitter architectures for envelope varying full duplex signals (e.g. CDMA).

Using a polar architecture, data are presented showing high quality implementation of uplink (handset) transmitters for the following deployed and proposed cellular systems: GSM, EDGE, ANSI-136, AMPS, IS-95, UMTS (IMT-2000-DS), and cdma2000-1XRTT (IMT-2000-MC). These signals range in bandwidth from <30 kHz to 5 MHz, a span of over 2 orders of magnitude. Power control is measured at over 90 dB in support of CDMA system requirements. Of prime economic importance is that this polar multi-mode radio design is a direct extension of a basic GSM radio. Thus, the economics of such polar radios are close to that of GSM, adding multimode capability including CDMA *to the GSM baseline* – not the other way around. Well beyond the technology development stage, products using this technique are available in the merchant market.

This paper is structured as follows. Section 2 presents important parameters for a single common multimode RF subsystem to be used within SDR. Section 3 presents two conventional transmitter architectures, and introduces corresponding polar transmitter architectures. Section 4 presents measured data from this polar transmitter for several signal types, spanning signal bandwidths from 30 kHz through 5 MHz. Conclusions are drawn in Section 5.

2. MULTI-MODE REQUIREMENTS

Beyond the choice of implementation architecture, there are additional signal and system characteristics that affect the ease or difficulty of realizing any hardware design for a radio communications system. As such, these characteristics directly or indirectly influence the cost of realization for a particular system. Experience has shown that the following list contains the major cost drivers in RF circuit design, in no particular order:

Signal Peak-to-Average Power Ratio	(PAR)
Signal Peak-to-Minimum Power Ratio	(PMR)
Transmitter Power Control Dynamic Range	(PCDR)
Signal Bandwidth	
Transceiver Duplex Mode	(full, half)
Bandwidth Confinement Requirements (Transmit Mask)	
Adjacent Channel Power	(ACP, ACPR, ACLR)

In general, the larger the value of these parameters, the greater the design effort and the tougher the manufacturing testing requirements are – both leading toward higher product costs. It is imperative that the engineering community find ways to bring these cost characteristics down. This is a major motivator for software designed radio (SDR).

In Table I, principal characteristics of deployed (and deploying) cellular radiotelephone systems around the world are summarized. The characteristics focused on are these cost drivers: PAR, PMR, duplex mode, and PCDR. It is seen that constant envelope signals (0 dB PAR / 0 dB PMR) are used for 1G and GSM/GPRS systems. Newer systems have adopted envelope-varying signals, principally to improve spectral efficiency. The analog 1G systems operate in full-duplex mode, while the 2G digital systems ANSI-136 and GSM use the generally less expensive half-duplex mode. Full duplex operation is required for the FDD CDMA systems IS-95, UMTS, and cdma2000. Time division duplex (TDD) versions of CDMA, such as the TD-SCDMA system being developed in China [1] use half duplex. Of course, the technical requirements on the radio subsystems for these cellular systems is far more detailed than shown in Table I. [2-6] This subset of characteristics is chosen to partially illustrate their relative difficulty in RF implementation, and thus provide a coarse guide to the relative cost of a mobile transmitter for one system compared to another.

In order to be implemented in a SDR, all of these systems must be implemented with a single, common radio subsystem. Issues in supporting all of these systems with one, general-purpose transmitter design are discussed below.

3. RADIO SUBSYSTEM ARCHITECTURES

To-date, each of the systems listed in Table I has generally developed with mobile-unit transmitter design in isolation. That is, handset transmitter designers have, with rare exception, had to only consider the transmit mode of the intended system without any need to also support any other system. The only major exception is the requirement for both IS-95 and ANSI-136 handsets to also support the first generation AMPS analog system. This dual-mode operation has traditionally been accomplished with two transmitters: one for the digital mode, and a separate set of circuitry for the analog mode. These designs have all had
a decade or more to evolve to their present configurations, so it is reasonable to assume that some sort of economic optimum has been reached for each (given their respective implementation technologies).

