International Telecommunication Union

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Radiocommunication Sector of ITU

Recommendation ITU-R SM.1600-1
(09/2012)

Technical identification of digital signals

SM Series
Spectrum management

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Note*: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R SM.1600-1

Technical identification of digital signals

(2002-2012)

Scope

This Recommendation describes process, methods and tools for technical identification of digital signals. It provides comparison of methods and tools and recommends application for different use cases. It does not provide in-depth explanation of the algorithms or design features of the hardware or software tools.

The ITU Radiocommunication Assembly,

considering

a) that the use of radio grows steadily;

b) that digital signals are being widely used;

c) that an increasingly large number of devices can be used without a licence or certification process, making it difficult for an administration to identify the source of an emission;

d) that sharing of the same spectrum by several radiocommunication technologies is an emerging trend;

e) that the interference complaints involving digital emissions are often difficult to resolve;

f) that technical identification often is an essential prerequisite to any measurement on digital signals with complex waveforms as used in many digital communication systems;

g) that signal databases are available which can associate modern digital signals with their respective external and internal parameters;

h) that new analysis and identification tools and techniques are available, that can lead to recognition of the nature of an unknown signal or to complete identification of modern digital standards,

recommends

1 that digital signals should be identified in the following order:

- general identification process based on signal external characteristics;
- identification based on the signal internal characteristics (modulation type and other internal waveform parameters) when low/partial *a priori* knowledge is available about the signal;
- identification based on correlation with known waveform characteristics when strong *a priori* knowledge is available about the signal;
- identification confirmed by signal demodulation, decoding and comparison with known waveform characteristics,

2 that the processes described in Annex 1 be followed.

Annex 1

Introduction

This Annex describes steps designed to be used either stand-alone or together in sequence to identify a digital signal of interest. The information is intended to provide fundamental, practical and logical advice on the handling of standard modern digital signals. The text addresses the use of external signal parameters, offers advice on the analysis of internal signal parameters to more completely classify the signal; and describes the use of software tools and techniques to positively identify a standard modern digital signal.

While some modern spectrum analysers have the capability to characterize signals, many do not have the capability of preserving and providing the in-phase and quadrature (I/Q) signal data that are useful for more advanced analysis of signal internals. While the focus of this Annex is on Vector signal analysers and Monitoring receivers, spectrum analysers possessing signal analysis features may in some cases be used as well.

Definitions

Standard modern digital signals: These signals typically include the following modulation schemes and multiple access formats:

– Amplitude, phase and frequency shift keyed (ASK, PSK, FSK) including Minimum shift keyed (MSK).

– Quadrature amplitude modulation (QAM).

– Orthogonal frequency division multiplexed (OFDM).

– Time division multiple access (TDMA).

– Code division multiple access (CDMA).

– (Coded) Orthogonal frequency division multiplex (Access) (C)OFDM(A).

– Single carrier frequency division multiple access (SC-FDMA).

– Single carrier frequency domain equalization (SC-FDE).

Signal identification systems and software: This is a class of system or software that can provide positive identification of a modern digital signal by correlating the signal waveform to a library of known patterns such as pre-amble, mid-amble, guard time, synchronization word, synchronization tones, training sequences, pilot symbols and codes, scrambling codes and by correlating the demodulated or decoded signal to a library of known patterns such as signalling data in broadcast channels.

I/Q signal data: I/Q refers to in-phase and quadrature signal data. The I/Q data resulting from sampling of a signal allows all of the amplitude, frequency and phase information contained in the signal to be preserved. This allows the signal to be accurately analysed or demodulated in different ways, and is a common method of detailed signal analysis.

Modulation recognition software: This is software that can operate on raw I/Q or audio demodulated recordings and estimate signal characteristics that include:

– Centre frequency and frequency distance between carriers;

– Signal bandwidth;

– Signal duration and inter-pulse duration (when impulsive);

– Modulation class: single or multiple carrier, linear or non-linear;

– Modulation format;

– Symbol rate;

– Signal-to-noise ratio (SNR)[1];
– Signal specific patterns (such as synchronization/pilot tones, guard times, guard intervals, frame structure).

Vector signal analysers (VSA) and VSA software: Instrument VSAs combine either super-heterodyne technology or direct conversion hardware with high speed Analogue to Digital converters (ADCs) and Digital signal processing (DSP), Field programmable gate arrays (FPGA) or embedded General programmable processors (GPP) to perform fast, high-resolution spectrum measurements, demodulation, and advanced time-domain and spectrum-time-domain analysis. VSAs are especially useful for characterizing complex signals such as burst, transient or digitally modulated signals used in communications, video and broadcast. They can provide users with the ability to collect raw I/Q data on signals of interest, modulation recognition capabilities and signal identification capabilities such as defined above. VSA software may or may not control a physical receiver. But, in all cases, it allows the user to analyse raw I/Q data either from a receiver or from files.

Monitoring receiver: A monitoring receiver selects a radio signal from all the signals intercepted by the antenna to which it is connected, and reproduces at the receiver output the information transmitted by the radio signal, while providing access to measurement of the detailed characteristics of the signal. This is typically accomplished by either:

– access to intermediate steps in the signal chain, or
– in most modern receivers, by recording or providing as an output, the complete amplitude and phase characteristics (usually by sampling and saving the I/Q data).

Error vector magnitude: The error vector is the vector difference at a given time between the ideal reference signal and the measured signal. Expressed another way, it is the residual noise and distortion remaining after an ideal version of the signal has been stripped away. EVM is the root-mean-square (RMS) value of the error vector over time at the instants of the symbol (or chip) clock transitions.

Steps to identify a digital signal

1 Evaluate signal externals

The first step in identifying a digital signal is to use the simplest approach. This involves comparing the signal's "external" parameters to the Regulator's licensed signal database and frequency plan. External signal parameters include:

– Centre frequency and frequency distance between carriers;
– Signal bandwidth;
– Spectral shape;
– Signal duration (when impulsive or intermittent);
– Frequency shift.

Visual inspection and matching of the signal of interest to the Regulator's license database provides a good start to identifying a digital signal of interest. If the signal matches all of the external parameters, chances are high that a correct identification can be made without further analysis.

[1] While this is not a common modulation parameter, it is often provided by modulation recognition software.

An example of a Frequency Allocation Table is shown in Table 1. The table provides a general description of the services licensed to operate in the band, the operational parameters, bandwidths and channelization. These can all be used to match external signal parameters and make an initial assessment of the identity of the signal of interest.

TABLE 1

Sample Frequency Allocation Table

Table of Frequency Allocations			698-941 MHz (UHF)		Page 29
International Table			United States Table		FCC Rule Part(s)
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table	
(See previous page)	698-806 FIXED MOBILE 5.313B 5.317A BROADCASTING	(See previous page)	698-763	698-763 FIXED MOBILE BROADCASTING NG159	Wireless Communications (27) LPTV and TV Translator (74G)
			763-775	763-775 FIXED MOBILE NG158 NG159	Public Safety Land Mobile (90R)
			775-793	775-793 FIXED MOBILE BROADCASTING NG159	Wireless Communications (27) LPTV and TV Translator (74G)
790-862 FIXED MOBILE except aeronautical mobile 5.316B 5.317A BROADCASTING			793-805	793-805 FIXED MOBILE NG158 NG159	Public Safety Land Mobile (90R)
	5.293 5.309 5.311A		805-806	805-806 FIXED MOBILE BROADCASTING NG159	Wireless Communications (27) LPTV and TV Translator (74G)

By using a spectrum analyser, vector signal analyser or monitoring receiver, the Regulator can determine the signal centre frequency, frequency distance between adjacent carriers and signal bandwidth. The frequency should be checked against the frequency plan to make sure the signal is centred on one of the allocated channels. Also, the signal bandwidth should be checked for compliance with the standards of channelization for the frequency band of interest. Figure 1 shows how display markers can be used to determine centre frequency, signal bandwidth and power measured at the receiver input.

FIGURE 1

Sample spectral display with markers

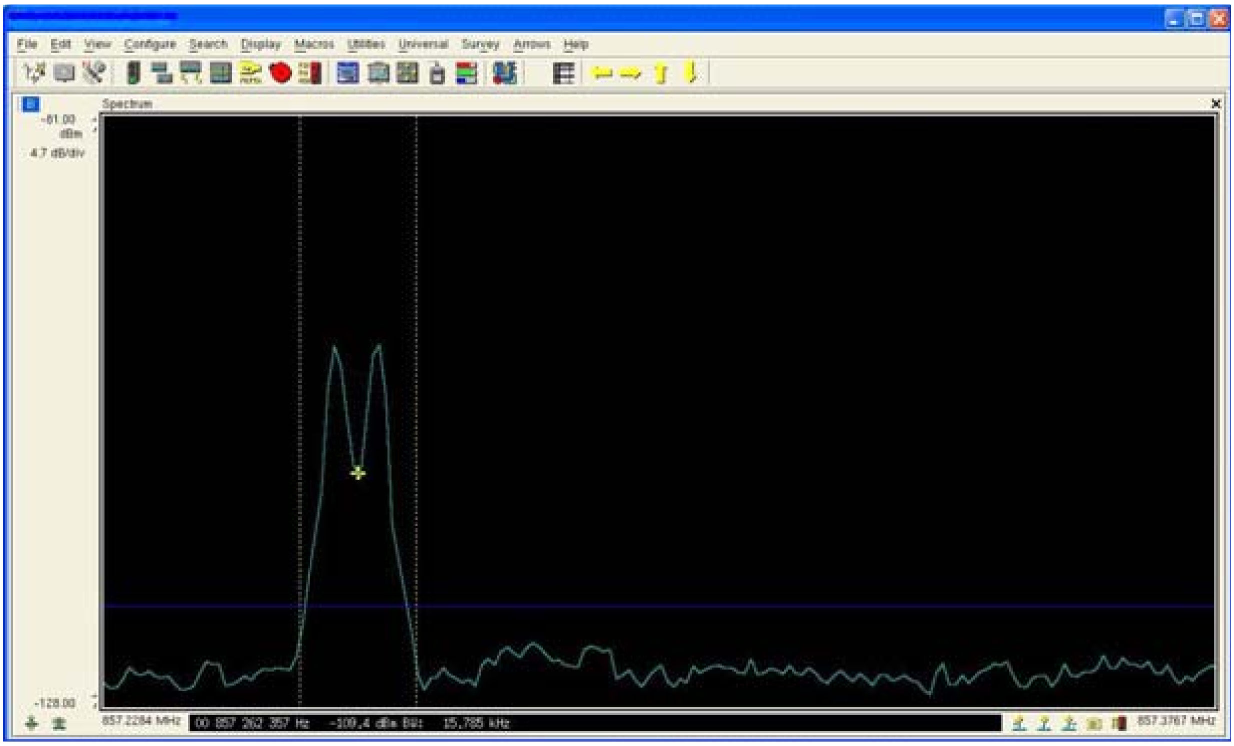

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Table 2 provides a comprehensive set of analysis methods that may be employed by the Regulator to detect signals and estimate signal external parameters. Many signal analysis software packages have the ability to perform mathematic operations on time or spectral data or a series of spectral data. Such packages can be used to make these kinds of estimations of signal external parameters.

