Modern Wireless Signals

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***Abstract* — With the evolution of wireless systems and services, the on-air signals themselves are also undergoing very significant transformations. This paper provides a survey of the active and coming-soon signal types adopted for wireless systems around the world. Focus is on modulation schemes, along with various measures used to characterize the signals before and after power amplification. Cost-benefit tradeoff information is introduced to provide perspective on this signal evolution.**

I. Introduction

As two-way wireless communication becomes ubiquitous from relative obscurity 20 years ago, the signals used have evolved from those which are very simple to now include very complicated and high order modulations. And with economics demanding that older systems are not taken down before newer ones are installed, many of these signals must exist and operate side by side. This demands that the actual radio hardware used in any network infrastructure, as well as that in the mobile, remote, or subscriber devices, must usually be much more general purpose than optimized specifically for one signal type.

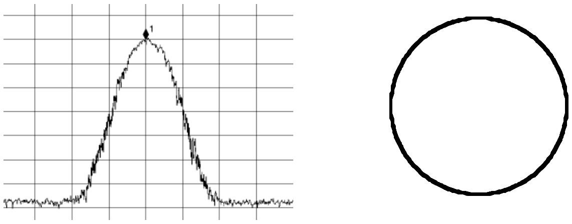
In the design and test of this radio hardware it is very important to understand the fundamental characteristics of the signal(s) that it must support. With such a wide variety of signals, even the metrics used in their characterization are not uniform in type and application.

To address these issues this paper is organized as follows. After this introduction, Section II surveys the major measures used with modern wireless communication signals. Section III then illustrates how these measures are applied (or not) to the signals used in particular systems. Comparisons among these signals, including their relative advantages and disadvantages are presented in Section IV. Conclusion is achieved in Section V.

II. Measures Used With Modern Signals

In the earliest days of cellular wireless communication the signal of choice was narrowband frequency modulation (NBFM). Because this signal had already been used for decades in the Public Service and other Land Mobile systems, adopting it for cellular communication meant that the existing experience base could be fully leveraged. Important characteristics of NBFM are illustrated in Fig. 1.

Measures used for NBFM are very simple. Besides measuring the output power, little else is needed because the transmit amplifier cannot distort this constant envelope signal in ways to change its occupied bandwidth or to distort the modulation. This provides an *extremely* low cost of implementation. However it became clear within just a few years that the bandwidth efficiency (η_{BW}) of this signal was not good enough to support the amount of traffic that the cellular system was attracting. And though the cost to implement signals with higher bandwidth efficiency is much higher than that for NBFM, revenue from the larger amount of traffic justified the additional expense.



(a) (b)

Fig. 1. The NBFM signal: a) one representative power spectral density, and b) its vector diagram showing the constant envelope property.

All of the modern signals are digital in nature, meaning that the information that they contain is quantized in value and held constant for a set length of time. However *this does not mean* that the signal itself is digital (quantized in both value and time). Rather, all transmitted wireless signals are continuous time, meaning that they are analog in nature so we need to pay detailed attention to the entire waveform.

The following set of measures are all based on knowledge that the signal itself is analog in nature, even though we may sample this continuous waveform only at discrete times. The waveform value of the wireless signal for any particular signal sample is not quantized at all. These measures include error vector magnitude (EVM), envelope value probability (PDF), envelope cumulative probability (CDF), and envelope complementary cumulative probability (CCDF). Bandwidth occupancy (OBW) is characterized using adjacent channel power (ACP) and alternate channel power (AltCP) measures. Finally we consider several efficiency measures related to the signal, including bandwidth efficiency and transmitter *energy* efficiency – not to be confused with the signal *power* efficiency.

EVM

The modulation quality metric error vector is defined as the difference vector between what the signal phasor should ideally be at a particular time and what the signal phasor actually is at that time. [1] As a metric, only the magnitude of this vector is used. The times at which EVM is evaluated can be selected to be the ideal symbol sampling instants, giving the EVM relation

$$\mathrm{EVM_{rms}} = \sqrt{\frac{\sum_{k=1}^{L} \left| \hat{x}(\mathrm{kT_S}) - x(\mathrm{kT_S}) \right|^2}{\sum_{k=1}^{L} \left| x(\mathrm{kT_S}) \right|^2}} \tag{1}$$

It is also possible to evaluate the signal EVM throughout the modulation waveform. This necessitates much finer sampling, and the corresponding relation changes to

$$\mathrm{EVM_{rms}} = \sqrt{\frac{\sum_{n} \left| \hat{x}_n - x_n \right|^2}{\sum_{n} \left| x_n \right|^2}} \tag{2}$$

PDF

If a signal has envelope (magnitude) variations when modulated, then there is a probability associated with what output power the transmitter is putting out at any particular instant (or brief interval) in time. This is the probability that the signal envelope has a particular value, and is known as the envelope probability density function (PDF). One example of a signal envelope PDF profile is presented in Fig. 2b. In general the PDF curve curvature characteristic at the zero magnitude end relates to PA design difficulty with regard to linearity: if the curvature of the PDF curve is positive ($\cup$) then linearity requirements will normally be much easier to achieve than if the curvature is negative ($\cap$).