System	PAR (dB)	PMR (dB)	Duplex	PCDR (dB)
1G	0	0	full	25
ANSI-136	3.5	19	half	35
GSM	0	0	half	30
GPRS	0	0	half/full	30
EGPRS	3.2	17	half/full	30
UMTS	3.5-7	infinite	full	80
IS-95x	5.5-12	26 - infinite	full	73
cdma2000 -1xRTT	4-9	infinite	full	80
TD-SCDMA	2.5-7	infinite	half	80

Table 1
Principal Characteristics of Deployed (and Deploying) Cellular Systems

3.1 Conventional Transmitters

For GSM handsets, the predominant design is the tracking loop architecture shown in Figure 1. Most merchant IC manufacturers of GSM transceiver devices support this design, or close variants of it. The tracking loop transmitter works only for constant envelope signals, since the tracking phaselock loop (PLL) acts as a combination of: a frequency translator, bandpass filter, and a hard limiter. Burst ramping and power control are performed with the power amplifier. All signal modulation passes through the PLL, so its bandwidth must be wide enough to not distort the desired signal angle modulation.

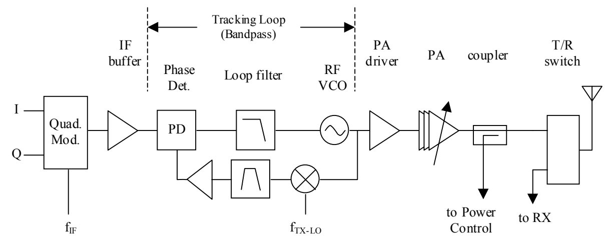


Figure 1. A conventional tracking loop architecture used in GSM/GPRS mobile transmitters.

CDMA systems have very different requirements on mobile transmitters. Besides supporting the non-zero peak to average ratio (PAR) of the CDMA signal, this transmitter must control its output power over a 75-80 dB dynamic range without incurring much distortion. In addition, CDMA systems use full duplex operation, so transmitter output noise in the receive band must be suppressed well below the receiver's LNA input noise. [6] A common architecture used in CDMA transmitters is shown in Figure 2a. With an envelope-varying signal, linear circuit techniques are used in the CDMA transmitter to minimize distortion. Issues encountered in the realization of this linear transmitter are discussed in detail in [7].

A mutual comparison of Figures 1 and 2 shows that, outside of the quadrature modulator and antenna, there is very little in common among these architectures. This suggests that constructing a single general-purpose multi-mode transmitter will be difficult, and that alternative approaches might be useful.

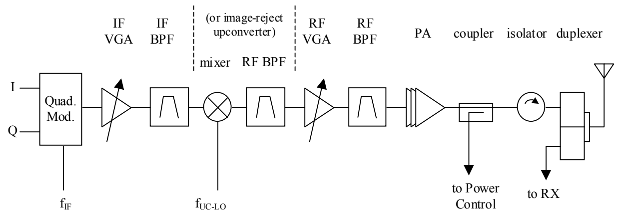


Figure 2. A conventional linear transmitter block diagram used for CDMA mobiles.

3.2 A Polar Alternative

Since the rectangular to polar coordinate transformation is well-known to be unique, it is straightforward (in principle) to convert quadrature into polar signal processing. Polar transmitters exist that support the cellular systems shown in Table 1. Architectures for these are presented in Figures 3 and 4. There are two designs shown, one for half-duplex systems (e.g. GSM, TDMA) in Figure 3, and the other for full-duplex systems (e.g. CDMA and 1G) in Figure 4.

The polar transmitter operates separately on the phase modulation (PM) and envelope or amplitude modulation (AM) components of the signal. Without any envelope variation on the PM path, these RF circuits have no linearity requirements. This includes the power stage, which operates in compression at all times (C-PA). Envelope variations are imposed at the final output power (in the power stage) using gain variation techniques. It is essential that the relative timing between the PM and AM components be accurate to maintain signal quality. With the output stage operated in compression, noise figure effects do not set the wideband output noise floor. Rather, it is observed that VCO phase noise dominates far-off noise from the main signal. [7]

For CDMA, the polar transmitter must also support a wide power control dynamic range and full-duplex operation. The phase component of the CDMA signal is of constant envelope, so linear RF circuitry is still not required. The power control dynamic range of the power stage is, however, expanded from that required for GSM/GPRS.

