Electronic measurements
Laboratory guide – Part B

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Contents

Chapter 1

Using a mixed-signal oscilloscope

Instruments

- Agilent Technologies MSO6012A mixed-signal oscillscope (MSO);
- demonstration board;
- flat cable;
- passive probes.

1.1 Introduction

A *mixed signal oscilloscope* (MSO), like the Agilent Technologies MSO6012A oscillscope that is employed in this laboratory activity, is a multichannel instrument combining both analogue and *digital* input channels.

In the MSO6012A two analogue channel inputs are provided on the instrument front panel. As in any general-purpose oscilloscope, their set-up can be defined by recalling the channel menu through the front panel keys ‘1’ or ‘2’ in the **Analog** part of the panel. A separate 16-line connector is present (on the rear part of the instrument) for the digital inputs. Up to 16 digital input lines can be configured using menus recalled from the front panel **Digital** section. In particular, the **Threshold** menu from **D15 Thru D0** allows to set logical threshold voltages, either by recalling the standard values for TTL (1.4V), CMOS (2.5V) and ECL (-1.3V) logic families, or by user-defined values.

An essential feature of the MSO is its ability to consider mixed trigger conditions, involving both analogue and digital signals. Event and state conditions can be defined by suitably the *pattern* associated with the synchronization command. When the **Pattern** menu is activated by pressing the corresponding key on the **Trigger** front panel section, the following indication is displayed on the lower part of the instrument screen:

Pattern = 1 XX 2 D15 XXXX XXXX XXXX XXXX D0

The pattern value is obtained by combining conditions regarding the two analogue channels (1 e 2) and 16 digital channels (from D15 to D0). Possible choices are:

- **rising edge** ↑ or **falling edge** ↓,
- **high level, 'H'** or **low level 'L'**,
- a don't care value **X**, meaning that **no condition** is set on the corresponding signal.

The software function **Channel** provides access to a drop-down menu where available channels are listed. A switch placed besides the the screen allows to select a channel, for which conditions may then be modified when necessary.

To demonstrate MSO features and operating modes, an *evaluation board* is provided, that gives access to 10 different analogue signals, as well as a group of 16 digital signals. For the latter, flat cable connectors are present both on the board and on the MSO rear panel, simply requiring a direct connection by a flat ribbon cable. Analogue signal have to picked up by high-impedance RC-compensated probes from a number of test points, suitably identified on the board.

An on-board group of *microswitches* allows to change the board configuration, so that different signals are available at the MSO digital input lines. Relevant switch positions and signal features are summarized in the two tables that follow.

1.2 Detection of a specific logic activity – Pattern trigger

Microswitch setting: S1=ON, S2=ON, S3=OFF. **Probe test points**: SDRAM D0, SDRAM CLK.

with this microswitch setting the evaluation board provides some digital lines that emulate the behaviour of a synchronous dynamic random access memory (SDRAM). In this exercise the emulated clock rate is actually lower than in a real SDRAM, to make signal acquisition easier.

Logic activity related to the SDRAM is related to a number of control signals, that can be observed among the MSO digital input lines. Specifically, the digital lines associated with SDRAM control signals are:

- **CS: Chip Select**: active-low chip enable signal;
- **RAS: Row Address Strobe**: control line – when active, the memory cell row address can be read on the address lines;
- **CAS: Column Address Strobe**: control line – when active, the memory cell column address can be read on the address lines.

Test Point	**Description**
SDRAM D0	*synchronous dynamic random access memory* (SDRAM) data line.
SDRAM clock	SDRAM clock line.
Unfiltered DAC	"Sinusoidal" output of an 8-bit digital-to-analogue converter (DAC) represented by a stepwise constant waveform.
Filtered DAC	Smoothed DAC sinusoidal output. This is a filtered version of the previous one.
I2C data	Serial I2C data bus.
I2C clock	Serial I2C bus clock line.
NTSC Video (*not used*)	analogue output from a CCD camera sensor in NTSC frame format.
Glitch/Burst (*not used*)	**Glitch**: periodic square wave with fundamental frequency 1.250MHz. **Burst**: a complex signal sequence (burst), with a repetition frequency of 1.00kHz. – A random glitch, approximately 21 ns long, is superposed on both signals.
AM (*not used*)	Amplitude-modulated signal with a 2 MHz carrier frequency and a modulating frequency of 2.3 kHz. An anomaly is present in the signal.
Sync (*not used*)	Synchronization signal at frequency 2.3kHz and peak-to-peak amplitude 4.10V.

S1	**S2**	**S3**	**Action**
0	0	0	(*not used*) Glitch
0	0	1	(*not used*) Burst
0	1	0	(*not used*) AM with glitch
0	1	1	DAC
1	0	0	I2C with DAC
1	0	1	SPI
1	1	0	SDRAM
1	1	1	Undefined

- **WE: Write Enable**: active-low control line – with CS, RAS and CAS active, data will be *read* from memory if WE is high, *written* into memory when WE is low.

Figure 1.1: **Label** menu softkeys are shown in the lower part of the screen.

The two MSO analogue inputs are employed to display signals **SDRAM D0** and **SDRAM CLK**, that can be picked up from the test points thus marked on the evaluation board, by means of passive probes. These are, respetively, one of the memory data lines and the clock signal that provides the timing for memory read/write operations. From the pre-arranged combination of digital lines on the MSO digital connector, inputs **D4 - D7** should be considered. These correspond to the following SDRAM control signals:

- D7 → WE,
- D6 → CAS,
- D5 → RAS,
- D4 → CS.

To help identification, labels can be associated to each line using the **Label** menu[1]

Identification of a SDRAM memory write cycle requires triggering on the correct combination of logic states on *five* signal lines, namely, RAS, CAS, WE, CS on digital input lines and the clock signal taken from one of the analogue input lines. Fig. 1.2): shows the pattern RAS → H, CAS → L, WE → L e CS → L, for the SDRAM control lines, that defines the condition where RAS is active, the memory chip has been activated (CS low) and a write operation is specified (WE low). The actual trigger instant is defined by the rising edge on the clock from input channel 2 (2 →↑).