TABLE 2

Manual methods to detect signals and extract external parameters

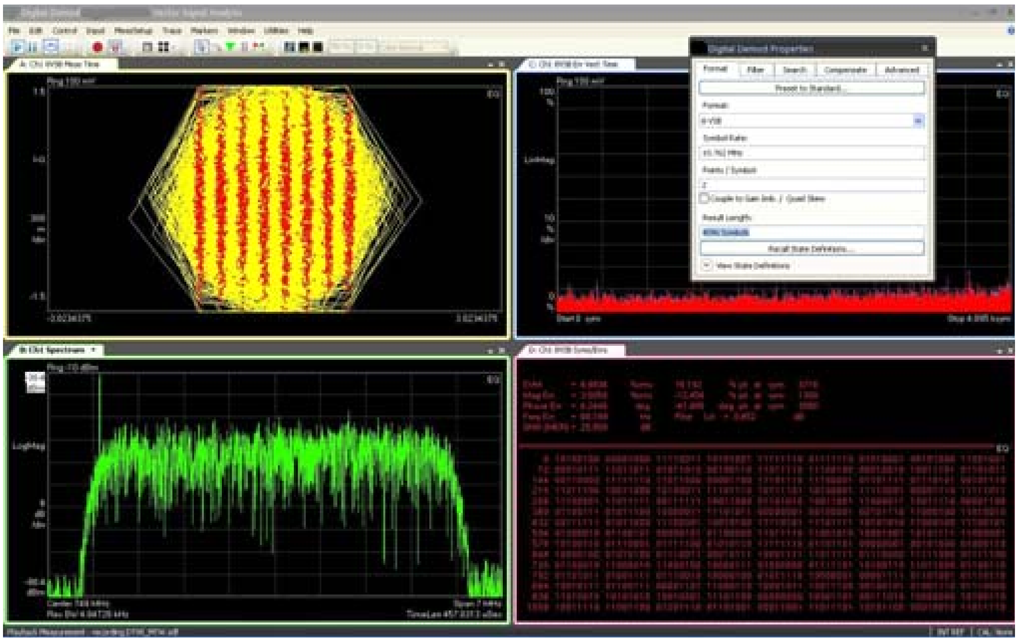
Parameters to be measured	Analysis tools	Modulation type	Radio environnent
Presence of a radio-communication signal	Cross-correlation of I-Q signal or of instantaneous amplitude A_i with reference signal	Any modulation type but especially for known TDMA, CDMA and DSSS signals	Any
	Spectral power density	Any modulation type	Medium and high SNR
	Auto-correlation and cyclic auto-correlation	OFDM, SC-FDMA, SC-FDE	Any
	Spectrum correlation analysis	Unknown DSSS and weak signals	Any
PRF or burst length	Amplitude time analysis of the signal	OOK, radar, IFF, other bursted signal	Medium and high SNR
Carrier frequency Subcarrier frequencies	Spectral power density	Any modulation type	Medium and high SNR
	Histogram of instantaneous frequency, F_i	FSK	Medium and high SNR
	Average of instantaneous frequency, F_i	FSK	Medium and high SNR
	Spectrum of I-Q signal raised to power N (=M(MPSK), 4 (QAM) or 1/h for CPM)	PSK, QAM, CPM	Positive SNR
	Spectrum correlation analysis	Any linear modulation, and especially ASK, BPSK, QPSK.	Any
	The spectrum of signal module raised to power 2 or 4 with severe filtering	Pi/2DBPSK, pi/4DQPSK, SQPSK	Positive SNR Any
Emission bandwidth and channelization	Spectral power density compared with mask or limit line function	Any modulation type	Medium and high SNR
Frequency distance between subcarriers (Shift for FSK)	Spectral power density. Harmonic search and/or harmonic markers	FSK, OFDM, COFDM	Medium and high SNR
	Histogram of instantaneous frequency, F_i	FSK	Medium and high SNR

Spectral Shape: Another method of signal identification using signal externals is to evaluate the spectral shape or signature. Most VSA software programs have a demonstration library of standard modern digital signals. These demonstrations enable the Regulator to view the signal external (and in some cases the internal) parameters including spectral shape, duration and others.

Some emissions have a feature that is unique to the type of transmission, for example a pilot tone. Some digital high definition television transmissions can have a pilot signal located on the low frequency side of the signal. The display shown in Fig. 2 depicts a television transmission (U.S. Channel 60, 749 MHz) using the ATSC system. Notice the lower left-hand trace and the unique shape of the spectrum with the presence of the pilot signal. This shape, combined with the centre frequency and bandwidth, provides a strong indication of the type of transmission.

FIGURE 2

VSA display illustrating a unique spectral shape



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If further information about the signal is required to make positive identification, examination of the internal signal parameters will be necessary.

2 Evaluate signal internals

After evaluation of the external signal parameters as described in § 1, the next step in digital signal identification is to analyse the time-domain (or internal) characteristics of the signal of interest. A VSA or Monitoring receiver (or suitable spectrum analyser) capable of making an I/Q recording will be needed. Internal signal parameters include:

– Modulation format (i.e. QPSK, QAM, GMSK, FSK, PSK).

– Symbol rate. Symbol rate is sometimes called baud rate.

a. *Make the I/Q recording:*

– Set the centre frequency: The VSA or Monitoring receiver should be centred on the frequency where the signal is known to occur.

– Set the bandwidth: The acquisition bandwidth should be set to include the entire signal – but not so wide as to collect into an adjacent channel. The VSA or Monitoring receiver display can be used to measure the signal centre frequency and bandwidth. Acquisition bandwidths available on modern VSAs and Monitoring receivers range from 1 kHz to 160 MHz.

For narrowband signals, the operator should use an appropriate bandwidth setting, B. The magnitude of suitable B values is:

B = 100 Hz to 4 kHz (telegraphic or telephone bandwidth emissions)

B = 15 to 45 kHz (emissions of medium bandwidth)

Use the values of typical channel bandwidth (B) as shown in Table 3 plus a suitable margin (10 to 50%), while allowing for post-processing with digital filtering and signal conditioning algorithms.

Higher bandwidth signal acquisition requires more sophisticated ADCs or digital oscilloscopes with signal processors. It is recommended to use a system with the following components:

– an analogue or digital receiver with fine adjustable centre frequency, high dynamic range, and adjustable gain control (50 to 60 dB);

– filters, baseband converters, analogue to digital converters and recorder providing:

  • 14 bits of magnitude or greater;

  • sampling rates providing more than 4 samples for each digital modulation symbol;

  • storage depth providing a recorded signal duration of a few milliseconds for wideband signals and a few seconds for narrowband signals.

Most modern digital communication signals have bandwidths less than 20 MHz, although there are some exceptions[2].

[2] For example, communication standards for WLAN (802.11ac and 802.11ad) for close range applications require bandwidths from 160 MHz to greater than 2 GHz.

TABLE 3

Example of channel bandwidth of common digital signals

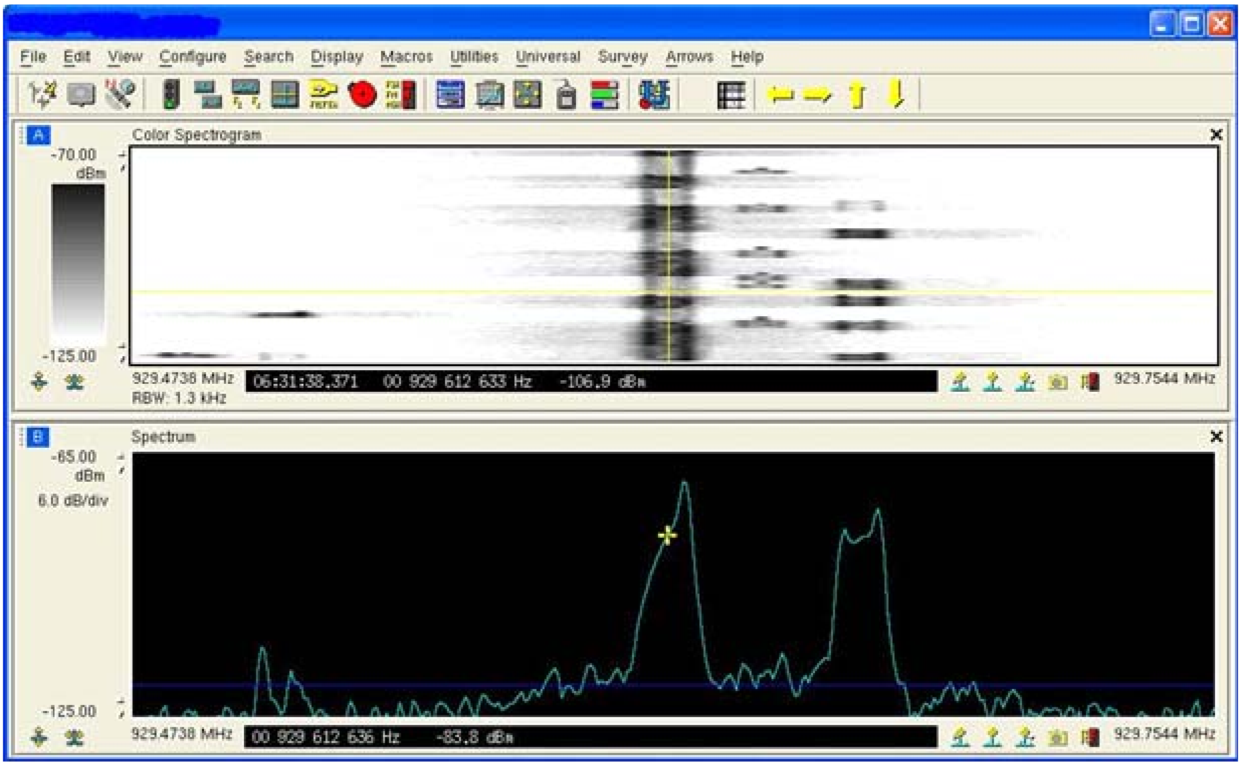
Type of signals	Channel bandwidth
GSM	200 kHz
CDMA (IS-95)	1.25 MHz
CDMA2000	1.25 MHz (channel bonding @ 1xEx-DO Rev. B, C)
3GPP WCDMA	5 MHz
3GPP TD-CDMA	5 MHz
3GPP LTE	1.4, 3, 5, 10, 15, 20 MHz
WIMAX IEEE 802.16xxx	3.5, 5, 7, 8.75, 10, 20 MHz
TETRA	25 kHz, 50 kHz, 100 kHz, 150 kHz
WLAN & WIFI	22 MHz (IEEE 802.11b) 20 MHz (IEEE 802.11a,g) 20 MHz, 40 MHz (IEEE 802.11n) 20 MHz, 40 MHz, 80 MHz (IEEE 802.11ac)
DECT	1.728 MHz
ZigBee	5 MHz
ATSC	6 MHz
DVB-H	5, 6, 7, 8 MHz
T-DMB	1.536 MHz

– Set the duration of the recording: Usually, only a short duration recording (less than one second) will be required to determine the modulation format and symbol rate of the signal. VSAs and Monitoring receivers have fixed signal recording memory, so wider acquisitions will fill the acquisition memory in a shorter amount of time than acquiring narrow signals. If necessary, the user may observe the signal duration on a VSA to assure the proper recording length and make the best use of the acquisition memory.