CDF and CCDF

Cumulative probabilities are very useful for system design. The cumulative probability of interest here is the cumulative density function (CDF), which is the probability that the envelope is less than or equal to a particular value, meaning that the CDF curve is the integral of the PDF curve. This must be a monotonically increasing curve, since the probability that the envelope value is less than zero is, well, zero – and the probability that the envelope is less than the peak envelope value is unity. The CDF curve corresponding to the envelope probability density of Fig. 2b is presented in Fig. 2c.

The CDF curve provides a lot of resolution regarding lower envelope magnitudes. Correspondingly, very little information is available on the envelope peak characteristics. To address this problem the complementary cumulative density function (CCDF) is used, which is simply the CDF subtracted from one (CCDF = 1-CDF). The information in the CCDF, when plotted on logarithmic scales, provides high resolution on the peak characteristics of the signal at the expense of information resolution at low signal magnitudes. When needing to avoid compression at signal peaks, this is far more important than behavior near zero magnitude. Thus, it is much more common to see CCDF features in test equipment than either CDF or PDF measures. An example CCDF curve corresponding to the envelope probability density of Fig. 2b is presented in Fig. 2d.

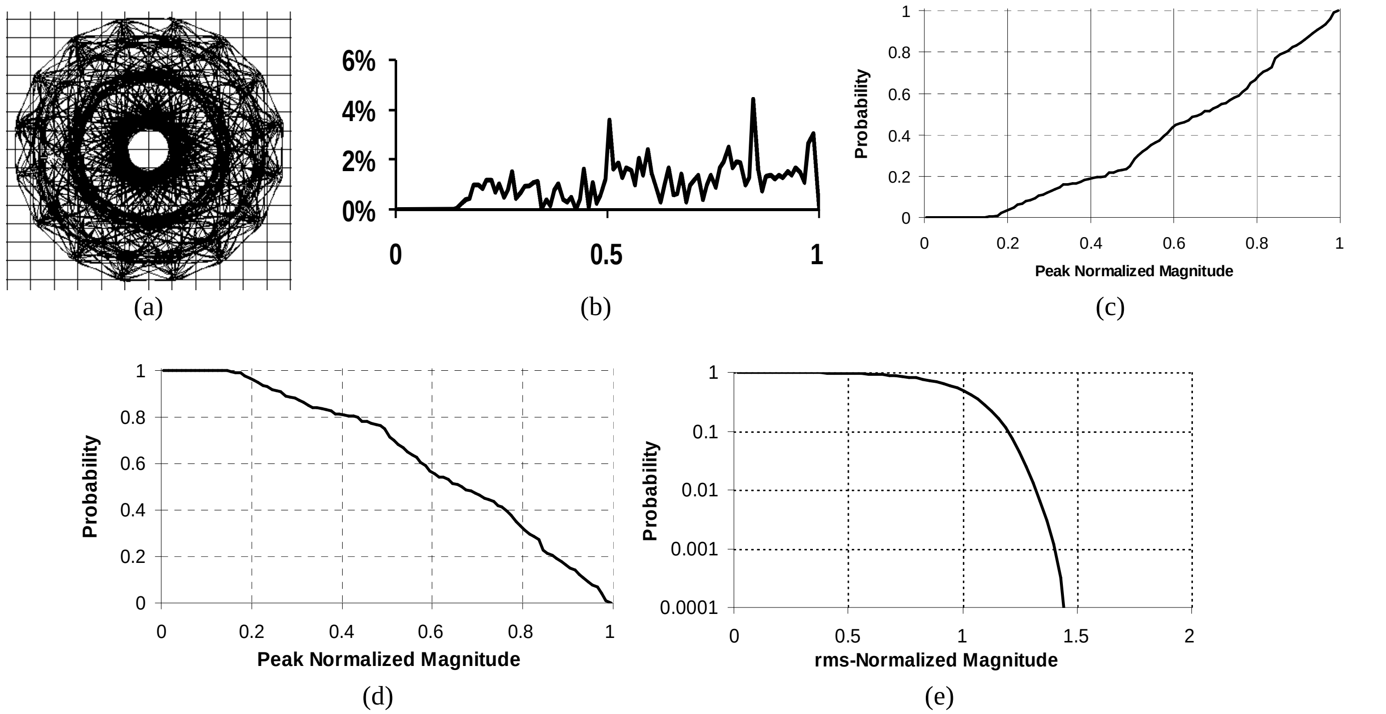


Fig. 2. Examples of envelope statistic measures: a) the example signal vector diagram, and the corresponding curves for b) the PDF, c) the CDF, and d) the CCDF; e) It is more common to normalize the CCDF curve to rms signal power and to show the probabilities on a logarithmic scale.