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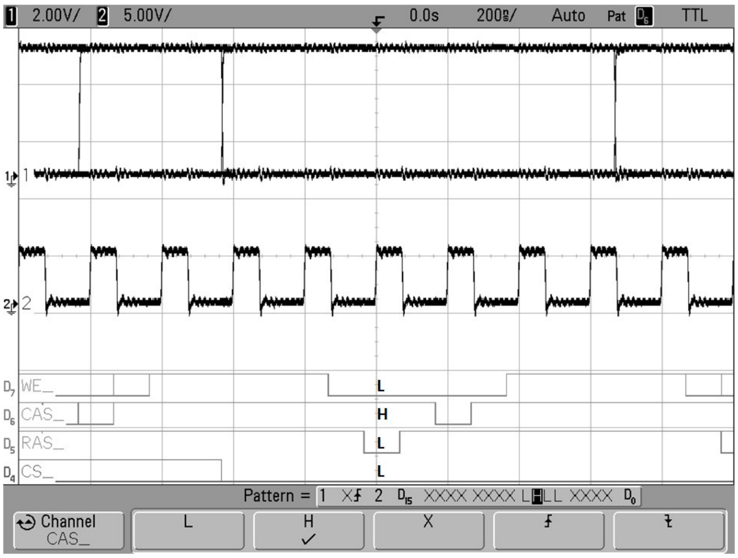
[1] The **Label** menu is selected by a front panel softkey. It is then necessary to select the channel to be labelled (**Channel** menu). Labels can be created at will, or predefined labels can be chosen from a library (**Library**). To confirm the label value, the **Apply New Label** softkey should be pressed.



Pattern = 1 X↑ 2 D_{15} XXXX XXXX LHLL XXXX D_0

Figure 1.2: Setting of the pattern trigger reference is shown in the lower part of the screen.

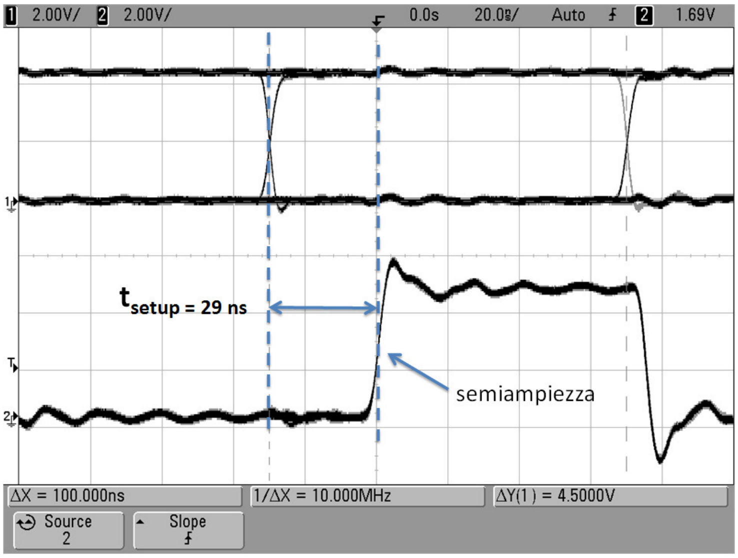
1.3 Eye diagram

Probe test points: SDRAM D0, SDRAM CLK.

An eye diagram provides information about signal timing and allows to check digital signal noise margins. Although referred here to digital signals, any oscilloscope can be employed for the measurement, since only analogue inputs are used. It is obtained by superposing multiple acquisitions of a timed signal, using the clock reference as the trigger input. The eye diagram that should be obtained for the data signal SDRAM D0 is shown in Fig. 1.3 together with the clock signal SDRAM CLK. In this case, SDRAM CLK is selected as the trigger source and the instrument display is set for *infinite persistence*: **Display** → ∞ **Persist**. The resulting superposition of successive acquisitions of signal SDRAM D0 enables the analysis of variability of the data line edges with respect to the clock edges.

The eye diagram display allows to measure the *set-up time* on data lines, that is, the distance between data line transitions and the clock active edge. Since data line values are read at the occurrence of the clock edge, a specififed non-zero set-up time if often necessary to ensure stable voltage levels have been reached in the circuit.

Analysis of the eye diagram allows to observe actual operating conditions and verify that set-up time specifications are met. A significant limitation may be caused by *jitter*, that is, the variability in the psoition of transition edges. In the example shown in Fig. 1.3, jitter is actually negligible.



ΔX = 100.000ns

1/ΔX = 10.000MHz

ΔY(1) = 4.5000V

Figure 1.3: Eye diagram display.

1.4 Measurements on an embedded system

This part of the exercise refers to a simple microcontroller-based system, contained in the evaluation board, whose block diagram is shown in Fig. 1.4. It is based on a 16-bit Microchip PIC 18F452-I/PT microcontroller unit (MCU) with an integrated ADC, an external 8-bit DAC to which data are tranferred by 8 digital I/O lines and a controller that is interfaced to the MCU by a serial I^2C bus.

The controller is employed to change some features of the DAC-generated waveform.

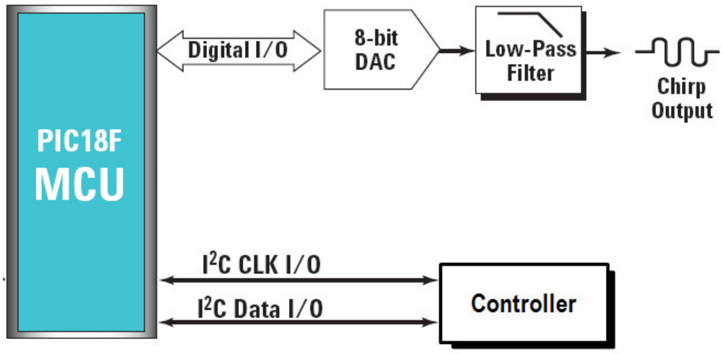


Figure 1.4: Functional diagram of the embedded system under test.