– Signal durations can be observed by using a spectrogram or waterfall display. This type of spectral display shows frequency, power and time characteristics on one screen (see Figs 3 and 4 below). Signal power is represented by changing colour or grayscale as indicated on the colour bar on the left side of the display. As time passes, the display scrolls from bottom to top and the current spectral trace is shown below the spectrogram.

FIGURE 3

Sample spectrogram with spectrum display



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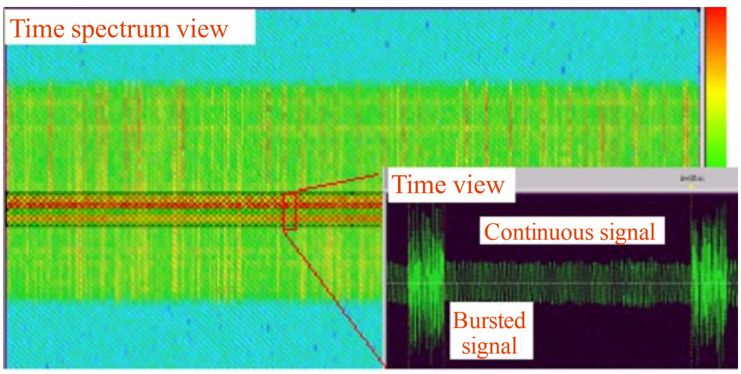
Vector signal analysis software can be used to create a time and spectrum view that will assist the Regulator in understanding the signal environment at the frequency of interest and in determining the proper duration setting when making I/Q recordings. Appropriate co-frequency signal separation techniques must be followed to assure effective analysis of signal internals.

FIGURE 4

Time and spectrum diagram (Frequency/Amplitude on Y-axis and time on x-axis):



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– Trigger the recording: If the signal has low duty cycle, an IF magnitude trigger can be used to initiate the recording. IF magnitude trigger is a typical feature on VSAs and Monitoring receivers. It allows the user to specify the received pre-detected RF power level at which the I/Q recording will be initiated. Setting the trigger level correctly is important and requires some knowledge of the signal and the noise behaviour at the frequency of interest. Setting the trigger level too low may result in a recording initiated by a noise spike that occurred inside the recording bandwidth. Setting the trigger level too high will result in missing the desired signal. If the signal of interest is bursted or very short duration, ADC memory or delay memory should be used to effectively start the recording prior to the time of the trigger and end after the signal is down or after an adequate recording duration is achieved.
– Check the recorded waveform: VSA software allows the user to immediately view the recorded signal to assure proper centre frequency, bandwidth, duration and triggering were used.

b. Classify the signal with modulation recognition software

After the I/Q recording has been successfully made, the user can "play" the signal through an assortment of software packages to gain insight into the signal internals. VSAs and Monitoring receivers from different manufacturers record raw I/Q data with their own proprietary header that contains signal information such as the centre frequency, bandwidth of recording, sample rate, date and time, etc. The data structure is usually published in the technical manuals and may be useful when setting up signal identification or modulation recognition software.

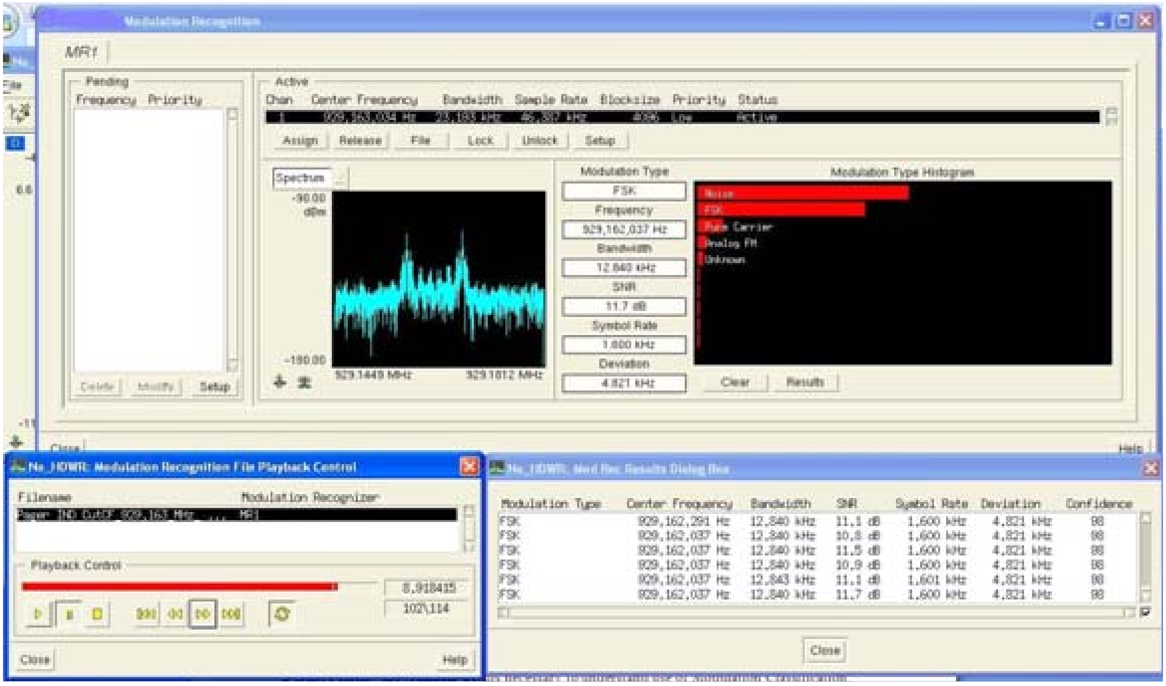
To make a successful modulation classification measurement, the software must be setup to process the recording properly. Adjustments necessary in the software typically include:

– Centre frequency;
– Sample rate or signal bandwidth;
– Adjacent channel filtering;
– Burst detection;
– Block size: this will determine how much I/Q data will be analysed for a modulation result. For example, if the I/Q sample is 16 Kbytes and the block size is set to 2 Kbytes, then the modulation recognition software will estimate the modulation type and symbol rate 8 (eight) times as it works through the file. If the signal is only present for a small part of the file, it is possible only one or two of the measurements will contain useful information.

In Fig. 5, an I/Q recording has been made and is being played into a Modulation recognition software package showing a non-linear modulation FSK. The Block size used for each measurement is 4 k (or 4,096) and there are a total of 114 blocks in this I/Q recording (as seen in the lower left-hand window). Delay memory was used to cause the recording to begin prior to the triggering of the signal. As a result, the first 61 measurements were classified either as noise or as a pure carrier. The process was paused when the signal first appeared and was classified as FSK at 1600 Baud as shown.

FIGURE 5

Example of Modulation recognition software



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After we processed a majority of the I/Q recording, the number of FSK measurement results with Symbol rate of 1600 had grown to a significant percentage. This is evidenced by the histogram of modulation results (red bar graph) shown in the upper right-hand window. We also see that 102 blocks of the recording have been processed.

At the end of the processing, all 114 blocks of data have been processed and the signal is no longer visible in the display window. The measurement result reverts back to noise but enough information is available to conclude the signal to be FSK, 1600 Baud with a 4.821 kHz deviation, and SNR of about 11 dB. This file was processed one block at a time by stepping through the recording manually. This technique offers the most control over the analysis process.

In Fig. 6 is another example of processing to estimate modulation parameters on a linearly modulated (16 QAM) signal. This processing shows a spectrum of statistical moments and non-linear transform of the signal in the upper left hand display and the spectral power density in the upper right hand display. This type of software is very useful for the determination of signal internal parameters and a good step toward parameter demodulation.

FIGURE 6

Example of signal processing for estimation of modulation parameters

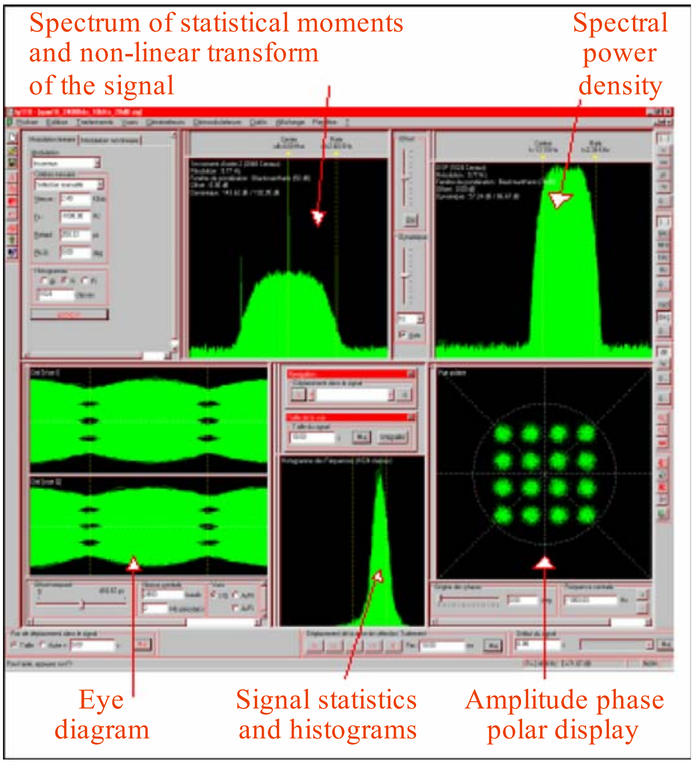

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Figure 7 illustrates statistical estimators applied to digital single-carrier signals such as PMR, GSM, and UMTS that may be used for measurement of signal internal parameters.

