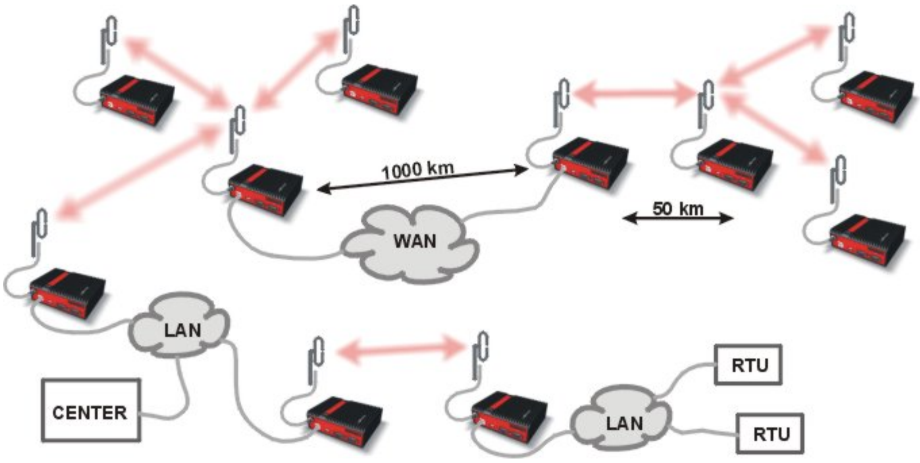
RADIO DATA NETWORKS

Application notes



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Introduction

The industrial narrowband *land mobile radio* (LMR) devices, as considered in this paper, have been the subject to European standard ETSI EN 300 113 [1]. The system operates on frequencies between 30 MHz and 1 GHz, with channel separations of up to 25 kHz, and is intended for private, fixed, or mobile, radio packet switching networks. Data telemetry, SCADA, maritime and police radio services; traffic monitoring; gas, water, and electricity producing factories are the typical system applications. Long distance coverage, high power efficiency, and efficient channel access techniques in half duplex operation are the primary advantages the system relays on. Very low level of adjacent channel power emissions and robust radio receiver architectures, with high dynamic range, enable for a system's co-existence with various communication standards without the additional guard band frequency intervals.

On the other hand, the strict limitations of the referenced standard as well as the state of the technology, has hindered the increase in spectrum efficiency, with which the system has used its occupied bandwidth. With its modification as well as with the new emerging specifications (ETSI EN 302 561 [2], ETSI EN 301 166 [3]) it is now possible for the up-to-date architectures of narrowband LMR devices to make the utilization of more efficient modes of system operation practically applicable.

The main objective of this paper is to describe the favorable properties of operational modes based on advanced nonlinear and linear digital modulation techniques in order to easy the decision on their usage and thus to help system integrators to increase the efficiency of the narrowband radio channel utilization allocated to the new generation of industrial LMR devices.

1. Narrowband radio transmitter

From the very advent of the radio transmission, it was evident that a radio device should not only use its occupied channel bandwidth effectively, but, in addition, should also avoid any unnecessary interference with other systems. Since then the frequency spectrum had been proving its importance and has become a scarce resource nowadays.

The narrowband radio devices under consideration are specified mostly by the European standard ETSI EN 300 113 [1]. Such radio equipments have to face challenging environmental and radio conditions all over the world. The dynamic range in the vicinity of 100 dB, very strict adjacent channel transmitted power attenuation requirements, high data sensitivity, adjacent channel selectivity, high level of radio blocking or desensitization and high co-channel rejection [1], are its most important radio characteristics to mention. It is no wonder that for such high dynamic range demands, super heterodyne transceiver architectures with a majority of analog components are still widely used. But yet the radio transceiver has to be small in dimensions, consumes low power and maintains all its parameters over the wide industrial temperature range and over extensive period of time for reasonable price. At the same time, it should provide enough flexibility to accommodate different channel bandwidths, digital modulation formats, data rates, and techniques, to combat negative effects of radio channel. From this point of view, the *software defined radio* (SDR) concept is, indisputably, a prospective alternative and has not been widely used by these systems. The rapid expansion of the digital signal processing, together with the advancements in signal analog-to-digital converters technology have, in recent years, made such projects economically feasible.