1.4.1 DAC input and output

Microswitch setting: S1=OFF, S2=ON, S3=ON. **Probe test points**: Unfiletred DAC, Filtered DAC.

Data line values in a digital system usually vary in a rather unpredictable way, unless some repetitive activity is carried out. This is indeed the case with the generation of a periodic waveform, when a sequence of sample values are cyclically transferred to a digital-to-analogue converter (DAC).

In this example 8-bit samples of a sinusoid are taken from a memory table where they are stored, and transferred to a DAC to reproduce the signal. Waveform amplitude, frequency and phase can be varied by changing the output voltage range, reading speed and start memory location.

The aim of this part of the exercise is to acquire and analyze data both from the DAC digital lines and from its analogue voltage output line. Analogue signals are acquired by means of passive probes connected to two test points: **Unfiltered DAC** and **Filtered DAC**, while suitable digital inputs are present at the MSO digital input lines **D0-D7** after the **Autoset** key has been pressed. Stable portions of the signals are presented on the MSO display, as shown in Fig. 1.5.

The trace observed at the DAC output (*Unfiltered DAC*) is a quantized sinusoid. The use of an 8-bit DAC produces a stepped waveform, which is made apparent by the fact that only a small subset of the 256 output levels is actually employed. By interpreting logic levels on the digital trace display, the binary bytes encoding the DAC output levels can be obtained, remembering that line

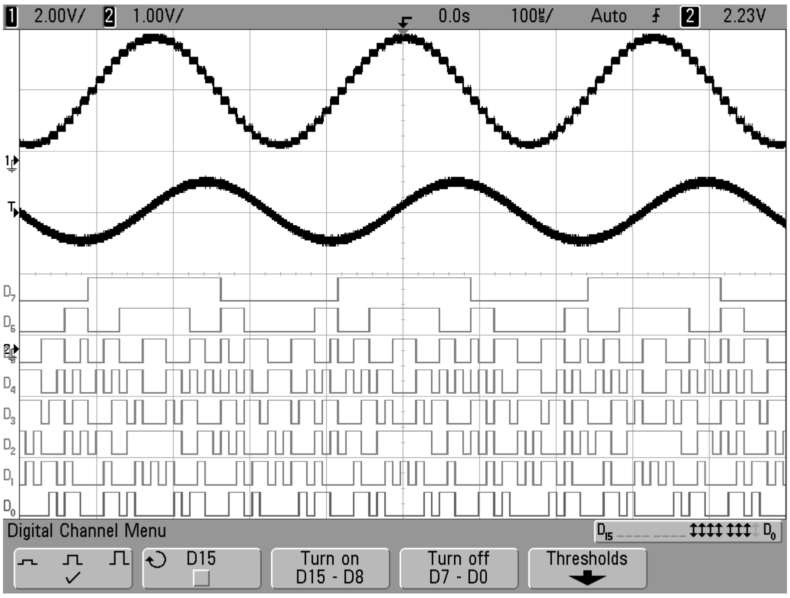


Figure 1.5: Mixed-signal trace showing digital data lines and analogue DAC output of the measured embedded system.

D7 provides the most significant bit. Just 17 different codes can be found.

1. determine the **decimal DAC codes** employed by the DAC from the interpretation of displayed digital line traces;
2. determine the **quantization step**;
3. find the **DAC clock rate** – the DAC clock interval can be measured either as the length of the shortest step on the analogue waveform, or as the length of the shortest pulse on the digital lines (of course, the two values should coincide);
4. measure the sinewave period, comparing values obtained from signals *Unfiltered DAC*, *Filtered DAC* and from the displayed digital lines (they should agree, of course;
5. measure the delay of *Filtered DAC* from *Unfiltered DAC* (can you think of a possible reason for this delay?)

Try synchronizing the MSO on a specific DAC level using the pattern trigger. Note that some codes may be used on both slopes of the sinewave, but the pattern trigger gives no possibility to select trigger *slope*. However, it is possible to define a pattern trigger condition also for the analogue lines and this should help achieve a unique pattern.

For instance, to trigger on binary word 1000 0000 (that is, DAC code 128, in the middle of the DAC output range) it is also necessary to set a logic level condition on the analogue signal. For a *low* level value, it is then:

Pattern = 1 LX 2 D15 XXXX XXXX HLLL LLLL D0

The DAC code corresponding to the Unfiltered DAC peak value is instead a unique condition, for which a pattern trigger can be defined using only values of the digital lines.

1.4.2 Serial data acquisition – I^{2}C bus

Microswitch setting: S1=ON S2=OFF S3=OFF (same as above). **Probe test points**: SDA, SCL.

The serial Inter-IC bus, (I^{2}C) bus has been conceived as an interface among integrated circuits on a board. It is composed of two lines:

- a data line (**SDA**), that can be observed at test point **I2C data**,
- a clock line (**SCL**), that can be observed at test point **I2C clock**.