FIGURE 7

Use of statistical estimators for estimation of modulation parameters

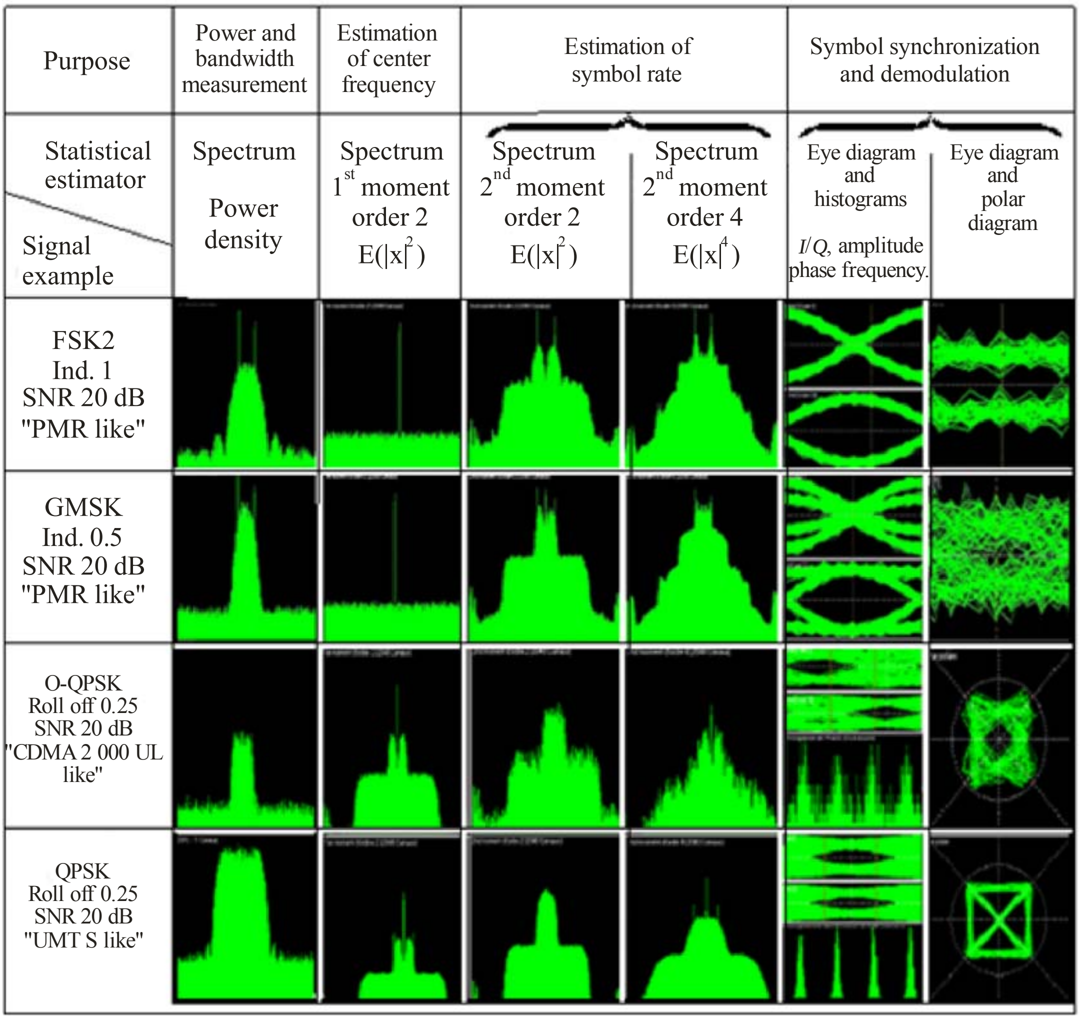

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Table 4 provides additional guidance on methods to extract signal internal parameters using mathematical operations when commercially available signal analysis software is unavailable or unsuitable for handling the signal of interest.

TABLE 4

Manual methods to extract signal internal parameters

Parameters to be measured	Analysis tools	Modulation type	Radio-environnent type
Modulation – rate of asynchronous or synchronous modulation (Symbol rate)	Spectrum of instantaneous amplitude, A_i	PSK (filtered or not) Unfiltered CPM or after severe filtering QAM (filtered or not)	Medium and high SNR
	Spectrum of instantaneous frequency, F_i raised to power N (N = 2 (2FSK), 4 (4FSK))	FSK (unfiltered)	Only ideal: High SNR. No multipath.
	Spectrum of zero crossing on instantaneous frequency, F_i	FSK (filtered or not) PSK, QAM, MSK	Only ideal: High SNR. No multipath.
	Spectrum of signal module raised to power N (=2 or 4 or …) after severe filtering in frequency	PSK, QAM (filtered or not) FSK (filtered or not)	Positive SNR
	Spectrum of the signal raised to power N (N = 1/h)	CPM (filtered or not)	Positive SNR
	Spectrum of signal raised to power N	π/2DBPSK, π/4DQPSK, SQPSK	Positive SNR
	Auto-correlation and cyclic auto-correlation	OFDM, SC-FDMA, SC-FDE	Any
	Spectrum correlation analysis	PSK, QAM, ASK, SQPSK, pi/2DBPSK, pi/4DQPSK	Any
	Spectrum of Harr wavelet transform	FSK	Any, especially complex multiple paths channels

TABLE 4 (*end*)

Parameters to be measured	**Analysis tools**	**Modulation type**	**Radio-environnent type**
Number of states (Modulation type)	Constellation diagram/vector diagram in association with Blind equalization (i.e. Constant modulus algorithm (CMA), Beneviste Goursat)	Any linear modulation and mainly PSK, QAM, ASK	Medium and high SNR Complex multiple paths channels
	Spectrum raised to *N* power (*N*=2, SQPSK and π/2DBPSK; *N*=4, π/4 DQPSK)	SQPSK, π/2 DBPSK, π/4 DQPSK,	Positive SNR
	Fine resolution spectral power density	OFDM, COFDM, multiplexing	Medium and high SNR
	Histogram of instantaneous frequency, F_i	FSK	Medium and high SNR
Parameters to be measured	Analysis tools	Modulation type	Radio-Environnent type
Number of sub-carriers or tones	Spectral power density	Any modulation	Medium and high SNR
	Histogram of instantaneous frequency, F_i	FSK	Medium and high SNR
Symbol synchronization	Eye diagram I/Q, A_i F_i Φ_i vector diagram	PSK & QAM filtered or not	Medium and high SNR
	Eye diagram A_i F_i Φ_i histogram display frequency, F_i	FSK filtered or not	Medium and high SNR
	Constellation diagram, histogram display of frequency, F_i and phase, Φ_i	CPM filtered or not	Medium and high SNR
	Cyclic auto-correlation	OFDM, SC-FDMA, SC-FDE	Any
	Cross-correlation with known signals	TDMA, CDMA Several OFDM and SC-FDMA and SC-FDE	Any

These methods must be associated with suitable representations of the signal after the various transforms it undergoes in order to extract and validate the signal characteristics.

3 Use signal analysis software to gain additional insight

The first two steps have revealed basic characteristics about the signal of interest:

– Centre frequency;

– Signal bandwidth;

– Signal-to-noise ratio;

– Duration;

– Modulation format;

– Symbol rate.

Typically, this information is adequate to positively identify the type of signal by matching to published frequency allocation tables and technical specifications of communication systems in use in the area of interest. If further evidence is required about the signal of interest, in-depth analysis or decoding of the signal may be necessary.

Vector signal analysis software has decoding schemes for most modern digital communication formats. These demodulation and decoding algorithms do not process the I/Q recording back to the original content, but rather measure quality of the signal versus an ideal model. This can provide further evidence that the I/Q recording has been correctly identified.

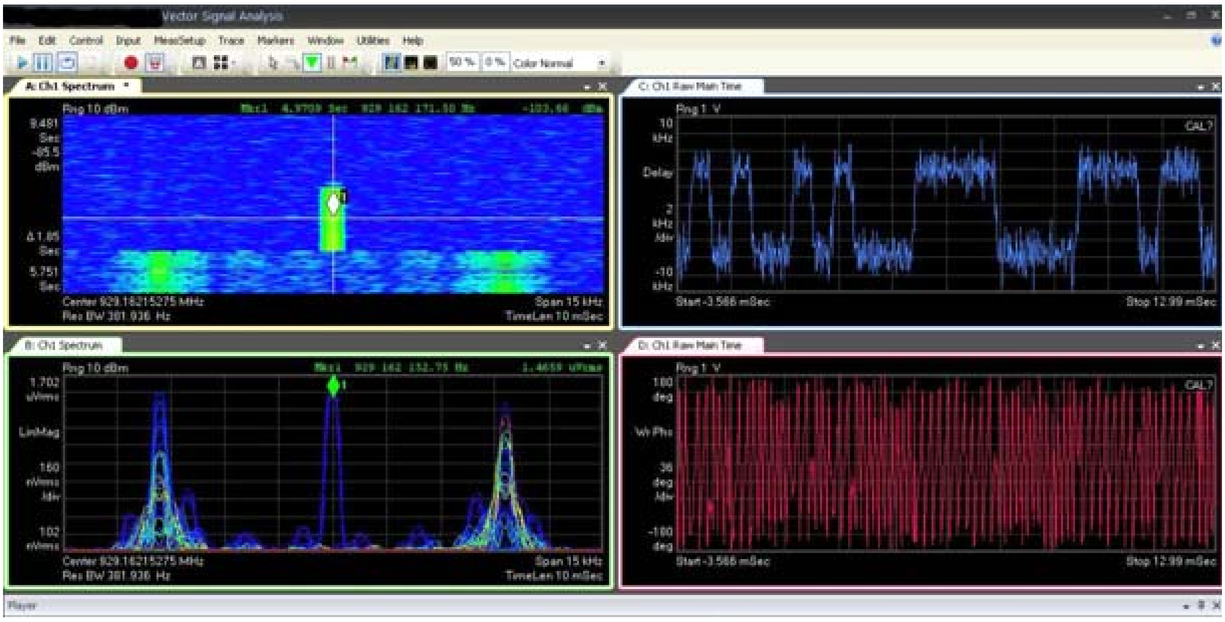
In the case that positive identification of a specific transmission is required, a signal decoding software package or inter-, auto- or cross-correlation techniques will be required. Commercial decoding packages can be found for sale and are useful for some – but not all – modern communication formats.

a. View the I/Q recording with VSA software

VSA software offers the user several different analytic views of the signal. In Fig. 8, the same signal used above is displayed in VSA software. The top left display is a spectrogram and is showing the signal start up – including the carrier and first part of the modulated signal. The bottom left is the spectrum shown with digital persistence enabling the user to observe short duration characteristics in the context of more persistent aspects of a transmission. The top right display shows Group delay or frequency versus time. Since this is a Frequency shift keyed signal, the individual symbols being transmitted can be observed. The lower right pane shows Phase versus time – especially useful if the signal of interest is phase modulated.