Today's LMR systems, being subject to [1], use mostly exponential constant envelope modulations GMSK, 2-CPFSK and 4-CPFSK. The application of the continuous phase modulations is mainly due to the extreme *adjacent channel transmitted power* (ACP) attenuation requirements, and inherent robustness against channel nonlinearities. Relatively simple implementation of non-coherent demodulators and synchronization algorithms also significantly contributes to the efficient channel usage, especially in packet-based switching networks. The systems thus maintain good power efficiency while the spectral efficiency reaches compromising values not exceeding 1 bit/s/Hz.

1.1. Digital modulation for narrowband channel

The prime classification of the digital modulation techniques into a *nonlinear* (or *exponential*) and *linear* modulation class is based on the way how the modulated signal has been generated. The complex modulation envelope of the linearly modulated signal such as M-PSK, M-QAM etc. can be described by a linear superposition of the properly filtered modulation impulses weighted by the information symbols. In case of the nonlinear modulation techniques, this general rule is valid only for the modulation signal which modulates the phase of the fundamental carrier signal. Thus the modulation process itself is nonlinear, exponential. The M-CPFSK in this case is recognized as a general class of nonlinear or exponential digital modulation with a continuous phase change.

1.2. Adjacent channel power and spectrum efficiency

The adjacent channel power or *adjacent channel interference* (ACI) is that part of the total output power of a transmitter under defined conditions of modulation, which falls within a specified pass-band centred on the nominal frequency of either of the adjacent channels. This power is the sum of the mean power produced by the modulation, hum and noise of the transmitter. Adjacent channel power is usually referenced to the unmodulated carrier power [1]:

> *For a channel separation of 25 kHz, the adjacent channel power shall not exceed a value of* ***60 dB*** *below the transmitter power without the need to be below -37 dBm.*

It is interesting to note that, until 07/2007, the standard strictly demanded the adjacent channel power ratio of -70 dB.

The ACP parameter is particularly important in LMR systems, since it influences the density of the radio channels that can be used in a given area. Its value originated in the use of the traditional analog *frequency modulated* (FM) radio systems. Ironically, it was one of the main limitations for why those systems were – for many years – not able to utilize spectrally more efficient modulation schemes. The problem in this case is that all the advanced multi-level modulation techniques such as M-PSK, M-QAM, OFDM, CDMA or FBMCM have one negative property and that is a non-constant modulation envelope.

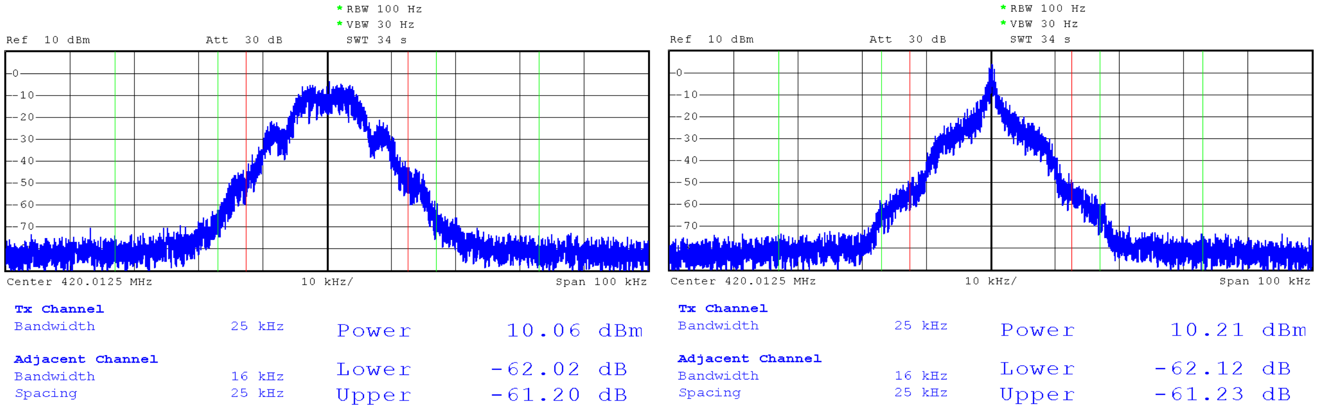

*Fig. 1.1: Modulated signal spectrums. (**left**) 2CPFSK with R=10.4 kBaud, modulation index h~0.6. (**right**) 2CPFSK with R=17.3 kBaud, modulation index h~0.2. 30 dB attenuator used in series.*