These are acquired by means of the two passive probes connected to the MSO analogue inputs [2]

Trigger conditions for serial bus analysis refer to **sequences** of binary values. The MSO provides a dedicated **serial bus trigger** for the I^{2}C bus. The

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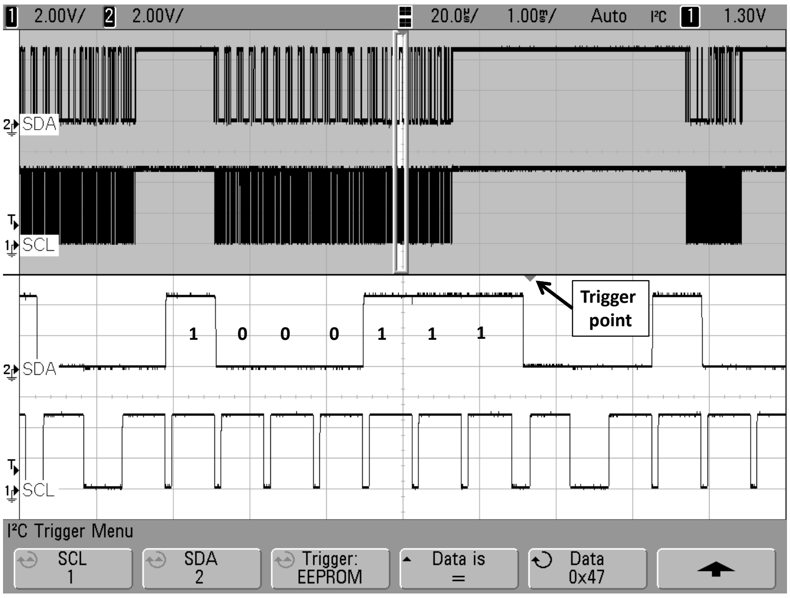
[2] After pressing the **Autoscale** key digital lines are also displayed. For this part of the exercise they can be disabled by pressing the **D15 Thru D0** key at the side of the screen.

configuration menu is activated by the key **More** in the MSO front panel *trigger* section. The option **Trigger I^{2}C** should be selected from the **Trigger Type** menu.

WARNING: the serial bus trigger mode is designed for digital input lines, but it is also applicable to the two MSO analogue inputs. In this case, a vertical scale factor of 2 V/div on both channels is suggested to avoid triggering errors.

After setting the trigger type, the menu **More** → **Settings** enables to:

- set the SCL clock source input.
- set the SDA data source input.
- select the trigger condition among the following options provided in the **Trigger on** menu:
  1. **Start Condition** – the trigger condition is a *high-to-low* level transtion on the SDA line while SCL level is high;
  2. **Stop Condition** – the trigger condition is a *low-to-high* level transtion on the SDA line while SCL level is high;
  3. **Missing Acknowledge** – the MSO is triggered if SDA logic level is high when an acknowledge bit is found on the SCL line;
  4. **Restart**: the MSO is triggered when a *start* condition follows a *stop* condition;



SCL 1
SDA 2
Trigger: EEPROM
Data is =
Data 0x47

Figure 1.6: Oscilloscope display of the SCL and SDA serial I^{2}C bus lines. Trigger condition is **EEPROM data read** for the 7-bit value **0x47 = 100.0111**. The lower half of the screen is a zoomed-in display around the trigger condition of the traces shown in the upper half and corresponds to the highlighted part.

5. **EEPROM Data Read** – the trigger condition is a combination of events (Fig. 1.6): a control byte for the EEPROM memory (that is, 1010xxx) is sent over the SDA line, then a Read bit, followed by an *acknowledge* (Ack) bit.

   When this trigger condition is selected, the *qualifier* **Data is** must be set to one of the following values: = (equal), ≠ (not equal), < (less than), > (greater than). Then, the reference value is set in the field **Data** in hexadecimal form. Values in the range 0x00 to 0xFF can be specified, the indication 0xXX expressing a “don’t care” condition.

   When the condition defined by the qualifier and reference value is met, triggering occurs on the rising edge of the Ack bit that follows the data byte. Fig. 1.6 shows an example where data value 0x47 on the SDA data line is taken as the trigger condition.

6. **Frame (Start: Addr7: Read: Ack: Data)** or **Frame (Start: Addr7: Write: Ack: Data)** – the trigger condition is a read or write operation for the device whose address is specified in the field **Address**. Like in the previous case, a **Data** value can also be specified;

7. **10-bit Write** – the trigger condition is a 10-bit *write* frame, in the format: Start: Address byte 1: Write: Adress byte 2: Ack: Data.

Test trigger modes: 1, 2, 3, 4, 5. For trigger mode 5, use the ’=’ qualifier and chech that data: 0x21, 0x41, 0x45, 0x47, 0x49, 0x4C, 0x4D, 0x4E, 0x4F, 0x53 e 0x54 are transmitted along the bus.

It should be remarked that voltage on the data line must be at a stable level when the clock line is a logic high. Otherwise, the situation might be mistakenly interpreted as a *start* or *stop* condition.

1.4.3 Digital trigger for analogue display

Microswitch setting: S1=ON S2=OFF S3=OFF. **Probe test points**: Unfiletred DAC, Filtered DAC.

This part of the exercise retains the same configuration and microswitch setting as the one before, however passive probes connected to the MSO analogue inputs should now be moved to pick up signals from test points **Unfiltered DAC** and **Filtered DAC**. The I^{2}C bus trigger option is still employed and, since serial bus lines are also included among the acquired MSO digital input lines, trigger **Settings** should be modified accordingly. Channels **D14** and **D15** then provide, respectively, the clock (**SCL**) and data line (**SDA**) sources.

Fig. 1.7 shows the pattern of the signals of interest in the acquisition board. Analogue signals are formed by a sequence of short sinusoidal bursts, that in the following will be called (somewhat improperly) *chirps*[3].

Three chirps with different lengths are generated, their lengths being, respectively, **three**, **two** and **one** period of a sinewave. Their sequencing is controlled by the exchange of control information through the I^{2}C bus. Chirp length is

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[3] A proper *chirp* is actually a constant-amplitude sinusoid whose frequency is modulated by a linear frequency ramp and varies in a given range.

determined by the value of the data field, that can be selected to define the bus trigger condition.

In particular, generation of a *1-cycle chirp* may be initiated by the binary word **0x21**, corresponding to ASCII character '!', as shown in Fig. 1.8.

Correspondence between chirp length and control word, as shown in the following table, can be verified by suitably stting the trigger data field.