The peak to average power ratio (PAPR) is taken as the ratio of the signal peak to its rms value. It is customary to define the signal peak as the magnitude value where the CCDF curve passes through 0.0001 probability. The signal from Fig. 2e has a PAPR of $10\log_{10}(1.45^2) = 3.2$ dB.

ACP (OBW)

The occupied bandwidth (OBW) of a signal is a critical measure since this is often strictly regulated by a licensing or type-approving authority. It is clearly desired to only transmit signal power within the assigned bandwidth. Practically all transmitters do however transmit some power outside of the assigned bandwidth. If the outside power lies within the adjacent signal channel (see Fig. 3), this is called adjacent channel power (ACP). If there is any transmitter output power in the next channel further removed, this is called alternate channel power (AltCP). Some applications are more tolerant of adjacent- or alternate-channel power than others. It is usual to measure the ACP and AltCP using the same filter bandwidth that is used in measuring the main signal power. However there are some standards which use different measurement bandwidths, so extreme care is required to be sure that the measurement is made properly. Common names for this test are adjacent channel power ratio (ACPR) and adjacent channel leakage ratio (ACLR).

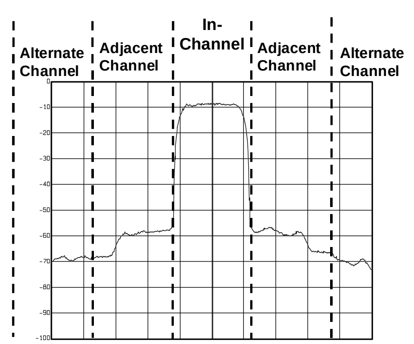


Fig. 3. Definitions of adjacent channel power and alternate channel power

Efficiency Metrics: Energy, Power, and Bandwidth

Many measures involve the word "efficiency", so many that there is a large amount of confusion surrounding this word. The most important measures of "efficiency" are presented here to provide clarity in their purposes, differences, and values to signal design and hardware evaluation.

***Energy Efficiency* (*η*)** is a critical metric, relating how effectively electrons that are drawn from the supply are used to generate the signal. There are a finite number of electrons available from any battery, so a design that uses each of them more effectively naturally results in a longer operating time from that battery, all else being equal.

Output efficiency, also known as Drain Efficiency or Collector Efficiency depending on whether the RF power transistor is a FET or bipolar respectively, is defined by

$$\eta_{OE} \equiv \frac{\mathrm{P_{RF}}}{\mathrm{P_{DC,F}}} \cdot 100 \quad \% \tag{3}$$

where $\mathrm{P_{RF}}$ is the output power $\mathrm{P_o}$ at its maximum (saturated) value, and $\mathrm{P_{DC,F}} = \mathrm{V_F} \bullet \mathrm{I_F}$ is the DC power supplied only to the final stage. This is a useful metric for evaluating and comparing output transistors. But with limited exposure to the currents of the complete amplifier, this result is naturally higher than the result of other more inclusive efficiency calculations.

From an amplifier point of view, the energy efficiency measure of greatest importance is power-added efficiency (PAE) defined by

$$PAE\left(\mathrm{P_o}\right) \equiv \frac{\mathrm{P_o} - \mathrm{P_i}}{\mathrm{P_{DC}}} \cdot 100 \quad \% \tag{4}$$

Here, $\mathrm{P_o}$ is the output power at its maximum value, $\mathrm{P_i}$ is the input power to the amplifier at this output power, and $\mathrm{P_{DC}}$ is the supplied power to the entire amplifier, including the bias circuitry. An equivalent relationship to (3) for PAE is

$$PAE\left(\mathrm{P_o}\right) \equiv \frac{\mathrm{P_o}}{\mathrm{P_{DC}}}\left(1 - \frac{1}{G}\right) \cdot 100 \quad \% \tag{5}$$

Here, G is the gain factor (linear, not in dB) of the amplifier at the output power $\mathrm{P_o}$, and $\mathrm{P_{DC}}$ remains the supplied power to the entire amplifier. We see that if gain is high the input power term is negligible when calculating PAE, and (5) reduces to (3) at maximum output power.