In the systems, where the transmitter power efficiency is of high importance, the *transmitter nonlinearity* also creates an important issue. Generally speaking, the higher the transmitter nonlinearity, the higher the transmitter efficiency can be reached. Unfortunately, the device with a nonlinear transfer function also tends to distort the spectrum of the transmitted signal, especially if the modulated signal exhibits the non-constant modulation envelope. In contrast, it is also true that only the non-constant envelope modulation can withstand a strict band limitation by means of modulation filtering – characterized by the roll-off parameter α in the following text. In other words, if the signal has a constant modulation envelope, it has an unlimited spectrum, and, if it has a band limited spectrum, it experiences the amplitude variations, which after passing through the nonlinear power amplifier, would be suppressed, but would also regenerate the side-lobes of the modulated signal spectrum. The phenomenon is known as the spectral *re-growth*, and it depends mainly on the three transmitter characteristics. Those are *peak to average power ratio* (PAPR) of the digital modulation scheme in use, *transmitter nonlinearity* and *the efficiency of the power amplifier linearization* or *pre-distortion technique* and all have to be considered when selecting the digital modulation technique for the system, where both power and spectrum are the key issues.

In light of these facts one can arrive at the conclusion that setting up the limit at −60 dB[1] rather than −70 dB was a reasonable step, while the initial limit has been left to be beyond the state of the present linearization technology for equipments production which in turn hindered the use of spectrally more efficient modulation techniques.

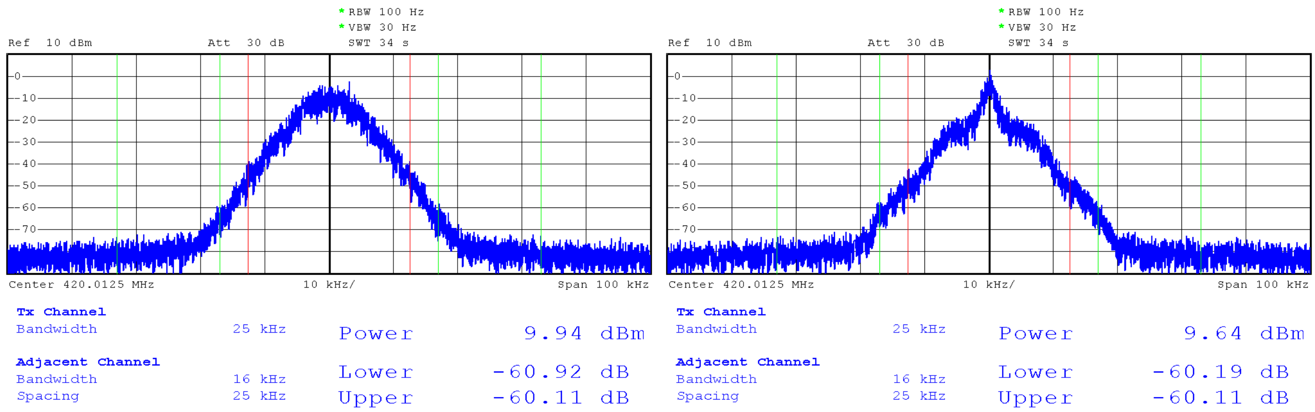

*Fig. 1.2: Modulated signal spectrums. (**left**) 4CPFSK with R=10.4 kBaud, modulation index h~0.3. (**right**) 4CPFSK with R=17.3 kBaud, modulation index h~0.1.*

1.3. Transmitter power efficiency

In this section, the measurement results concerning the overall narrowband transmitter power efficiency are presented. It is no ambition however, to provide exact power efficiency analysis of the particular high power amplifier with the selected linearization circuit proceeded. It is rather to give the example of the practically achievable overall transmitter power efficiencies and to show the differences related to selected digital modulation formats of each of the linear/nonlinear class.

[1] The standard [2] specifying the conformity testing for TETRA-like devices allows -55 dBc in normal or -50 dBc in extreme temperature conditions, assuming channel separation of 25 kHz.