3-cycle chirp	**2-cycle chirp**	**1-cycle chirp**
A = 0x41	M=0x4D	!=0x21
G = 0x47	S=0x53	
I = 0x49	O=0x4F	
L = 0x4C		
E = 0x45		
N = 0x4E		
T = 0x54		

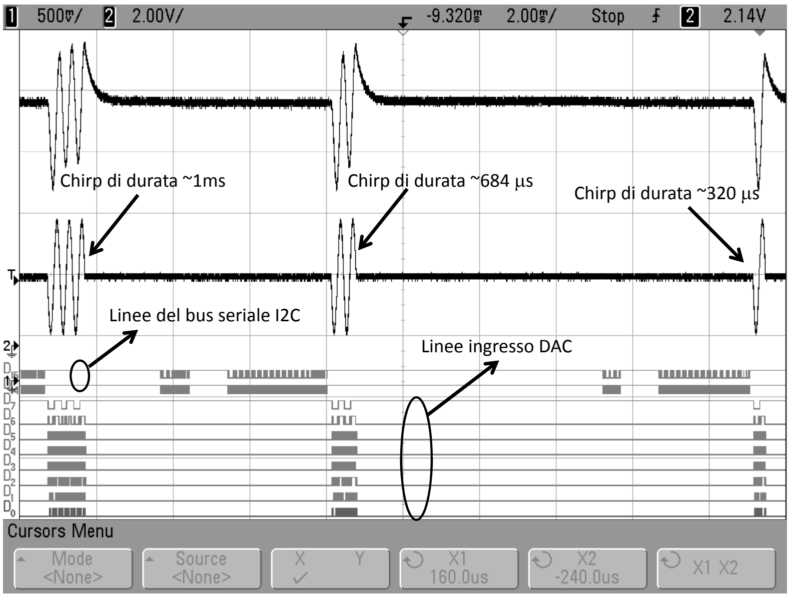
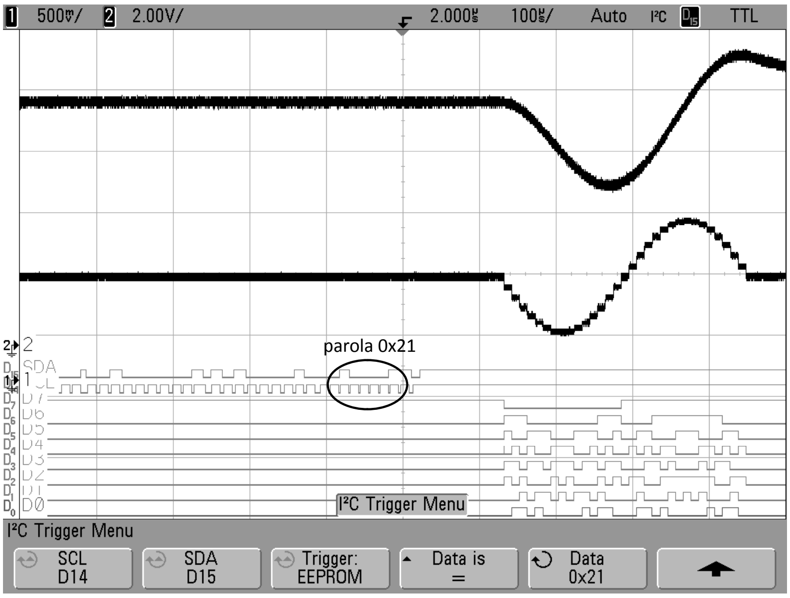


Figure 1.7: Generation of different sinewave lengths under I^2C bus control.



I²C Trigger Menu

SCL D14

SDA D15

Trigger: EEPROM

Data is =

Data 0x21

Figure 1.8: Digital and analogue acquisition for a 1-cycle chirp.

Chapter 2

Spectrum analyzer measurements for RF signal sources

Instruments

- Keysight 33600A Series Waveform Generator;
- Rohde & Schwarz FPC 1500 Spectrum Analyzer;
- broad-band antenna.

2.1 Presentation

This laboratory exercise is intended to introduce the main features of a spectrum analyzer by considering some variety of signal spectra, that provide opportunities to test several instrument functions and understand their use. The exercise is divided in two parts:

- measurement of RF signals from a receiver antenna;
- measurement of specific signals obtained from an AWG generator.

The main spectrum analyzer set-up options are usually grouped under three main multiple-choice functions (Fig. 2.1):

- a *frequency* (**Freq**) key, that provides access to *centre* frequency, *start* frequency and *stop* frequency settings;
- a **Span** key, that provides access to various settings, including determination of the span width (for a **given** centre frequency), selection of the *zero span* mode, etc.;
- an *amplitude* (**Ampl**) key, which allows to configure the vertical scale factor and reference level, the input attenuator setting, etc. – **Note**: manual setting of the input attenuator is **for experienced users only**.

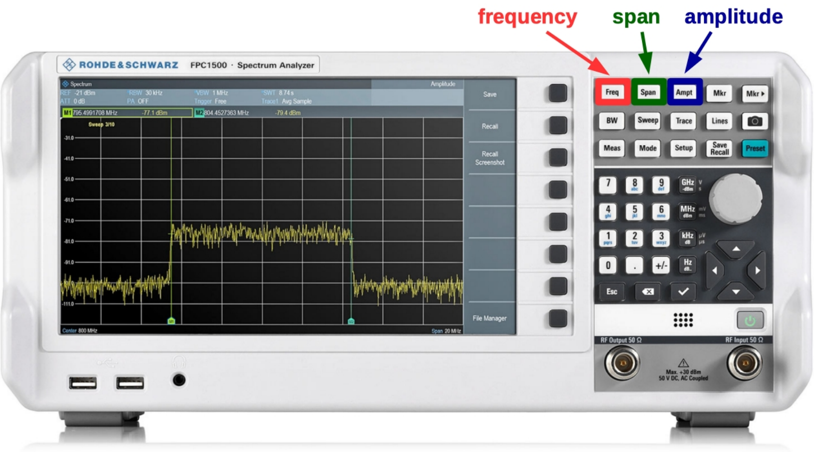


Figure 2.1: Front panel of the Rohde & Schwarz FPC 1500 Spectrum Analyzer.