***Power efficiency* (*ψ*)** is VERY OFTEN confused with energy efficiency. The use of these terms in the technical literature is quite sloppy, actually, almost to the point where the two terms are used interchangeably. They are not at all interchangeable. Power Efficiency is actually a *modulation metric.* [2] A more power efficient signal is a signal which requires a lower amount of transmitted power to achieve an identical communication throughput or bit-error rate (BER).

Power efficiency is most easily visualized using constellation diagrams. In an additive noise limited environment, the probability of the demodulator making an error is dependent on the closest spacing between any two points in the signal constellation. This means that the signal will be more robust in the presence of noise with larger minimum spacing (distance) between constellation points. We define these distances as

- Constellation point ($\mathrm{I_i}$, $\mathrm{Q_i}$) distance from the origin $\quad d_i = \sqrt{I^2{}_i + Q^2{}_i}$
- Distance between constellation points ($\mathrm{I_i}$, $\mathrm{Q_i}$) and ($\mathrm{I_j}$, $\mathrm{Q_j}$) $\quad d_{ij} = \sqrt{\left(I_i - I_j\right)^2 + \left(Q_i - Q_j\right)^2}$

At the same time we wish the transmitter to put out lower power when generating this signal, always normalizing the most distant constellation point(s) from the origin to unity magnitude. Both of these characteristics enhance their desirable directions when Power Efficiency is defined as the ratio

$$\psi_{\mathrm{PE}} \equiv \frac{\mathrm{d_{min}}}{\mathrm{d_{rms}}} \tag{6}$$

where

$$\mathrm{d_{min}} = \min\left(d_{ij}\right)\;; \quad i \neq j \quad ; \quad 1 \leq i, j \leq M \quad \text{and} \quad \mathrm{d_{rms}} = \sqrt{\frac{1}{M}\sum_{i=1}^{M} d_i{}^2} \quad .$$

Bandwidth efficiency relates to the data rate that is achieved within the occupied bandwidth. Taken as a modulation metric there is no account taken of whether a transmitted bit is payload, coding, or protocol overhead. Here "a bit is a bit" so only modulation characteristics (constellation and filtering) matter to this result. But when bandwidth efficiency is taken as a system metric, only the payload bits are counted – which is what ultimately matters to the application. When testing hardware we only consider bandwidth efficiency as a modulation metric.

Bandwidth efficiency as a modulation metric is simply the number of bits per second that are transmitted within the (occupied) spectrum bandwidth

$$\eta_{BW} = \frac{R}{B} \qquad \text{[bits/sec]/[Hz(BW)]} \quad , \tag{7}$$

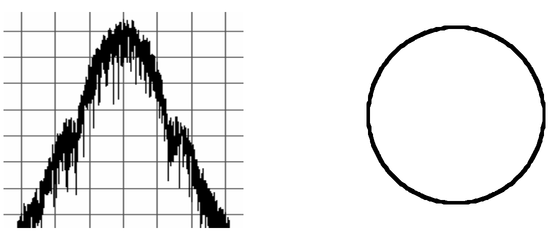
where R is the actual on-air data rate, and B is the channel bandwidth. Huge arguments have arisen about what measure should be used for this bandwidth B. Should this be the channel bandwidth allocated by some government regulatory agency, or the signal occupied bandwidth? And is the signal occupied bandwidth measured from the PSD at the -3dB points, the -6dB points, the -60dB points; or by some other measure entirely like the 99% power containment bandwidth? Most theoretical values for bandwidth efficiency assume ideal brickwall bandlimiting, making them upper bounds since such signals cannot actually be built.

III. Survey of Modern Wireless Signals

In the world today the dominant cellular communication signals are standardized through the Third Generation Partnership Project (3GPP). At the time of this writing, network operators using 3GPP signals carry over 90% of all cellular traffic. In addition, Bluetooth™ and multicarrier (OFDM) signals, like that used for WiMAX, are presented. Information for this survey is a subset of the signals examined in detail in [8].

GSM/GPRS [3]

In an attempt to keep the low implementation cost from NBFM used in first generation cellular networks, GSM adopted the constant envelope GMSK (1 bit per symbol) signal. Basic characteristics of GMSK are shown in Fig. 4. The PSD in Fig. 4a shows slopes with increasing offset frequency (from the carrier). This makes the occupied bandwidth of the GSM signal impossible to absolutely define.



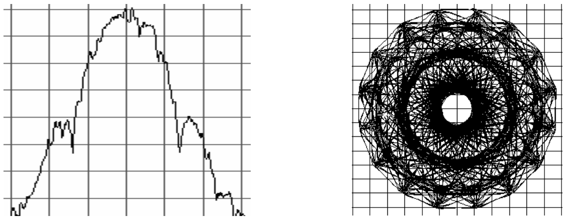
(a) (b)

Fig. 4. The GSM GMSK signal: a) power spectral density, and b) vector diagram showing the constant envelope property.