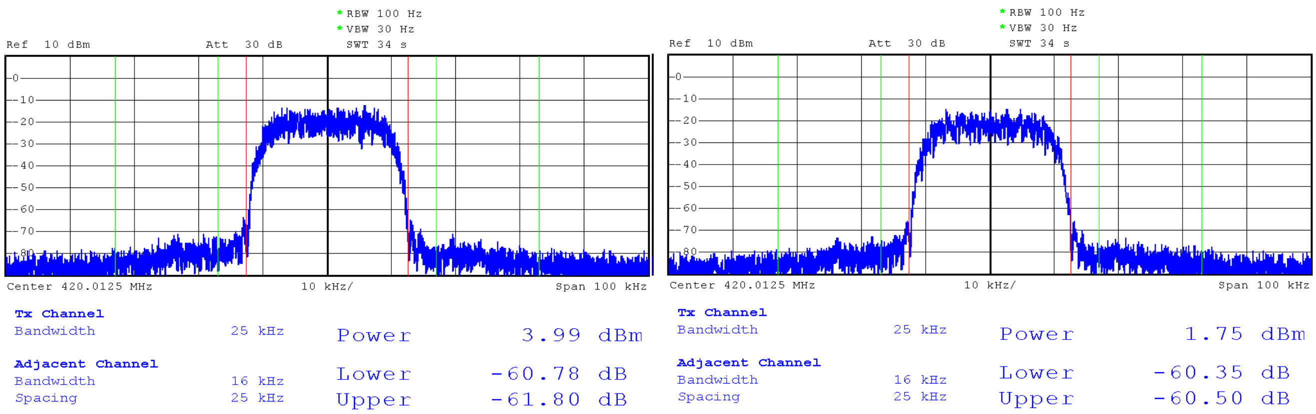

*Fig. 1.3: Modulated signal spectrums. (**left**) π/4-DQPSK with R=17.3 kBaud, (**right**) 16-DEQAM with R=17.3 kBaud.*

As for the linear modulation techniques, the differentially encoded formats π/4-DQPSK, D8PSK and 16-DEQAM have been selected and tested mainly due to their low modulation envelope variations and inherent robustness against negative effects of signal propagation through the narrowband radio channel.

The 2CPFSK and 4CPFSK have been selected from the nonlinear modulation class. There is one particular parameter of high importance essentially influencing the characteristics of these modulation formats and that is a *modulation index*. It expresses the relation between the modulation rate and the maximum frequency deviation according to simple rule (1.1)

$$h = \frac{2\Delta f}{R(M-1)}, \qquad (1.1)$$

where *R* is the modulation rate, *M* is the number of modulation states and *Δf* is the maximum frequency deviation representing the outermost symbol frequency position. The selection of the modulation index in most practical applications of narrowband LMR has been driven by compromising requirements between the modulation rate, receiver sensitivity and adjacent channel power level. Its value usually converges to *1/M* with a well known example of MSK, particularly GMSK where M=2, thus h=0.5 as the lowest value needed to maintain an orthogonal signaling. In order to compare the modulation formats at the same spectrum efficiency we also measured the properties of 2CPFSK and 4CPFSK modulations with very low modulation index resulting in use of high symbol rate of 17.3 kBaud.

The examples of transmitted signal spectrums can be seen in Figure. 3.1 to Figure. 3.3. It is interesting to note the degradation of the signal spectrum with increased symbol rate in case of 2CPFSK and 4CPFSK that implicitly points out that the assigned bandwidth is not used effectively. It can be seen that the significant amount of the signal power is concentrated within the close vicinity of the carrier frequency and thus it results in poor ratio between the occupied signal bandwidth and the noise bandwidth of radio receiver (Table 3.1).

Tab. 1.1: Measurement results of the transmitter parameters for selected modes of operation.

Modulation Format	Symbol Rate	Modul. Parameter	P_{out}	ACI Lower	Upper	Occupied Bandwidth @ 99.9%	P_{IN}	η_{TX}	Spectrum plot
[-]	[kBaud]	[-]	[dBm]	[dBc]	[dBc]	[kHz]	[W]	[%]	[-]
2CPFSK	10.4	h=0.6, α=0.28	40	-62	-61	19.8	35	29	Fig. 3.1
	17.3	h=0.2, α=0.28	40	-62	-61	16.6	35	29	Fig. 3.1
4CPFSK	10.4	h=0.3, α=0.28	40	-61	-60	19.6	35	29	Fig. 3.2
	17.3	h=0.1, α=0.28	40	-61	-60	17.2	35	29	Fig. 3.2
π/4-DQPSK	17.3	α=0.4	35	-61	-62	22.0	22.8	14	Fig. 3.3
D8PSK	17.3	α=0.4	35	-61	-61	22.0	22.8	14	-
16-DEQAM	17.3	α=0.4	35	-60.5	-60.5	22.0	20.4	10	Fig. 3.3
Measurement uncertainty ±2 dB									