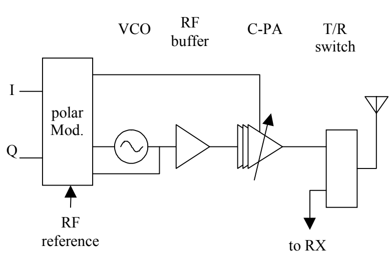


Figure 3. A polar transmitter block diagram for half-duplex radio systems

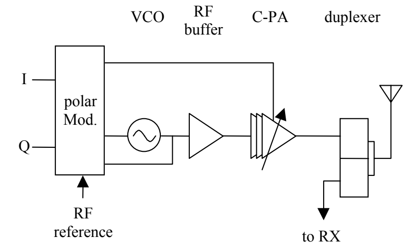


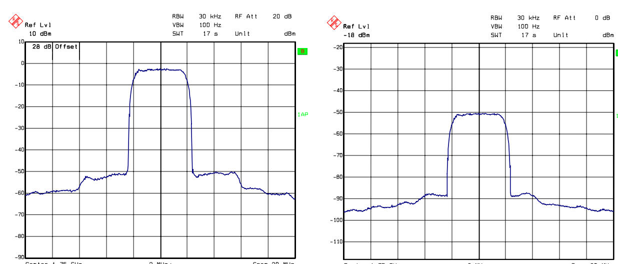
Figure 4. A polar transmitter design for full duplex radio systems, with extended PA dynamic range for CDMA operation.

4. POLAR TX MULTIMODE PERFORMANCE

A comparison of Figures 3 and 4 shows that there is a lot of overlap between these polar architectures, suggesting that a general multi-mode design could be reasonably implemented. Toward this end, the signals of Table 1 have been implemented in a polar transmitter. Partial results are presented in this section. The following signals are presented in the order of decreasing signal bandwidth.

4.1. UMTS

UMTS (IMT-2000-DS) is a CDMA signal with a bandwidth of 5 MHz. The PAR is about 3.5 dB with one data channel active, and the power control dynamic range specification requires the mobile transmitter to span from full power to -50 dBm. Since the polar power stage is operated in compression at all times, signal distortion is actually quite minimal at full power, as seen in Figure 5a. At minimum output power, the signal quality is well above the minimum requirement of 0dB ACLR, shown in Figure 5b.



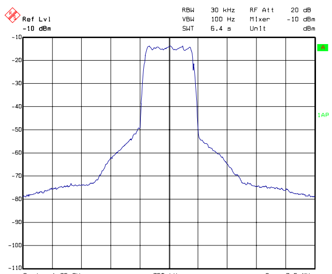
(a) (b)

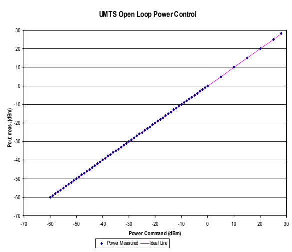
Figure 5. Mobile transmitter output for 5 MHz UMTS signals at a) +28 dBm (ACLR=-49dB) and b) -50 dBm (ACLR=-41dB).

4.2. IS-95 CDMA

The IS-95 CDMA signal occupies a bandwidth of 1.25 MHz. The PAR is strongly dependent on the number of supplemental channels that are active in the uplink. The author is unaware of any commercial implementations that use more than the minimum configuration, so for this measurement the minimum configuration, with a PAR value of 5.5dB, is used. This is 2dB higher than the UMTS signal above. To achieve nearly the same output power, the polar transmitter envelope modulator was driven into clipping, partially mitigating the higher PAR. This clipping results in some signal distortion, seen in Figure 6a. Even with this envelope distortion, significant margin remains to the specification.

Power control for the CDMA implementation is shown in Figure 6b. Since the polar transmitter controls RF power as an AM operation (they are not independent), transmitter open loop power control assumes the accuracy of the amplitude modulator. The points of Figure 6b are CDMA transmitter power measurements from +28 to -60 dBm, with the ideal power control line superimposed.