EDGE

With the intent of tripling the bandwidth efficiency of the GSM network, enhanced data for GSM evolution (EDGE) adopted an 8PSK modulation (3 bits per symbol). Filtering is carefully chosen to provide a signal PSD nearly identical to that of GSM, seen by comparing Fig. 5a with Fig. 4a. The specified filter provides significant ISI, a necessary byproduct of transmitting 3 bits with essentially the same PSD as GSM.

The EDGE modulation encoder also adds a 3π/8 phase shift to each symbol. Besides making the 8PSK vector diagram (Fig. 5b) look like 16PSK, this consistent phase rotation causes the signal envelope to not fall below a fixed value. This is very good for transmitter amplifiers because the signal phase remains continuous and well bandlimited. Envelope statistics are shown in Fig. 2. PAPR is 3.2 dB, due solely to the filtering applied (not the 8PSK constellation)

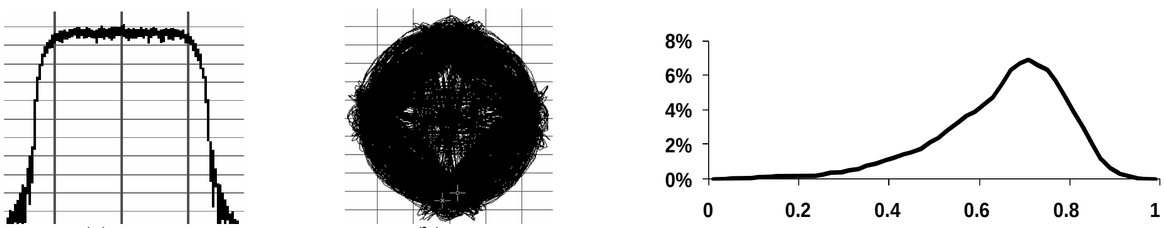


(a) (b)

Fig. 5. The EDGE 8PSK signal: a) power spectral density, and b) vector diagram showing envelope varying characteristics

UMTS (Wideband CDMA) [4]

What is called "3G", the Universal Mobile Telephone Service (UMTS) uses a large set of QAM signals for modulation. These are linearly filtered with a spectral root-raised cosine filter, so the signal PSD is much more defined (shown in Fig. 6a) than for GSM/GPRS and EDGE. This signal by nature has zero crossings, where the modulated signal phasor temporarily has a magnitude of zero (and undefined phase), as seen in the vector diagram in Fig. 6b. The symbols however are not completely independent from each other. There is intentional correlation among symbols to reduce the number of zero crossings which is seen in the PDF curve of Fig. 6c. This correlation technique is called Hybrid PSK (HPSK). [5]



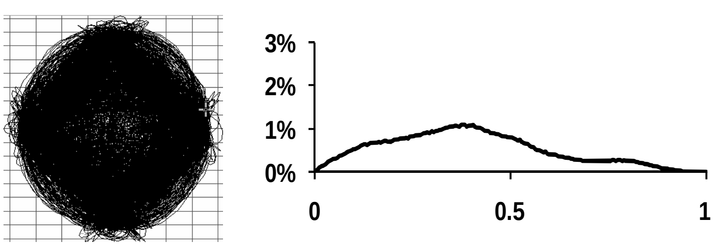
(a) (b) (c)

Fig. 6. The UMTS signal: a) power spectral density, b) one representative vector diagram showing envelope varying characteristics, and c) a PDF curve

By adopting a QAM style modulation, PAPR for the UMTS signal now has contributions from the signal constellation as well from the root raised cosine filtering used. Typical values for the PAPR of UMTS signals range within 3.5 to 5.5 dB, slightly larger than seen in the EDGE signal.

HSPA

High speed packet access (HSPA) is an extension to UMTS intended to significantly increase payload data rates. The signal PSD is identical to that of UMTS, but the higher data rates require that the order of the QAM modulation be increased. The number of zero crossings is significantly increased, as we see from the vector diagram in Fig. 7a and its corresponding PDF curve in Fig. 7b.



(a) (b)

Fig. 7. Representative HSPA signal characteristics: a) a vector diagram, and b) a PDF curve

The shape of this PDF curve is quite different than that for UMTS in Fig. 6c. The mean envelope value is noticeably lower for HSPA than for UMTS, meaning that the PAPR is higher for this higher data rate signal. Like in UMTS, this PAPR is a consequence of both the elaborate QAM constellations and the long impulse response of the bandlimiting filter. PAPR values for uplink signals vary from 4.9 to 7.2 dB, depending which of the more than 300,000 signal options is used.