The measurement values of achievable output power P_{out}, amount of adjacent channel interference *ACI* and overall transmitter power efficiency η_{TX} are collectively given for all the modulation formats in Table 3.1. It can be seen that the ACI limit (-60 dBc) is maintained for all of these settings; however, there are two penalties in case of linear modulation schemes that typically have to be paid for higher spectrum efficiency. Firstly, it is the lower output power level achievable. For this specific transmitter architecture it is in particular 35 dBm @ π/4-DQPSK, D8PSK and 33 dBm @ 16-DEQAM. Secondly, it is the lower value of the overall transmitter power efficiency reached. Comparing to exponential modes of system operation the efficiency of linear operational modes has decreased to 14% and 10%. Despite this negative trend, the achieved values of output power exceeding 3 W, and 2 W respectively, are considered practically applicable for next generation of narrowband LMR devices and as it will be shown in the next section they enable the system to use its occupied bandwidth with even higher communication efficiency.

2. Narrowband radio receiver

The most important parameters which describe the quality of narrowband radio receiver are *maximum usable (data) sensitivity, co-channel rejection, adjacent channel selectivity, desensitization* and *intermodulation response rejection*. Besides the maximum usable sensitivity, all other receiver parameters can be classified as the measures of the *receiver degradation parameters* used to analyze the degradation of its performance due to the presence of unwanted (interfering) signals. Although there is a strong relation between all of these parameters, in this paper the attention is given only to the first of them, to the maximum usable sensitivity in particular.

According to [1], the maximum usable data sensitivity is the minimum level of the signal (emf) at the receiver input, produced by a carrier at the nominal frequency of the receiver, modulated with a normal test signal, which will, *without interference*, produce, after demodulation, a data signal with a specified *bit-error-ratio* (BER) of 10^{-2} or a specified *successful message ratio* (SMR) of 80%.

> *The maximum usable sensitivity shall not exceed an electromotive force of **3.0 dBμV** under normal test conditions.*

Assigning this value as *S*, one can also express what *signal-to-noise ratio* (SNR) can be expected in relation to *noise figure* (NF) and transformed to the receiver input

$$SNR = S - (10.\log(kT) + 10.\log(B_N) + NF) \quad [dB]. \qquad (2.1)$$

In (2.1), k is the Boltzmann’s constant, T is the absolute temperature in Kelvin and B_N is the receiver noise bandwidth of e.g. 25 kHz.

2.1. Maximum usable data sensitivity

In this section, the results of maximum usable data sensitivity measurement (Figure 3.4) for the complete narrowband radio transceiver are presented. All the results are given for 25 kHz channel separation.

Firstly, let us focus on operational modes with exponential modulations, Figure 3.4. It can be seen that the *emf* sensitivity limit of +3 dBμV (-110 dBm @ 50 Ω) is fulfilled with margin for both modulations (2CPFSK, 4CPFSK) when running at the symbol rate of 10.4 kBaud. When higher symbol rates are selected, these modulations loss their power efficiency rapidly and for the selected symbol rate of 17.3 kBaud, the sensitivities lower down to the values of −107 dBm @ BER=10^{-2} and −102 dBm @ BER=10^{-2} for 2CPFSK and 4CPFSK respectively. This discrepancy is caused mainly due to the fact that there is a significantly lower frequency deviation used at the higher symbol rates. The decrease in power efficiency with increasing spectrum efficiency is not linear as for the typical linear modulations. Although possible, this example documents that the increase in spectrum efficiency of exponential modulation techniques cannot be considered for efficient use of assigned bandwidth.