(a)

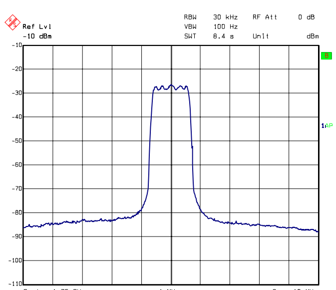


(b)

Figure 6. a) Mobile transmitter output for 1.25 MHz IS-95 CDMA signal (+27 dBm, -54 dB ACPR (885kHz)); b) open loop power control dynamic range measurements

4.3. cdma2000-1xRTT

cdma2000-1xRTT (IMT-2000-MC) occupies the same bandwidth as the IS-95 signal. The signal coding defined for radio configuration 3 (RC3) results in lower PAR than that experienced with IS-95. Including two active supplemental channels, the PAR is around 4 dB. The reduced PAR results in low signal distortion, as seen in Figure 7.


(a)

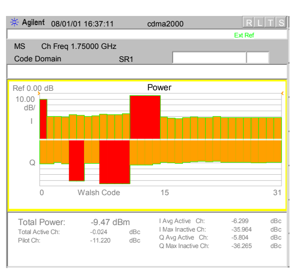

(b)

Figure 7. a) Mobile transmitter output for 1.25 MHz cdma2000-1xRTT (RC3) signal (-56 dB ACPR (885 kHz)); b) measured channel structure for this RC3 test signal.

4.4. GSM/GPRS

As the most widely deployed cellular system in the world, GSM is often considered to occupy 200 kHz – though as the spectrum of Figure 8 shows the actual value is between 400 and 600 kHz. The modulation is constant-envelope within a burst. However, to maintain spectral confinement in the presence of TDM bursting the RF rise and fall profile must be carefully controlled. Therefore, even though GSM has adopted a constant envelope modulation, envelope control is still vital to meet all of the specifications.

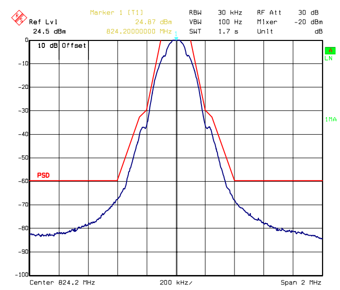


Figure 8. Mobile transmitter output for the 200kHz GSM/GPRS signal at +33 dBm.

4.6. EDGE/EGPRS

The GSM system has defined a growth path to triple its on-air data rate using an 8PSK signal with essentially identical spectral properties to the original GMSK. The price is that the signal no longer has a constant envelope. Rather, the EDGE signal has a 3.2dB PAR and a 17dB PMR. This is amazingly similar to the digital extension for AMPS, where ANSI-136 was developed to triple call capacity while keeping within the existing bandwidth. [The ANSI-136 signal has a 3dB PAR and 19dB PMR.]

Polar transmitters, with their output amplifiers always operating in compression, require no backoff from peak saturated power for an envelope varying signal. Thus, a 2 watt PA for GMSK will provide 1 watt of EDGE, as shown in Figure 9. Signal spectral quality is well within the specification.

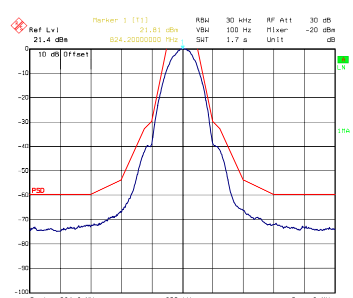


Figure 9. Mobile transmitter output for 200 kHz EDGE/EGPRS signal at +30 dBm.

Beyond the requirement to implement this variety of signals using only one radio design, the SDR radio subsystem must also be mode-agile, switching modulation dynamically as desired. This polar transmitter possesses this agility, with one case shown in Figure 10. This measurement shows 6 active slots in a GSM uplink frame, with the slots mixed among GMSK and EDGE 8-PSK modulations. Complete power down and up ramping is performed between each slot, with the modulation configuration changed in the digital signal processor following power-down, before the next ramp up. So not only is the modulation type independently settable from slot to slot (as EGPRS requires), but power level is as well.