FIGURE 8

VSA software – A selection of signal analysis windows



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The reader should note that this signal was received at a very low power level. The carrier was measured at a level of –103.7 dBm at the input to the receiver. As a result, there is significant noise present on the top right trace (which shows the FM waveform). Since VSA software is operating on a recording of I/Q data, measurements are possible using the signal power, frequency and phase information.

b. Confirm recognition and identification by demodulating the I/Q recording with VSA software

It is recommended to have within the same analysis tool a large selection of digital demodulators dedicated to both non-linear and linear modulation types, associated with various algorithms of channel equalization, and with charts and displays which allow the evaluation of the convergence of the demodulation.

Continuing with the previous I/Q recording, we can use the digital demodulation capability of VSA software to validate the modulation format and symbol rate of the signal of interest. By putting the VSA software into Digital demodulation mode, we can input the specific modulation format (2-level FSK) and symbol rate (1600) determined in the previous step to validate the signal internal parameters.

In Fig. 9, which shows the example non-linear FSK signal, the upper left trace shows an I/Q (or polar) plot with 2 frequency states of the signal – the left state (red dot) represents symbol “0” and the right state represents symbol “1”. If you have correctly determined the modulation format and symbol rate, this I/Q trace should be very stable and the red dots (or states) settled onto the proper fields. This convergence implies the correct demodulation values have been selected and the proper filtering and equalization applied.

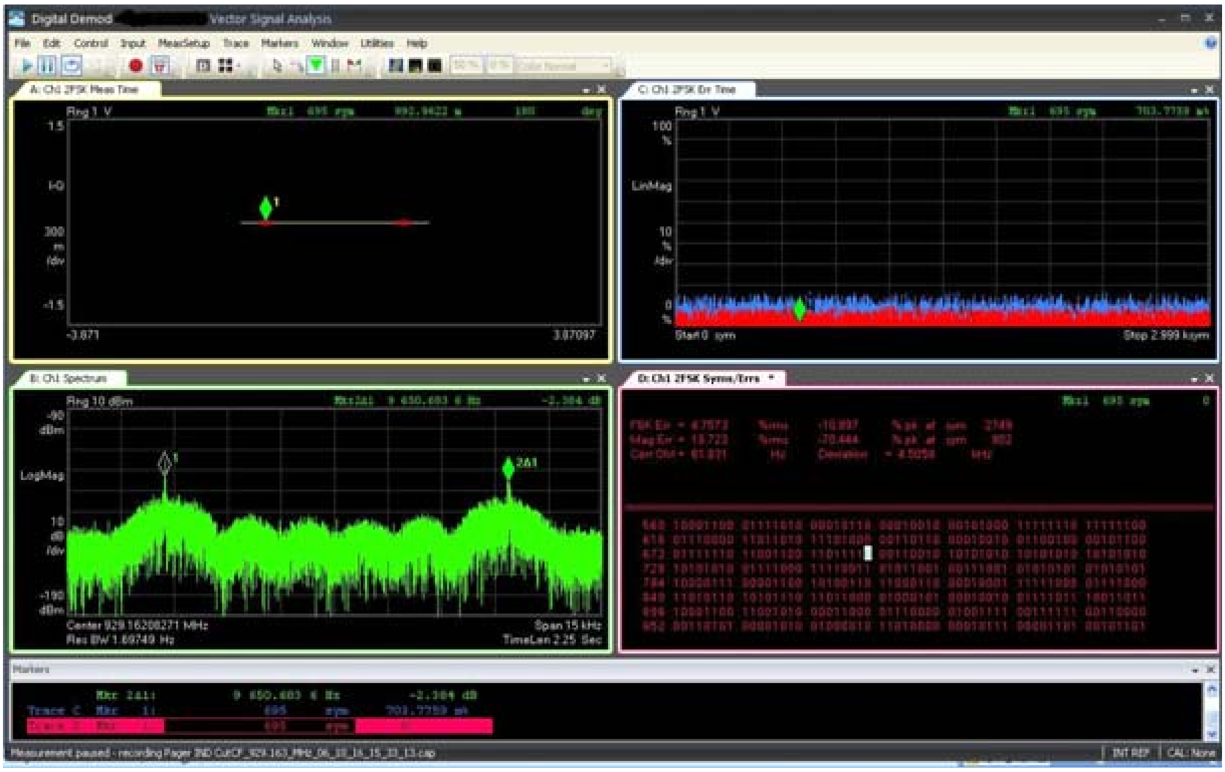
The lower left trace is a spectrum plot of the signal integrated over the number of symbols demodulated – in this case, 3 000 symbols were demodulated. This spectral display should closely match with the signal observed initially.

The upper right trace shows Error vector magnitude (EVM) for each symbol that was demodulated. EVM is the phase and magnitude difference between an ideal reference state of "0" or "1" and the actual demodulated states obtained with the settings used in the Digital demodulation setup. EVM can be viewed as an overall average or on a symbol by symbol basis. All error values associated with this demodulation are below 1% so we have high confidence the bits associated with this signal are good.

The lower right trace is a summary display of the actual demodulated bits and of the errors. Notice the markers on the four traces are linked to show the symbol "0" associated with symbol # 695 of 3 000. These markers track as you move it along the I/Q recording to provide feedback to the user that the demodulation settings are correct.

FIGURE 9

VSA software – Digital demodulation tools



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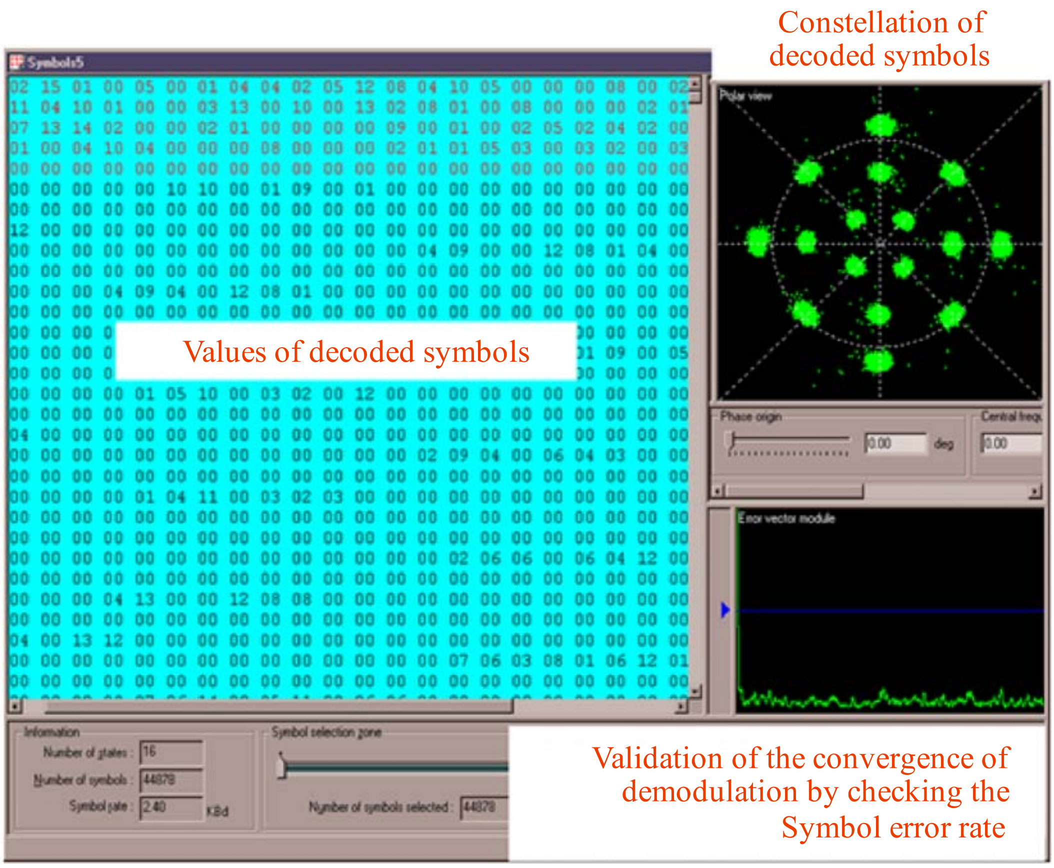
For completeness, shown in Fig. 10 is a signal identification result from a higher order signal (16QAM V29) using a similar technique and a different analysis package dedicated to linear modulations types:

FIGURE 10

Example of demodulated 16QAM V29 signal



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4 Process the I/Q recording

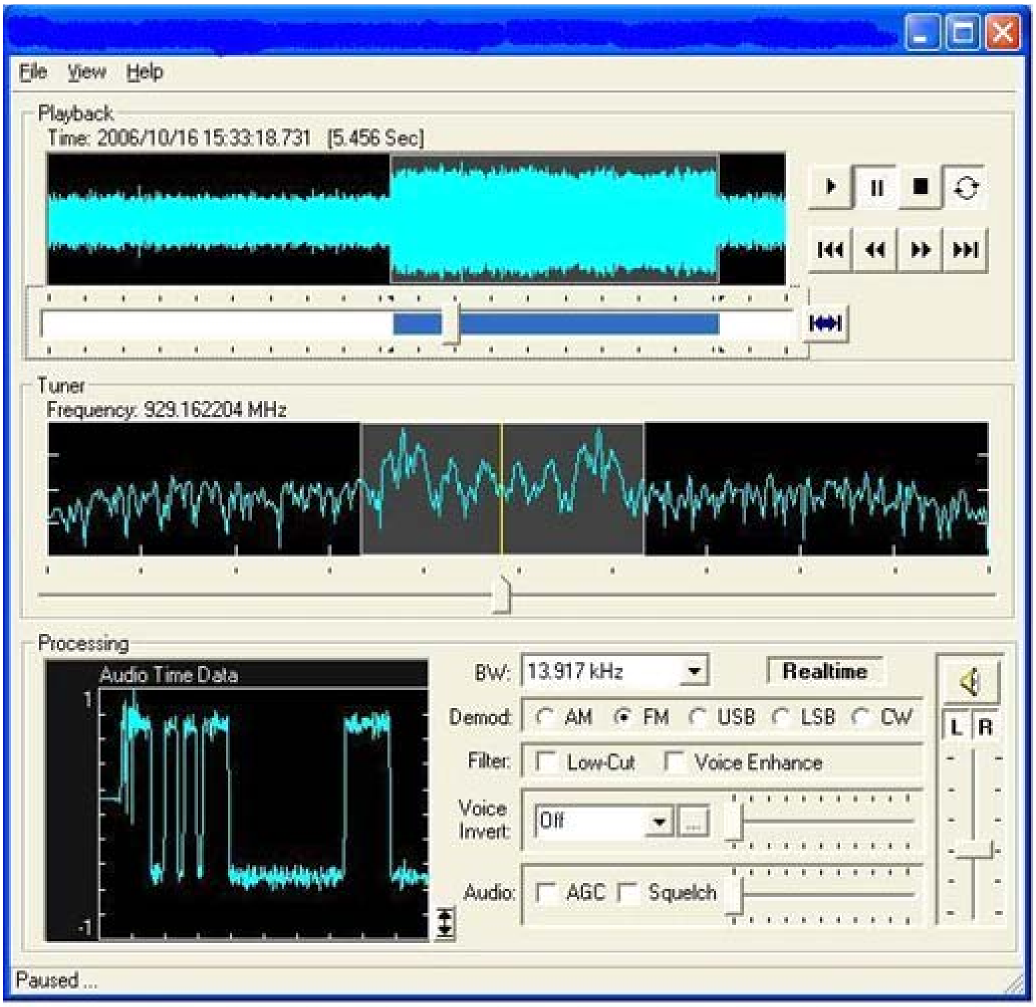
The last step in technical identification of an unknown digital signal is to decode the I/Q recording to extract part or all of the original content. The step must be performed in accordance with legal and ethical restrictions regarding the use of the information. For our example, the same I/Q recording made can be processed with commercially available decoding software to positively identify the source of the transmission.

a. Processing with audio demodulation software

Some decoding software works by processing the audio signal created by demodulating the signal with standard formats (AM, FM, U/LSB or CW). In this case, a software program that can create the audio will be needed. The program shown in Fig. 11 is an example. This program will play an I/Q recording and output audio. Since the recording has not previously been "detected", the program allows the user to adjust the centre frequency and bandwidth of the demodulation process. This offers flexibility when working with decoding algorithms that are highly sensitive to centre frequency and span of the audio signal.

FIGURE 11

Example of I/Q audio player software



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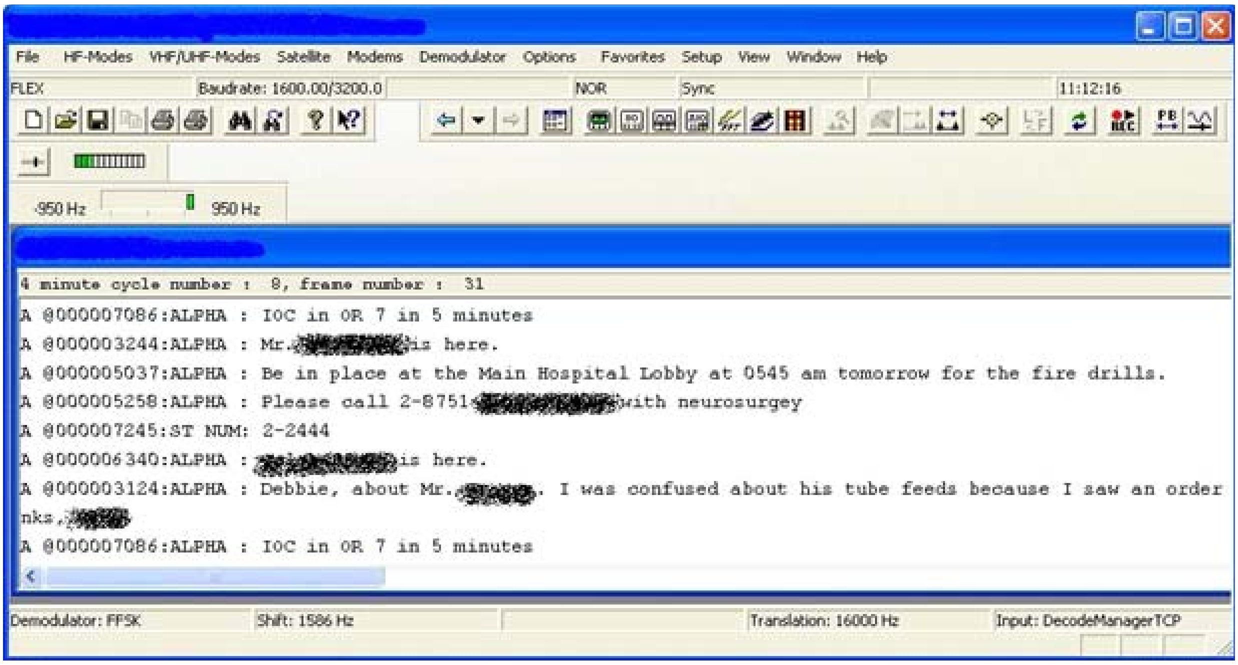
Another benefit of working with I/Q recordings is that different detection schemes can be employed to obtain the best audio for decoding. This flexibility reduces the anxiety for an operator making recordings "in the field". If the centre frequency of the recorded I/Q waveform is off centre, the recording can be re-sampled and/or re-centred (as shown above) to obtain good results.

b. Processing with signal decoding software

Signal decoding software will apply the selected scheme to the recording and output the results into a window or save the results to a text file. There are usually several adjustments for every decoding scheme. Some of these programs include "signal identifiers" but they are often for very simple modulation schemes like FSK or PSK. In the example below, the I/Q recording has been input to a decoding scheme and the format was set to FLEX and POCSAG, two commonly used paging signals. These formats were chosen based on the centre frequency (929.162 MHz), bandwidth (12.5 kHz) – or signal externals and the modulation format (FSK) and symbol rate (1600) – or signal internals. POCSAG produced no decoding results. The results of FLEX decoding are shown below.

FIGURE 12

Example of commercially available decoding software



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The information content extracted from the original emission will enable the user to positively identify the source and take appropriate regulatory actions with sufficient proof.

5 Correlative and other advanced methods

This section is dedicated to describing advanced algorithms that can be employed by the Regulator for digital signal identification. General methods are described and specific examples are highlighted for consideration in Annex 2.

a. Correlation methods

Cross-correlation: Cross-correlation is a measure of similarity of two waveforms as a function of a time-lag applied to one of them. This is also known as a sliding dot product or sliding inner-product.

Auto-correlation: Auto-correlation is the cross-correlation of a signal with itself. Informally, it is the similarity between observations as a function of the time separation between them. It is a mathematical tool for finding repeating patterns, such as the presence of a periodic signal which has been buried under noise, or identifying the missing fundamental frequency in a signal implied by its harmonic frequencies. It is often used in signal processing for analysing functions or series of values, such as time domain signals.

Use of these algorithms can enable detection and recognition of embedded periodic sequences that may be used as the known reference signal in further processing.

These are commonly used for searching a long-duration signal for a shorter, known feature (such as a pre- or mid-amble, synchronization word or pilot code). In practice, these known features are modulated inside standard digital waveforms and offer a pattern that can be used to uniquely classify a signal of interest:

– Synchronization words are found in many standard continuous waveforms (such as Frequency division multiplexing (FDM) and Frequency division multiple access (FDMA) that are encountered in many radios, pagers and PMR (NMT, TETRAPOL, etc.).
– Training sequences are found in TDMA standardized waveforms; such as waveform encountered in several 2G cellular and PMR (GSM, D-AMPS, TETRA, PHS).
– PILOT codes or synchronization words are found in standardized CDMA or TDMA/CDMA waveforms, etc., that are often encountered in 3G cellular systems (3GPP/UMTS, 3GPP2/CDMA2000).
– PILOT symbols or PILOT scattered sub-carriers are found in OFDM, OFDMA, COFDM, and SC-FDMA/SC-FDE modulated signals that are very often encountered in radio broadcast systems (DAB, DVB-T/H) and in 4G cellular systems (3GPP/LTE).

The practical implementation of these techniques uses sliding time-domain windows to determine the arrival time of the signal, and Doppler compensation techniques to compensate for movement of the signal source. Generally, the methods use two steps:

Step 1: Estimate the Doppler frequency error and the time synchronization instant.

Step 2: Correct the Doppler frequency error and optimize detection and source separation.

b. Other advanced methods

Haar wavelet transform: "With the help of this scheme, automatic modulation classification and recognition of wireless communication signals with *a priori* unknown parameters are possible. The special features of the process are the possibility to adapt it dynamically to nearly all modulation types, and the capability to identify. The developed scheme, based on wavelet transform and statistical parameters, has been used to identify M-ary PSK, M-ary QAM, GMSK, and M-ary FSK modulations. The simulated results show that the correct modulation identification is possible to a lower bound of 5 dB. The identification percentage has been analysed based on the confusion matrix.[3] When SNR is above 5 dB, the probability of detection of the proposed system is more than 0.968. The performance of the proposed scheme has been compared with existing methods and found it will identify all digital modulation schemes with low SNR." (See Reference [1]).

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[3] In the field of artificial intelligence, a confusion matrix is a specific table layout that allows visualization of the performance of an algorithm, typically a supervised learning one (in unsupervised learning it is usually called a matching matrix). Each column of the matrix represents the instances in a predicted class, while each row represents the instances in an actual class. The name stems from the fact that it makes it easy to see if the system is confusing two classes (i.e. commonly mis-labeling one as another). Outside artificial intelligence, the confusion matrix is often called the contingency table or the error matrix.

Spectral correlation analysis: Many signals used in communication systems exhibit periodicities of their second order statistical parameters due to the operations such as sampling, modulating, multiplexing and coding. These cyclostationary properties, which are named as spectral correlation features, can be used for signal detection and recognition. In order to analyse the cyclostationary features of the signal, two key functions are typically utilized:

1) The cyclic autocorrelation function (CAF) is used for time domain analysis and;
2) the spectral correlation function (SCF), which exhibits the spectral correlation and is obtained from the Fourier transform of the cyclic autocorrelation.

Different types of signal (i.e. AM, ASK, FSK, PSK, MSK, QPSK) can be distinguished based on several characteristic parameters of SCF and SCC. This algorithm is also effective on weak signals and can be used for classification of unknown signals. (See Reference [2])

6 Summary

The examples provided in this Recommendation serve to illustrate the identification process and the use of commercially available software tools and techniques to gain insight into modern digital signals. The correlation examples are provided to illustrate advanced processing techniques that can be employed for identification of complex signals.