- a **knob** that allows to vary the numerical value of parameters from any instrument set-up menu;
- a **keypad** with numerical keys for direct input of parameter values, as well as (⇑) and (⇓), keys enabling stepwise parameter variation according to an instrument-defined sequence.

WARNING
The instrument **Preset** deletes any previous instrument setting. After the *preset* routine is completed, the input attenuator is set to a safe value and the spectrum analyzer is configured for **full span** analysis. Thus, any particular choice of *frequency* and *span* setting (as required, for instance, when a specific signal source is monitored), is **lost**.

To observe the spectrum in some specific frequency bands, a frequency measurement range should be selected. To set the range, either of two ways can be adopted:

- set the frequency interval limits:
  Freq → **Start Frequency** → ···
  Freq → **Stop Frequency** → ···
- or, set the interval centre frequency and width:
  Freq → **Center Frequency** → ···
  then the analyzed frequency span, around the centre frequency::
  Span → **Manual Span** → ···

If needed, the *reference level* on the instrument display can be varied using:
Ampt → **Reference Level** → **{⇑ / ⇓}**

This operation modifies the **display** range of the instrument. The vertical scale is normally logarithmic and the vertical scale factor may also be modified if needed.

It must be remembered that the input attenuator setting is an **entirely different** kind control input, and directly affects the **total power level into the mixer**. **This setting should not be changed at all by inexperienced users**, as an improper setting can overload the mixer, causing irreversible and expensive damage to the instrument.

By default, input attenuation is automatically adjusted by the instrument, but it is still important to remember that automatic adjustment also takes into account the reference level setting. As a practical rule, it is advisable to set the reference level to about 10 dB greater than the largest displayed signal component.

WARNING
Ensure that *Auto* setting remains the selected option for the input attenuator:
Ampt → Attenuator AUTO

2.2 RF signals from a receiver antenna

This activity can be seen as a monitoring of frequency allocations in different bands, followed by the analysis of specific sources in each band. Proper use of the instrument functions requires to understand the specific signal features of each analyzed source, to ensure that spectral traces and marker indications are then correctly interpreted.

The instrument input is provided by an antenna, that allows to receive signals in a broad frequency range. It should be remembered that power measurements obtained in this exercise refer to the power level **at the instrument input**. The whole measuring system includes the antenna and a connecting cable, which means a correctly calibrated measurement of **received** power would need to account also for antenna gain and cable attenuation, plus insertion losses. This aspect is not considered in the following.

Frequency allocation

Frequency bands in the electromagnetic spectrum are allocated to a variety of telecommunication services. Table 2.1 presents an extract of significant services between 87.5 and 1215 MHz, drawn from the Italian national frequency allocation plan[1].

Power levels associated to different services vary significantly, depending on the intended range of the emitter, its frequency and the relevant regulatory requirements. Of course, the received power level also depends on the distance from the emitting source. In general, measured power level are higher for FM broadcast stations whereas, for instance, DVB-T video signal power appears considerably lower.

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[1] Piano Nazionale di Ripartizione delle Frequenze (PNRF) – supplemento ordinario n. 49 alla Gazzetta Ufficiale del 19 ottobre 2018, n. 244

Service	**Frequency band [MHz]**	**Notes**
FM radio	87.5 - 108	Frequency modulation (FM) radio broadcasting
RF aviation aids	108 - 137	ILS, VOR, airport communications
VHF – Video / audio	174 - 230	digital video / audio broadcasting
ISM band	440 - 470	unregulated frequency band, allocated for ISM (industrial, scientific, medical) communications
UHF – Digital video	470 - 791	DVB-T multiplex
GSM-R	876 - 880	mobile services for railway companies
GSM900 – mobile telephone services	880 - 915	Second-generation European digital cellular system (GSM) - Uplink (from user equipment to base station)
GSM-R	921 - 925	railway mobile services
GSM900 – mobile telephone services	925 - 960	Downlink (from base station to user equipment)
Military air navigation aids	960 - 1215	DME/TACAN/SSR

Table 2.1: Current frequency allocations in Italy.

A preliminary overview of the distribution of signal sources over the analyzable frequency range can be obtained by a *full-span* measurement, that is, with the default instrument set-up at turn-on.

Since some sources are discontinuous (e.g., using burst transmission), or their frequency spectrum may vary, it is advisable to employ the *Max Hold* display mode, that is selected by the command:
Trace → Trace Mode → Max Hold

Afetr allowing some time for repeated sweeps, the spectrum analyzer will eventually record and display all signal sources emitting RF power in the analyzed freqeuncy range. The trace shows the maximum power, but it should be remebered that power indications might be inaccurate, because of the wide resolution bandwidth of the IF filter in the full-span setting. The purpose of this preliminary analysis is then to record the positions of different sources, so that the analysis can be focussed on any of them.

Some guidelines are given in the following for the analysis of different signals.