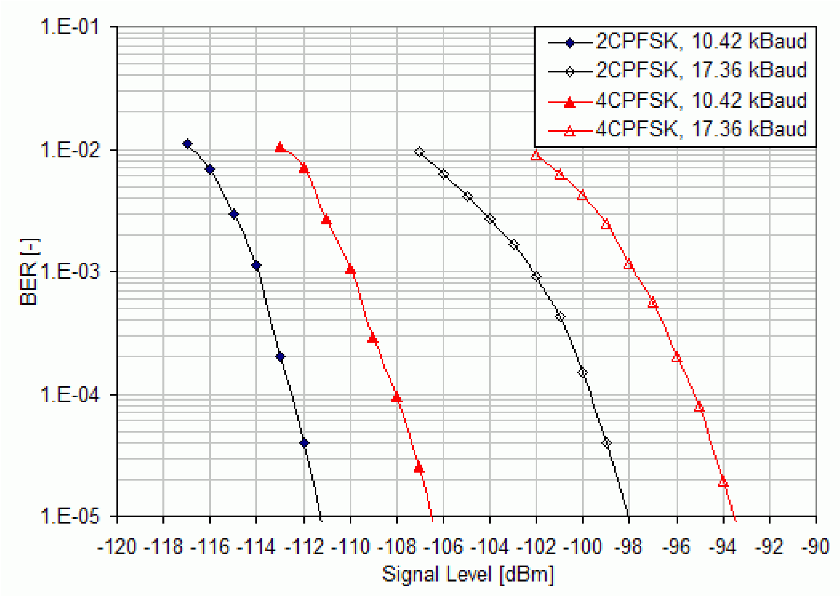

Fig. 2.1: Maximum usable sensitivity measurement results for different settings of exponential modulations.

The second set of measurement results, presented in Figure 3.5, documents the power efficiency analysis of operational modes based on the linear modulation techniques. It can be seen that when using the linear π/4-DQPSK, the radio receiver can still reach the data sensitivity limit even for 17.3 kBaud with a 2 dB margin. Even from this comparison it is evident that the π/4-DQPSK mode of operation outperforms the 4-CPFSK at higher spectrum efficiencies. Further increase in spectrum efficiency can be reached by higher order constellations such as D8PSK and 16DEQAM and the radio receiver can still maintain practically applicable sensitivities of −107 dBm @ BER=10^{-2} and −105 dBm @ BER=10^{-2} respectively.

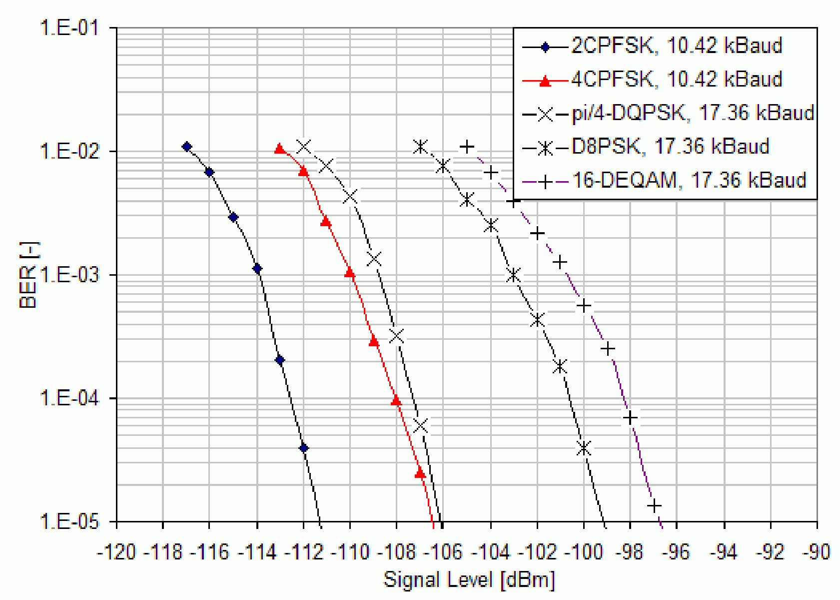

Fig. 2.2: Maximum usable sensitivity measurement results. Channel separation 25 kHz.

2.2. Efficient use of narrowband radio channel

As it has been written in the Section 1, the radio transceiver in exponential modulation mode can make use of higher transmitter power. In order to take this fact into account the *system gain (SG)* or the *maximum allowed path loss* (2.2)

$$SG\ [dB] = P_{out} - S\ , \qquad (2.2)$$

is usually calculated for the wireless communication systems. Here the P_{out} is the available transmitter power expressed in dBm and S is the measured value of radio receiver sensitivity, also in dBm. It expresses the referential value of the link budget, assuming 0 dBi of antennas gain and together with the *spectrum efficiency* given by (2.3) it expresses how effectively the radio device uses its assigned bandwidth

$$\eta\ [bit/s/Hz] = \frac{R_b}{B}\ . \qquad (2.3)$$

In (2.3), the R_b is the *raw bit rate* given in [bits/s] and B is the frequency bandwidth assigned to the radio system, 25 kHz in particular.