More important though is the change of curvature of the HSPA PDF curve near zero magnitude. Unlike EDGE and UMTS where this curvature is positive, now for HSPA the curvature is negative. This signal therefore spends significant time near zero magnitude with its corresponding rapid phase excursions, making acceptable linear performance more difficult to achieve.

Bluetooth

The Bluetooth™ signal is designed for short range applications at very low cost. At least, that was the intent of the original standard. In perfect alignment with the low cost objective the standards group selected GFSK for the modulation, which is constant envelope as shown in Figure 8a. This signal requires no linearity in the radio circuitry, allowing it to operate at maximum energy efficiency.

Just as was experienced in GSM, the bandwidth efficiency of this constant envelope signal is limited, here to about 0.7 bps/Hz. Therefore with the fixed bandwidth allocated by regulating agencies, this necessarily limits the possible on-air data rates. However Bluetooth is not immune from the marketing pressure to increase data rates available for applications to use. In order to increase the available on-air data rate the signal type must change to one with envelope variations, which also necessarily increases implementation cost by requiring linear circuitry in the radio design. By adopting the π/4-DQPSK Nyquist filtered signal for Extended Data Rate (EDR) Bluetooth, shown in Figure 8b, the bandwidth efficiency nearly triples to a value near 2.0. To the right of this vector diagram is the corresponding envelope PDF curve which clearly shows the envelope variation.

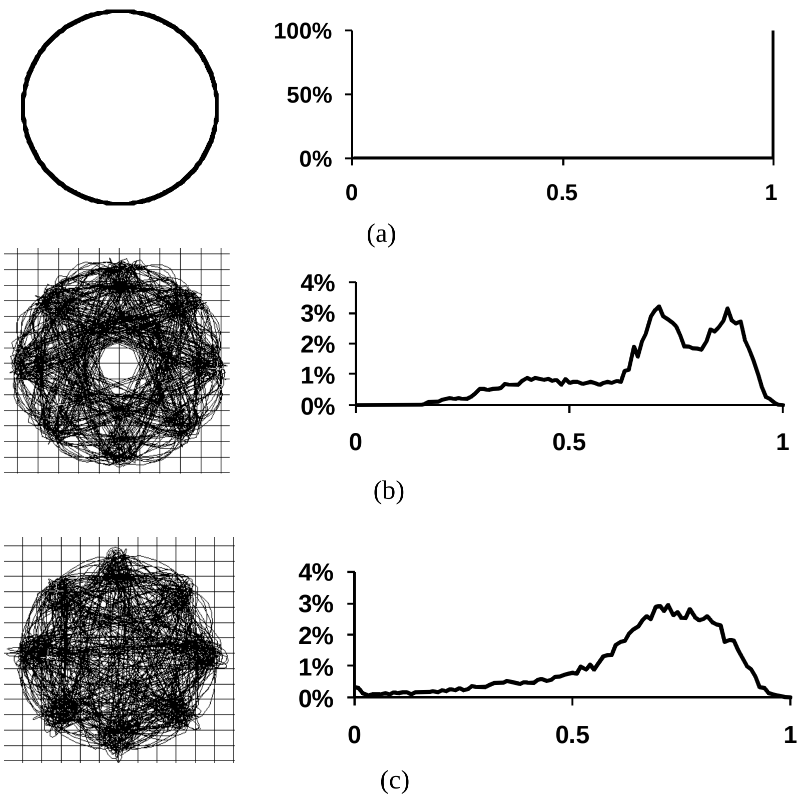


Fig. 8. Bluetooth signal characteristics evolution: vector diagram and envelope PDF curve for a) original Standard, b) EDR, and c) EDR 2.1

Pressure to further increase on-air data rates continues, and the standards committee has responded. The signal type adopted for Bluetooth EDR 2.1 is shown in Figure 8c, and is a Nyquist filtered 8PSK (really an 8QAM). This signal exhibits a bandwidth efficiency near to 3.0, a 50% improvement over the prior EDR signal. But nothing comes for free, and the cost for this additional data rate is visible in both the vector diagram and PDF curve in Figure 8c.

Unlike the EDR signal from Figure 8b, the EDR 2.1 signal does not have a finite minimum value for the signal envelope. Instead the EDR 2.1 signal has what are called ‘zero crossings’ where the signal envelope goes to zero and the signal phase suddenly inverts. This event has a moderate probability as shown in the corresponding PDF curve. The power amplifier supporting this EDR 2.1 signal has even more strict linearity requirements than the EDR signal in order to produce this signal accurately.