The ability to make I/Q recordings in vector signal analysers and monitoring receivers has become more common in recent years. Signal analysis, modulation recognition and signal identification tools have become far more accessible and more affordable as well. These tools allow spectrum Regulators to apply more automation to detect, record, classify and identify digital emissions of interest and to more effectively recognize and mitigate problems resulting from interference.

References on software tools

Demodulation schemes typically supported by VSA software:

– FSK: 2, 4, 8, 16 level (including GFSK);
– MSK (including GMSK) Type 1, Type 2;
– CPMBPSK;
– QPSK, OQPSK, DQPSK, D8PSK, π/4DQPSK;
– 8PSK, 3π/8 8PSK (EDGE); π/8 D8PSK;
– QAM (absolute encoding): 16, 32, 64, 128, 256, 512, 1024;
– QAM (differential encoding per DVB standard): 16, 32, 64, 128, 256;
– Star QAM: 16, 32;
– APSK: 16, 16 w/DVB, 32, 32 w/DVB, 64 VSB: 8, 16, custom APSK.

Standard digital communication formats typically supported by VSA software:

– Cellular: CDMA (base), CDMA (mobile), CDPD, EDGE, GSM, NADC, PDC, PHP (PHS), W-CDMA, LTE, LTE Advanced;
– Wireless networking: BluetoothTM, HiperLAN1 (HBR), HiperLAN1 (LBR), IEEE 802.11b, ZigBee 868 MHz, ZigBee 915 MHz, ZigBee 2 450 MHz;
– Digital video: DTV8, DTV16, DVB16, DVB32, DVB64, DVB128, DVB256, DVB 16APSK, DVB 32APSK;
– Other: APCO 25, APCO-25 P2 (HCPM); APCO-25 P2 (HDQPSK), DECT, TETRA, VDL mode 3, MIL-STD 188-181C: CPM (Option 21).

Document references

[1] PRAKASAM P. and MADHESWARAN M., Digital modulation identification model using wavelet transform and statistical parameters, Journal of Computer Systems, Networks, and Communications Volume 2008 (2008),

Article ID 175236, 8 pagesdoi:10.1155/2008/175236

[2] HAO Hu, JUNDE Song, Signal Classification based on Spectral Correlation Analysis and SVM in Cognitive Radio, 22nd International Conference on Advanced Information Networking and Applications, Dept. of Electronic Engineering, Beijing University of Posts and Telecommunication and Yujing Wang, Dept. of Telecommunication Engineering, Xidian University

Annex 2

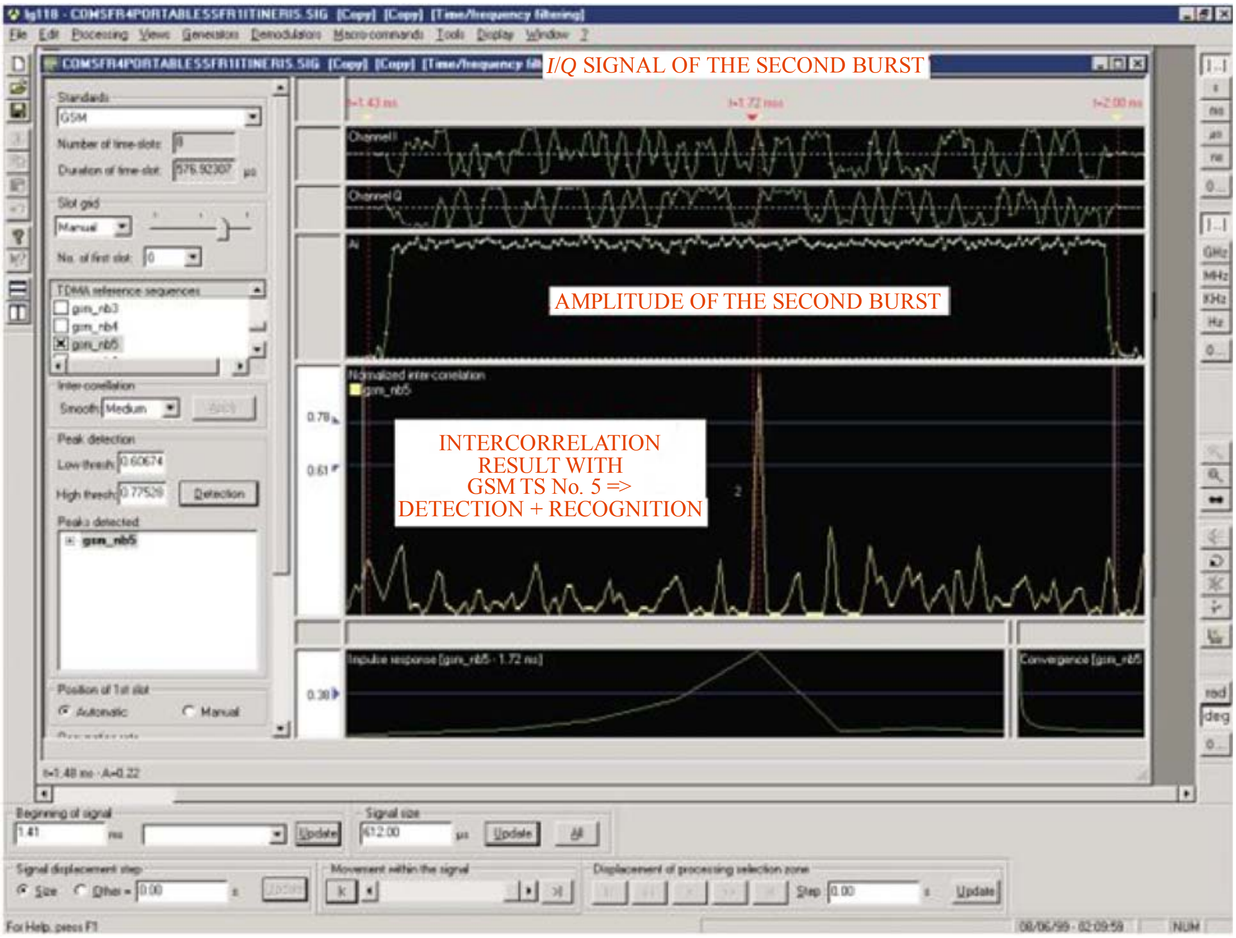
This Annex provides examples of specific complex digital signals and outlines approaches to identification.

a. Example of GSM signal (TDMA) identification

An example of correlation of a GSM burst is illustrated in the display below. In this example, the I/Q recording is compared with a known element of the GSM signal (mid-amble) and the correlation results are shown in the second window from the bottom.

FIGURE 13

Example of inter-correlation technique for signal identification



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b. *Example of signal identification method for OFDM, SC-FDMA, SC-FDE*

Cyclic autocorrelation provides many advantages when analysing partially known signals such as OFDM, OFDMA, SC-FDE and CDMA signals. It can assist in determining periodic and cyclic characteristics of the waveform. One application of the cyclic-autocorrelation processing is the recognition of repeated sequences inside transmission signals, such as guard times in OFDM like symbols. For example, an accurate detection and recognition process of OFDM, (O)FDMA and SC-FDE modulated signals may be reached by cyclic-autocorrelation calculation.

For the determination of the modulation rate and symbol synchronization, it is possible to exploit the duplication of the beginning or the end of the symbol to build the guard time. Thus, for exploiting the duplication of the signal in the case of OFDM signals, the basic mathematical functions are the autocorrelation function and the cyclic-autocorrelation function that were introduced before.

The practical implementation of OFDM identification may be performed in three stages:

Stage 1: Counting of sub-carriers, that can be made using a very fine spectral display (frequency resolution better than 1/(2.TS)). One recommends:

– panoramic representations of the signal with variable spectral resolution (and consequent integration time),

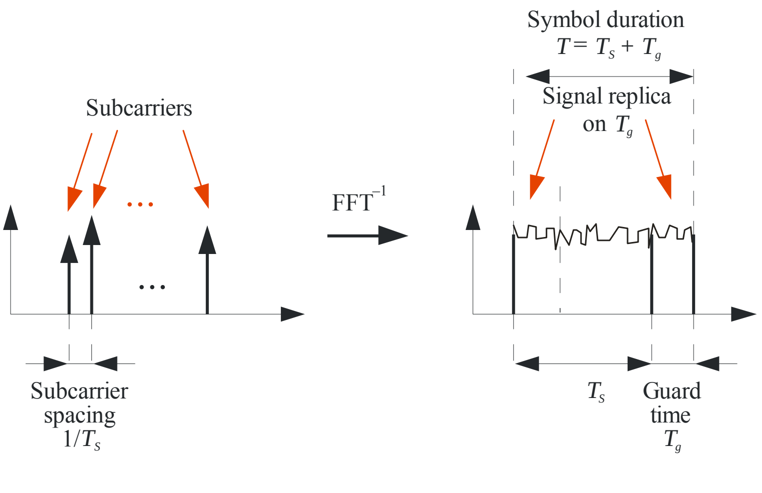
– the use of a large number of points for FFT computation with suitable interpolation techniques,

– added zoom functions and measurement capabilities by cursors.

Stage 2: Calculation of auto-correlation of the signal is made to reveal a peak corresponding to the delay $\tau = T_S$ to determine spacing between sub-carriers $1/T_S$ (see Fig. 14, left part). It should be noted that the series of peaks corresponding to the echoes of the channel cannot be confused with the peak giving the symbol duration of the sub-carriers because of their values.