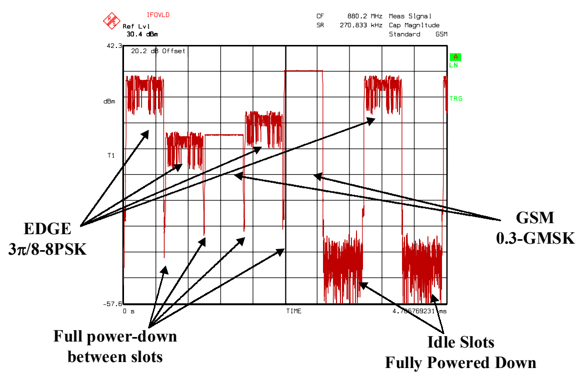


Figure 10. Dynamic modulation within one GSM frame with each slot having either GMSK or EDGE modulation, individual power levels (or off), and full power down between each.

4.7. ANSI-136

This TDMA system, designed to fit within the frequency raster and channel filtering for AMPS, is widely deployed in the Americas. Mobile transmitters have generally exhibited high levels of third- and fifth-order distortion on the output signal due to compression in the output amplifier (to improve efficiency). As Figure 11 shows, the polar transmitter produces this signal at high quality, even at 1 watt of output power. The low level shoulders on this signal are due to synthesizer noise.

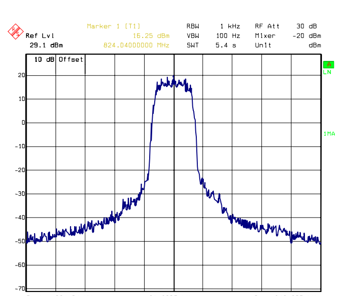


Figure 11. Mobile transmitter output for 30 kHz ANSI-136 signal at +30 dBm (-35 dB ACP).

4.8. AMPS (FM/FSK)

Though it is waning in importance, the analog AMPS system is still widely deployed and operational. Support of the AMPS system is implemented here as a general FM process, where the transmitter processor accepts samples of an input waveform and directly modulates the carrier. Power control is effected with the amplitude path.

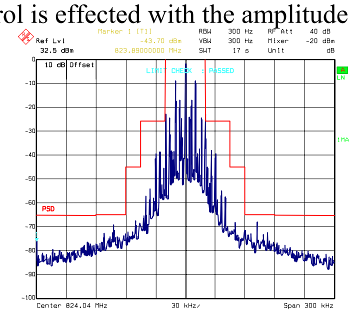


Figure 12. Mobile transmitter output for 30 kHz AMPS signal at +30 dBm.

5. CONCLUSION

Polar technology is investigated as an approach to mobile transmitter design for a single, universal, multi-mode radio subsystem in support of SDR. Measurements show that one polar design readily supports a wide range of signal bandwidths, from the 5 MHz bandwidth UMTS (IMT-2000-DS) signal, the 400 kHz bandwidth signals GSM/GPRS and EDGE/EGPRS, and the intermediate bandwidth signals IS-95 (1.25 MHz), cdma2000-1XRTT (IMT-2000-MC) (1.25 MHz), as well as the 30 kHz bandwidth signals ANSI-136, and AMPS. All of these signals show excellent performance from this one, common, and un-reconfigured radio subsystem. This is an important step in the development and deployment of SDR based handsets.

6. REFERENCES

[1] H-H Chen, C-X Fan, W.W. Lu, ‘China’s Perspectives on 3G Mobile Communications and Beyond – TD-SCDMA Technology,’ *IEEE Wireless Communications (formerly IEEE Personal Communications)*, Vol. 9, No. 2, April 2002

[2] TIA/EIA-627, ‘ANSI Version of TDMA Dual-Mode Air Interface Standard’

[3] 3GPP TS 45.005 v5.1.0, ‘Technical Specification Group GSM/EDGE Radio Access Network; Radio Transmission and Reception,’ 3rd Generation Partnership Project

[4] TIA/EIA IS-95B, "Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular Systems," 1998

[5] 3GPP TS 25.101 v5.0.0, 'Technical Specification Group Radio Access Networks; UE Radio Transmission and Reception (FDD),' 3rd Generation Partnership Project

[6] 3GPP2 C.S0002 v3.0, 'Physical Layer Standard for cdma2000 Spread Spectrum Systems,' Release 0, June 15, 2001

[7] E. McCune, 'Polar Modulation: An Alternative for Software Defined Radio,' *Proceedings of the International Symposium on Advanced Radio Technology (ISART)*, Boulder CO, March 2002, www.its.bldrdoc.gov/isart