2.2.1 FM Band

To observe the spectrum of some of the signals listed in the table above specific bandwidths should be selected.
Freq → Start Frequency → 87.5 MHz
Freq → Stop Frequency → 108 MHz

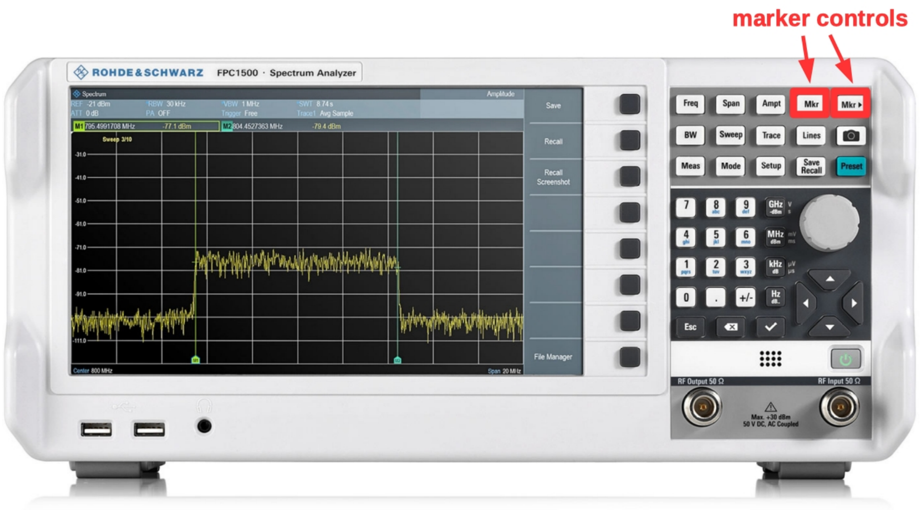


Figure 2.2: Marker function keys on the front panel of the Rohde & Schwarz FPC 1500 Spectrum Analyzer.

The analyzed span can be progressively narrowed down, until a specific channel is selected.

After a specific FM channel has been chosen, the use of a marker (**Mkr**) and of its associated *marker functions* (**Mkr ►**) facilitates instrument set-up (Figure 2.2). After placing the marker at approximately the centre frequency of the selected FM channel, the following command sequence can be used:

- **(Mkr ►)** → **Center = Marker/Level = Marker** → **Center = Marker Freq**

  which sets the spectrum analyzer centre frequency to the marker frequency value. This means the FM channel of interest is positioned at the centre of the instrument display;

- **(Span)** → **Manual Span** → **(⇓/⇑)**

  that allows to choose a suitable frequency span for a detailed analysis of the signal spectrum. A FM broadcast station occupies a bandwidth of approximately 150 kHz, the nominal spacing between neighbouring FM channels being 200 kHz. For example, a frequency span value between 0,5 and 2 MHz can be appropriate for FM channels.

FM modulation is an analogue modulation where instantaneous frequency varies proportionally to the modulating signal that contains the transmitted information signal, whereas amplitude remains constant. This means that the FM signal *total* power is constant, but its power spectral density varies continuously within the channel bandwidth.

In this case the *Max Hold* display mode can be useful, as it helps obtain a stable trace even with the kind of non-stationary signals found in the FM band. It is selected by the command:
Trace → **Trace Mode** → **Max Hold**

In *max hold* mode the spectrum analyzer records the highest level reached by the signal in subsequent scans at each frequency, and the displayed trace is formed by those maximum values. Thus, in view of the features of FM signals, the marker vertical position at any point within the passband indicates the measured power level.

Channel occupancy

After the centre frequency of the analysed channel has been determined, actual channel occupation can be measured, taking as a reference the -3 dB bandwidth. For this purpose, the trace marker can be moved along the trace using the front panel knob. Amplitude and frequency values associated to the current marker position are directly displayed on the screen, which makes this measurement straightforward.

Zero-span measurement of received power

Received power can be measured with the instrument in *zero span* measurement mode. In this case, after ensuring that the analyzer centre frequency coincides with the FM channel centre frequency (that is, with the FM *carrier* frequency), the *resolution bandwidth* of the IF filter should be set to be *close* to the FM channel bandwidth. At the optimal setting, the displayed zero span trace should be approximately constant (remember that the horizontal axis refers to *time* in zero span mode) and the marker value indicates received power *at the spectrum analyzer input.*

The *zero span* measurement mode is set by the two commands:

- **Freq → Center Frequency →** ···
- **Span → Zero Span**

To avoid interference from nearby signal sources, particularly if the power level in adjacent FM channels is high, resolution bandwidth should be just slightly larger than the signal bandwidth, to avoid measuring also some power from interference contributions. For an FM channel, for instance, it might be checked whether the measured power value changes when resolution bandwidth is varied, for instance from 300 kHz to 100 kHz.

When the marker on the spectrum analyzer trace is properly tuned to a FM broadcasting station, the received radio signal can be demodulated and the resulting baseband signal (i.e., voice and audio) is sent to the internal speaker and to the headphone jack on the instrument front panel. To activate this function a sequence of commands related to the instrument marker functions must be input:

- **Mkr → Marker Demodulation → FM**
- **Mkr → Marker Demodulation → Time ...**

where *demodulation time* indicates the length of the interval where the frequency sweep is stopped to allow signal demodulation. Values in the range of 100 ms to 500 s can be specified, sound being more clearly intelligible for intervals of at least 500 ms.

2.2.2 GSM band

The GSM900 cellular telephony system occupies two separate frequency bands, respectively for *uplink* communication (from user mobile terminals to base stations) and for *downlink* communication (from base stations to user mobile terminals). Each band comprises 1024 channels having a 300 kHz bandwidth.

GSM channels are employed for voice/data transmission, based on a time division multiplexing scheme that assigns to each user a fixed-length *time slot*. Each channel is divided into 8 time slots that are allocated to individual users, with transmission power adjusted to the minimum value that ensures error-free communication. This allows to minimize power consumption by the user cellphone and reduce inter-channel interference and results in a different power level at each time slot, depending on user position and conditions. A different situation can be found in the *downlink* band where, in addition to *user channels*, the are a few *service channels* that transmit continuously at a constant power level. These are employed for various purposes including initial call set-up[2].

Measurement will refer to ***downlink*** channels.
Freq → Start Frequency → 925 MHz
Freq → Stop Frequency → 960 MHz

Active GSM channels within the range of the receiving antenna can be detected using the *Max Hold* display mode (**Trace → Trace Mode → Max Hold**). Since most GSM channels use discontinuous transmission, *Max Hold* is necessary to enable their detection, otherwise only service channels would be detected reliably.