Multicarrier

Multicarrier (MC) operation comes in two major classes. The first major application of MC operation is used primarily in base stations where multiple independent signals are amplified simultaneously within a single amplifier. This approach clearly reduces the number of amplifiers needed in a multiple signal operation, and it completely eliminates the problem of combining the output signals from multiple amplifiers onto a single transmission line. The price paid includes additional effort to suppress intermodulation products among all of the desired signals, and additional headroom needed for the waveform resulting from the summation of the signals being amplified. There is also a “single point of failure” concern, which forces higher reliability requirements on a MC amplifier.

A second application of MC operation is for a “single” signal used in propagation environments where multiple paths result in significant delay spread within the channel. In this situation the most robust signal has a symbol time much longer than the duration of the delay spread. Long symbol times necessarily reduce data rates, so to provide higher data rates multiple carriers, each with a long symbol time and low data rate, are operated together in a strongly coordinated fashion. Interference among these parallel signals is a major concern, and the optimum frequency spacing between these multiple subcarriers is known to be the reciprocal of the symbol time. This provides *orthogonality* among the multiple coordinated subcarriers, leading to the name orthogonal frequency division *modulation* (OFDM).

OFDM

In OFDM the modulation used on each subcarrier is QAM, and there is no filtering used on the individual subcarriers. For each OFDM symbol the data is distributed among the subcarriers: 2 bits each when 4-QAM is used; 6 bits each if 64 QAM is used. The OFDM time waveform is the sum of the magnitude and phase scaled subcarrier sinusoids at each frequency used. Since all subcarriers use the same symbol time, the OFDM waveform also has this symbol time.

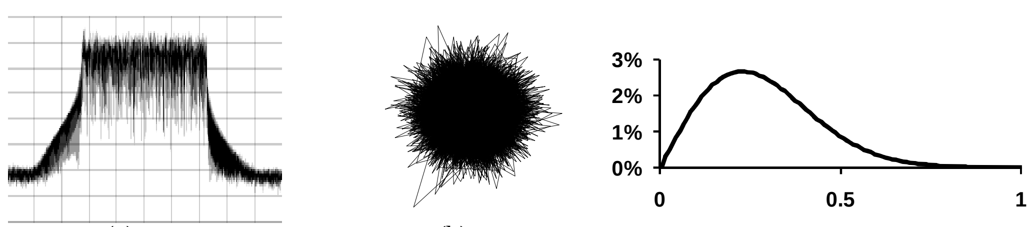
To avoid needing multiple modulators, it is universally accepted to use the inverse discrete Fourier Transform (iDFT) to generate this signal waveform. However there is no provision for signal filtering in the iDFT algorithm, so none is used in OFDM. The symbol time is long, so the resulting sidelobes do not spread far in frequency and are tolerated.

Another far more sinister effect, innate in this OFDM signal generation process, follows from the data independence of each OFDM symbol. Because each OFDM symbol is independent from all others, there is no requirement that the OFDM symbol waveforms are continuous at their boundaries. This waveform discontinuity has a far greater impact on the OFDM occupied bandwidth than the elimination of signal filtering, as seen in Fig. 8a measured from a WiMAX signal.

Any filtering used to smooth out these waveform discontinuities necessarily distorts each OFDM symbol waveform. And since the OFDM waveform is generated solely from the data on each subcarrier, any filtering distortion increases EVM. OFDM is not nearly as tolerant of EVM as filtered QAM signals are, as noted from comparing their respective EVM specification limits: 3% for OFDM, 10% or more for QAM. It is therefore very difficult to constrain OFDM signal bandwidth at -60 dBr.

The order (M) of the entire OFDM signal is the sum of the orders of each subcarrier, representing the total number of states available to the OFDM signal. For OFDM with N subcarriers we have

$$M_{OFDM} = N \cdot M_{QAM} \quad . \tag{7}$$



(a) (b) (c)

Fig. 9. Representative OFDM signal characteristics: a) measured WiMAX signal power spectral density, b) a simulated vector diagram showing the “peaky” envelope characteristic, and c) its Rayleigh shaped PDF diagram