All these performance characteristics are collectively given in Table 3.2. It can be seen that even with the lower available transmitter power, the radio transceiver can reach wider system gain at higher spectrum efficiencies while running in linear as oppose to the exponential modulation mode. On the other hand, if the long distance coverage is of the primary application concern, even the 2CPFSK modulation having spectrum efficiency of 0.4 bit/s/Hz, but the system gain of impressive, 157 dB, can be a reasonable option.

Tab. 2.1: Overall performance characteristics of the narrowband radio transceiver for selected modes of operation.

Modulation Format	**Modul. Param.**	**Symbol Rate**	**Raw Bit Rate**	**Spectrum Efficiency**	**Data Sensitivity @ BER 10^{-2}**	**Available Output Power**	**System Gain**
[-]	[-]	[kBaud]	[kbits/s]	[bit/s/Hz]	[dBm]	[dBm]	[dB]
2CPFSK	h=0.6, α=0.28	10.42	10.42	0.42	-117	40	157
	h=0.2, α=0.28	17.36	17.36	0.69	-107	40	147
4CPFSK	h=0.3, α=0.28	10.42	20.83	0.83	-113	40	153
	h=0.1, α=0.28	17.36	34.72	1.39	-102	40	142
π/4-DQPSK	α=0.4	17.36	34.72	1.39	-112	35	147
D8PSK	α=0.4	17.36	52.08	2.08	-107	35	142
16-DEQAM	α=0.4	17.36	69.44	2.78	-105	33	138
Measurement uncertainty ±2 dB							

3. Conclusion

As it was shown in this paper, the strict limits of the referenced standard as well as the state of the technology hindered increasing the communication efficiency with which the narrowband systems have been using the occupied frequency bandwidth. The key limiting factor that has been identified was the limit of adjacent channel power attenuation. Lessening the requirement from -70 dBc to -60 dBc in 2007 has opened up the closed door for implementation of linear digital modulation techniques. However, as it has been shown in later sections, a reasonable use of the exponential modulation can be still beneficial for these systems. Based on the results presented, the most important concluding notes can be seen in the following:

- When the long distance coverage as well as the overall power efficiency are of the primary application concern, the use of exponential modulation techniques 2CPFSK and 4CPFSK at relatively low symbol rates e.g 10.4 kBaud can be the recommended option. In this case, the nonlinear modulation techniques can make use of higher frequency deviation and increase the system gain by outstanding values of receiver sensitivities. At the 10 W of output power the system gain of 157 dB and 153 dB for 2CPFSK and 4CPFSK modulation techniques respectively can be expected.

- When higher symbol rates are selected, the exponential modulation techniques lose their power efficiency (and their main advantage) significantly. Further increase of the exponential modulation spectrum efficiency from the values currently being used by the narrowband systems (up to 1 bit/s/Hz) can be therefore considered inefficient.

- From all the modulation formats studied, the π/4-DQPSK can provide the narrowband LMR system with communication efficiency closest to the optimal communication systems. The proposed solution based on this modulation technique can reach the spectrum efficiency of up to 1.5 bit/s/Hz. The data sensitivity limit required by [1] can also by fulfilled with margin of 2-3 dB, resulting in the system gain of 147 dB.

- For applications where higher data throughputs are needed the additional increase in spectrum efficiency can be gained by D8PSK and 16-DEQAM modulation formats. However, compared to π/4-DQPSK, an increase in overall communication efficiency cannot be expected, while there is the inevitable penalty in power efficiency characteristic.

References

[1] ETSI EN 300 113-1 V1.6.2 (2009-11), Electromagnetic compatibility and Radio spectrum Matters (ERM), Part 1: Technical characteristics and methods of measurement. European Standard. ETSI, 11/2009.

[2] ETSI EN 302 561 V1.2.1 (2009-12), Electromagnetic compatibility and Radio spectrum Matters (ERM), Land Mobile Service; Radio Equipment using constant or non-constant envelope modulation operating in a channel bandwidth of 25 kHz, 50 kHz, 100 kHz or 150 kHz; Harmonized EN covering essential requirements of article 3.2 of the R&TTE Directive. European Standard. ETSI, 12/2009.

[3] ETSI EN 301 166-1 V1.3.2 (2009-11), Electromagnetic compatibility and Radio spectrum Matters (ERM), Part 1: Technical characteristics and methods of measurement. European Standard. ETSI, 11/2009.

Appendix A. Revision History

Revision 1.0 2017-11-20

First issue