FIGURE 14

Structure of a (C) OFDM symbol in the time and frequency domains



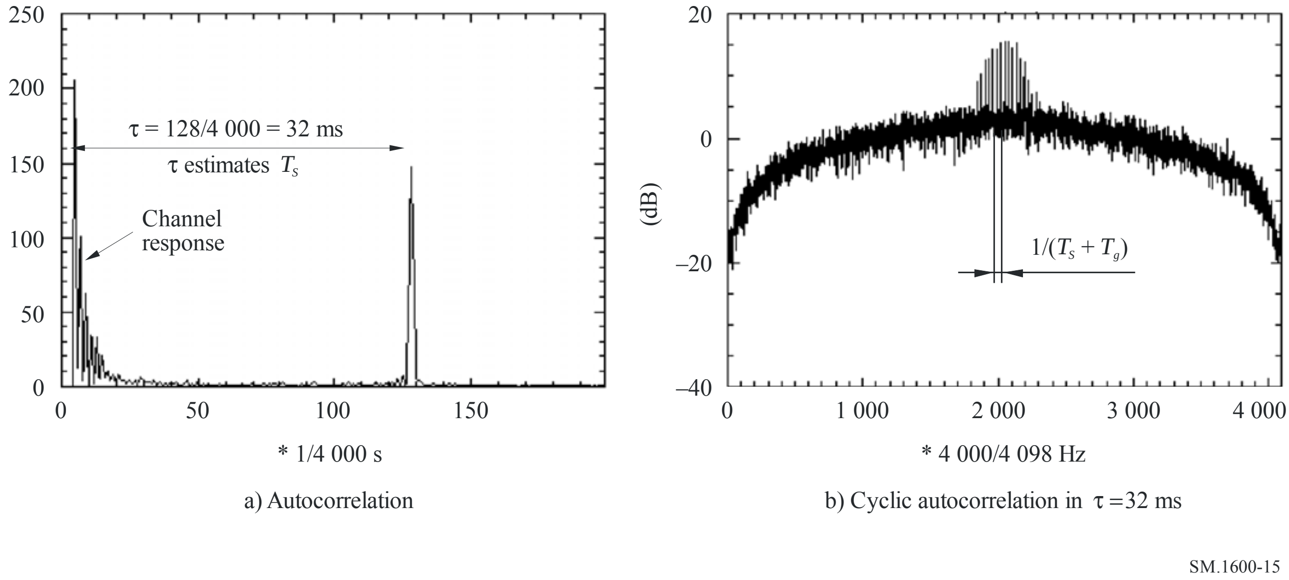
Stage 3: Calculation of cyclic autocorrelation for the delay τ (τ estimating T_S) given by the autocorrelation so that correlated signal parts corresponding to the duplication of part of the symbol to constitute the guard time can be extracted (see Fig. 14 right part):

– to confirm in addition the value of the symbol duration TS (the cyclic autocorrelation calculated for a value of τ other than TS does not present characteristic peaks);

– to determine the modulation speed of the sub-carriers 1/(TS + Tg) and the guard time Tg.

FIGURE 15

Correlation and cyclic auto-correlation methods applied to (C) OFDM signal



c. Example of signal identification method for WCDMA

The practical implementation of the WCDMA signal analysis may be composed of three stages:

Stage 1: Estimation of symbol rate

As an example, the symbol rate of 3GPP/WCDMA signals is 3.84 MHz and can be estimated by calculation of spectral correlation. This standardized symbol rate can be compared to the estimated value obtained by signal processing. When facing 3GPP/WCDMA networks, this allows to restrict the search domain for symbol rate in the spectral correlation computation to values close to 3.84 MHz so that computation is reduced. Figure 16 a) shows the estimation result of symbol rate.

Stage 2: Cell search: The cell search is typically performed in three steps as below.

Step 1: Slot synchronization: This is typically done with a single filter matched to the Synchronization channel's (SCH) primary synchronization code which is common to all cells. The slot timing of the cell can be obtained by detecting peaks in the matched filter output.

Step 2: Frame synchronization and code-group identification: This is done by correlating the received signal with all possible SCH's secondary synchronization code and identifying the maximum value. Since the cyclic shifts of the sequences are unique, the code group as well as the frame synchronization is determined.

Step 3: Scrambling-code identification: By using the frame timing and code group number found in the second step, the Common pilot channel (CPICH) is correlated with all possible eight different sequences within the code group. The code with the maximum correlation is considered as the scrambling code number of the cell.

The detailed description for cell search can be referred to 3rd Generation partnership project technical specification (3GPP TS) 25.214.

Stage 3: Carrying out measurements concerning the modulation of the WCDMA.

Descrambling of the received signal to acquire the CPICH symbol: The CPICH symbols are obtained by multiplying the received signal with the scrambling code sequence starting from the frame boundary found in *Stage 2* and by doing summation of 256 samples.

Confirmation of the QPSK modulation: After multiplying the descrambled signal with the Primary-Common control physical channel (CCPCH) code and compensating the frequency offset, the modulation type of the Primary-CCPCH signal can be checked. The frequency offset is estimated from the CPICH symbol as above.

Figures 16 b) and c) show the constellation of QPSK modulation and cell search results provided by the previously recommended analysis of real field WCDMA (3GPP/UMTS) signals that share a common carrier (9 Base stations (BS) are detected and measured), respectively.

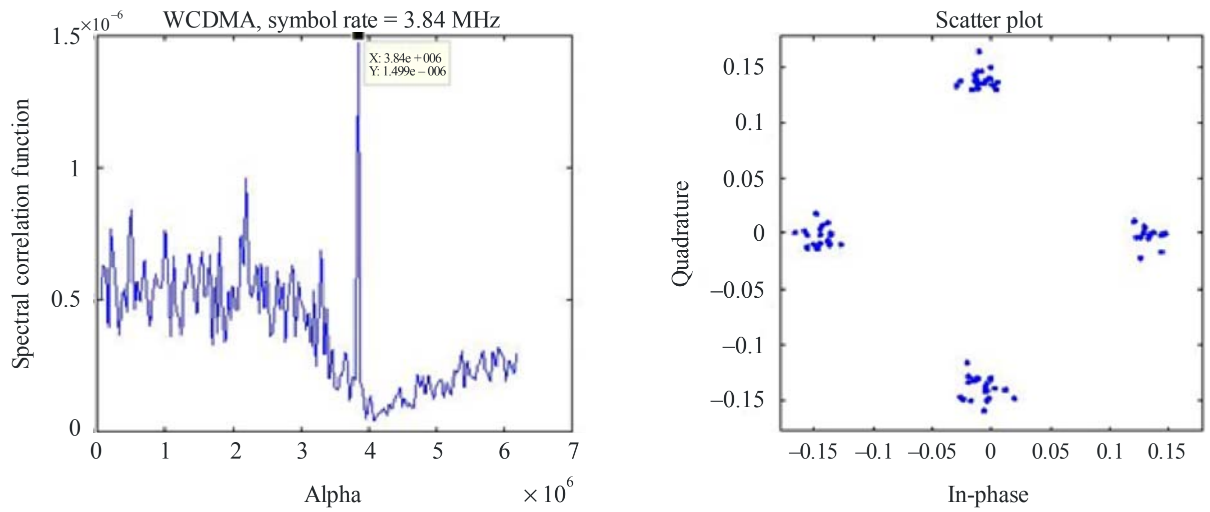
FIGURE 16

Illustration of the complete identification process of 3GPP/WCDMA signals in three stages

16-a) recovery of symbol rate

16-b) slot synchronization, CPICH descrambling and CCPCH demodulation

16-c) applying stages a) and b) for searching for WCDMA cells that share the same carrier



a) Estimation of symbol rate

b) Constellation of the primary-CCPCH signal

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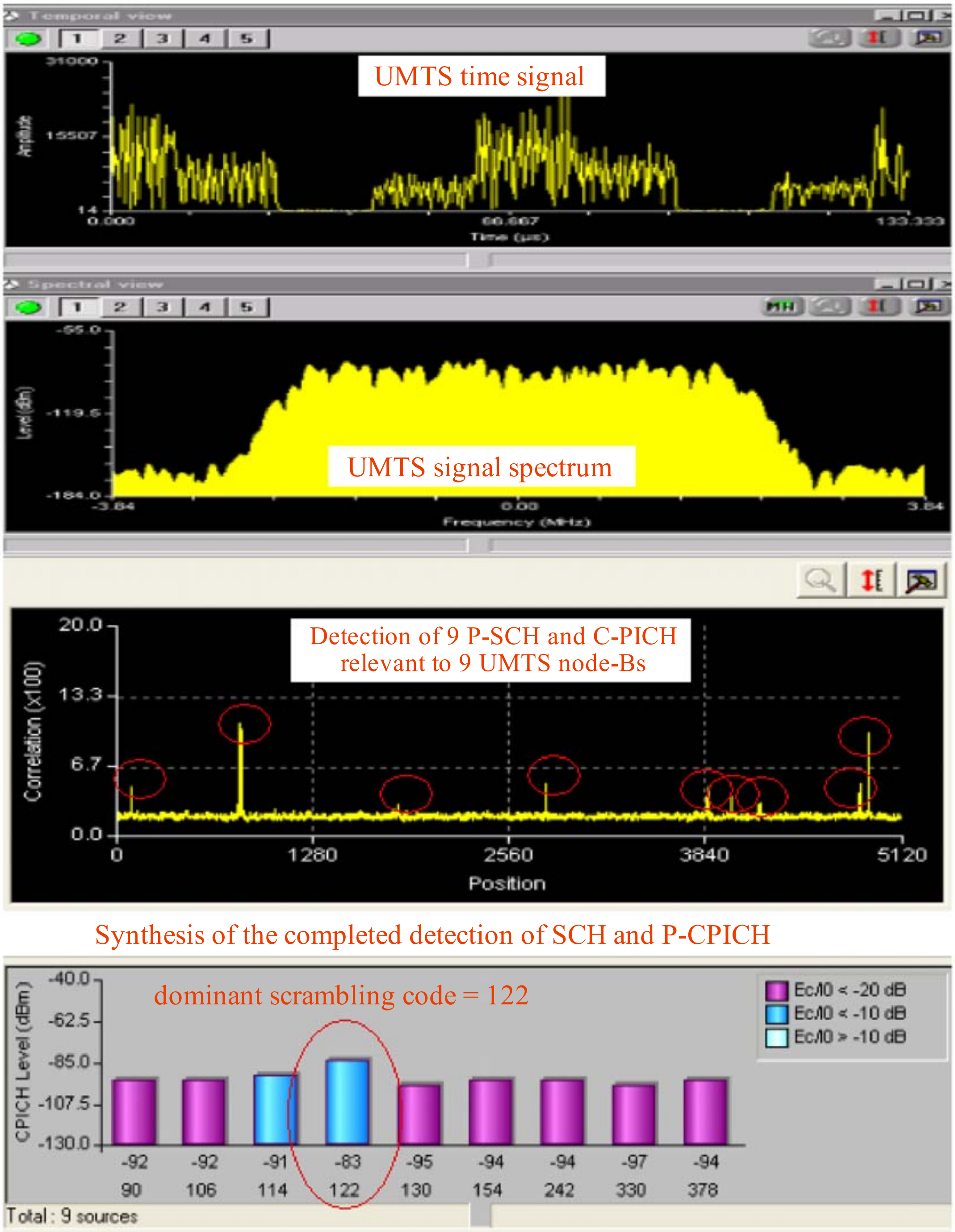
FIGURE 16c

Detecting and identifying several WCDMA cells sharing the same carrier after slot synchronization, CPICH descrambling and CCPCH demodulation



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