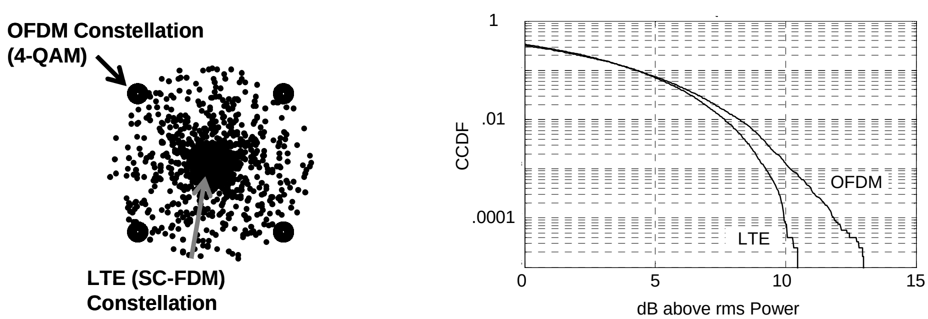
Bandwidth efficiency, as always, is defined as the ratio of the signal throughput to the bandwidth occupied by the signal. For OFDM, the signal throughput is the number of bits per OFDM symbol divided by the total time used for that symbol. This total time must include the cyclic prefix, which is a copy of a fraction of the end of the OFDM symbol waveform that is appended to the beginning of the OFDM waveform to provide robustness against delay spread. Assuming that all OFDM subcarriers are modulated with identical order M = M_{sub}, and further neglecting all OFDM signal power outside of the subcarriers themselves, the bandwidth efficiency is (upper bounded by)

$$\eta_{BW,OFDM} = \frac{N \log_2 M_{SUB} \big/ T_S(1+cp)}{N\Delta f} = \frac{(N \log_2 M_{SUB})}{N\Delta f\left(\frac{1+cp}{\Delta f}\right)} = \frac{\log_2 M_{SUB}}{1+cp} , \quad (8)$$

where the term cp, $0 \le cp < 1$, represents the fraction of the OFDM symbol waveform time (T_S) that is used to form the cyclic prefix. The OFDM signal bandwidth efficiency is actually lower than for the corresponding QAM signal of equal order to the modulation used on each subcarrier.

LTE [6], [7]

The 3GPP Long-term Evolution (LTE) signal is an OFDM signal where the signal constellation is essentially randomized through a complex-number to complex-number "filter". One example, for an OFDM signal using 4-QAM, is shown in Fig. 9a. This "scrambling" of constellation points reduces the probability that the phases and magnitudes of each subcarrier will align during a symbol time interval. The PAPR should therefore reduce from what we experience with OFDM, which is exactly what we see in Fig. 9b. However, dropping from 12 dB to 10 dB still leaves LTE far above the PAPR values of the QAM based signals UMTS (3.5-5.5 dB) and HSPA (4.9-7.2 dB). This means that an LTE PA must be designed to provide 10 dB more power than the specified rms value.



(a) (b)

Fig. 9. The LTE signal: a) constellation diagram compared to OFDM for identical information, and b) comparing LTE CCDF characteristics with OFDM

IV. Comparisons

Cost–benefit tradeoffs abound among these signals. Like nearly everything else in life, achieving any increased capability comes along with an increased cost. Whether this cost is worthwhile completely depends on the present value of the increased capability.

Increased bandwidth efficiency requires envelope variations in the signal. Viewing signal modulation in two-dimensional polar coordinates, a constant envelope signal has only one dimension (phase). Using the second dimension (magnitude) for information significantly increases bandwidth efficiency. At a price of course, which is increased sensitivity to amplifier linearity and amplifier size increases due to the signal PAPR.

Increased throughput requires higher order signals (bits per symbol) which are correspondingly less tolerant of EVM. However we see that OFDM signals have high order without a corresponding bandwidth efficiency increase. Specifically, in QAM if the signal order is M=1024 then there are 10 bits transmitted for each symbol and the bandwidth efficiency is (close to) 10. However for an OFDM signal using N=256 subcarriers with each using 4-QAM then the signal order from (7) is 1024. But from (8) the bandwidth efficiency is no greater than 2 for equal bandwidth signals. Clearly the high data rate achieved using OFDM style signals has more to do with the wider bandwidth they are allotted, and not from an inherent increase in bandwidth efficiency. Yet the OFDM signal is more expensive because the tolerance of EVM is lower and the requirements on the transmitter amplifier are more severe. We conclude from its adoption that the analyzed value of its frequency domain receive equalizer must be very high indeed.

V. Conclusion

Many different types of signals are used in modern wireless communications systems, including cellular and broadband digital access. In the quest to achieve ever higher throughput data rates the successive signals must provide ever increasing bandwidth efficiency and/or increased bandwidth. The 3GPP signal progression of GSM/GPRS/EDGE demonstrates improved bandwidth efficiency. Stepping to UMTS involved an increase in signal bandwidth as well, and then follows a similar bandwidth efficiency progression with the adoption of the HSPA signals. One common characteristic is that each of these signals drives a progressively higher implementation cost.

With the advent of the OFDM signal family, within which is included the 3GPP LTE signal, the tradeoff is changing from increased bandwidth efficiency to increased signal bandwidth. The nature of the OFDM signal is very robust in a strongly multipath propagating environment. The implementation cost of OFDM is among the highest seen to date.

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