Once a channel of interest has been located, frequency span may be narrowed down to about 1 MHz. Since power levels are signficantly **lower** than in FM transmission[3], the instrument ***Reference Level*** may have to be adjusted accordingly.

NOTE*: take care to keep cellphones* ***far away*** *from the receiving antenna. Power transmitted by a cellphone on an uplink channel is not high* per se*, but the source is* much closer *to the antenna than a base station transmitter. Any risk of overloading the spectrum analyzer must be prevented.*

A GSM signal is characterized by a continuous spectrum. To accurately measure its power spectral density (PSD) the spectrum analyzer resolution bandwidth should be narrow enough compared to the 300 kHz GSM channel bandwidth. As an indication, an appropriate setting may be $B_R \leq 10$ kHz.

The command: **BW → RBW: Manual →** (⇓/⇑) allows to manually set the bandwidth value. Then, using the command sequence:

- **(Mkr ▶) → Center = Marker/Level = Marker → Center = Marker Freq**
- **Span → Manual Span →** (⇓/⇑)

---

[2] *Uplink* service channels also exist and are accessed by individual mobile terminals for the same reasons. However, they are used for very short intervals before switching to an aestablished user channel. For this reason, they are harder to detect and are not considered in the following.

[3] Receiver minimum sensitivity in GSM900 terminal equipment is expected to be about -90 dBm.

the channel of interest can be centred on the instrument display and the freqeuncy span adjusted.

It should be remembered that, as the resolution bandwidth is narrowed, sweep time must increase considerably. This is automatically handled by the instrument but, as a consequence, measurement on real downlink signals may become difficult. Considering the relationship among *sweep time*, *frequency span* and *resolution bandwidth*, it can be realized that the minimum sweep time must necessarily take longer than a GSM time slot, whose length is slightly greatger than 500 μs. The multiplexing of up to 8 users means that the signal cannot be considered stationary due to power levels varying among time slots within a channel.

Two situations can be considered:

- when measurement is referred to a **service channel** a normal trace display can be employed, since the power level is almost stationary. A marker would indicate the received power (within the spectrum analyzer IF filter bandwidth) measured at the spectrum analyzer input;

- when measurement is referred to a **user channel** the measured power level varies continuously, therefore the *Max Hold* trace display mode should be employed. A marker would indicate the maximum received power (within the spectrum analyzer IF filter bandwidth) measured at the spectrum analyzer input.

It must be remembered that in both cases a normal marker indicates power measured at the selected spectrum analyzer IF filter bandwidth. To determine the actual **power spectral density** (PSD), this quantity needs to be normalized with regards to the resolution bandwidth.

Measured signal power is usually rather low (typically between -60 dBm and -80 dBm), resulting in a noisy displayed trace. Noise reduction can be obtained in either of two ways:

- *averaging*, using the command:
  Trace → Trace Mode → Average
  so that the **mean** trace over a number of consecutive scans is displayed;

- *trace smoothing*, achieved by reducing the **video filter** bandwidth using the command: **BW → VBW: Manual → (⇓/⇑)**
  The video filter is placed after the envelope detector; its bandwidth, that usually equals the resolution bandwidth, can be narrowed to achieve a smoothing effect that can be considered tha analogue equivalent of trace averaging. For this purpose, *video bandwidth* should be not wider than 1/100 of the resolution bandwidth.

"*Zero span*" operation

A spectrum analyzer can detect the number of active users in a GSM channel and assess the different power levels employed for transmission. As already noted, power levels in a channel dedicated to user traffic vary continuously, therefore the channel should be first detected and located using the *Max Hold* trace display mode.

After the desired GSM channel has been located marker functions can be employed, as usual, to centre the spectrum analyzer trace display on this channel. Resolution bandwidth for zero span measurement should approximately correspond to the bandwidth of the signal source of interest, therefore a suitable setting for a 300-kHz GSM channel is: **BW → RBW: Manual → 300 kHz**.

Now the spectrum analyzer can be switched to zero span mode by the command: **Span → Zero Span** and revert to the *normal* trace display mode: **Trace → Trace Mode → Clear/Write**.

In the *Zero Span* configuration no frequency scan occurs. Local oscillator frequency remains constant and the spectrum analyzer behaves like a freqeuncy selective measuring instrument, where the selective filter centre frequency coincides with the instrument *Center Frequency*, allowing to “isolate” the channel of interest from the neighbouring channels. The horizontal axis on the instrument screen displays *time*, and the observed interval length is equal to the *sweep time* value.

Therefore, the spectrum analyzer is now displaying the variations of *power* over time in the selected channel. Sweep time can then be varied to change the observation interval length, so that power level variations in different time slots can be displayed and measured.

Further analysis into the structure of a GSM signal is only possible with a dedicated demodulator function, since the basic system employs a Gaussian minimum shift key (GMSK) argument modulation that cannot be dealt with by the basic envelope detector within a spectrum analyzer.

2.3 RF signals from AWG signal generator

This activity is aimed at a more detailed understanding of basic spectrum analyzer measurements, as applied to simple signals obtained from an analogue AWG generator. For this purpose, ad-hoc signals to test the spectrum analyzer can be generated using the AWG as a ”radio signal” generator. This can be done using a coaxial cable provided with crocodile type terminals which can act as an antenna. When placed close to the broad band antenna, these signals will be received by it and then be visible on the spectrum analyzer display.

Once the coaxial cable with the crocodile terminals is connected to the AWG, different signals can be generated to check the impact of spectrum analyzer settings on the visualization of signals with known spectra.

2.3.1 Single frequency

After defining the setting of a sinewave at the desired frequency, enable the generator output (any frequency value can be selected). The spectrum analyzer is initially set-up to measure **full span**, that is, up to 3 GHz, and in this condition it will display a vertical line whose magnitude and position on the horizontal (frequency) axis approximately correspond to the signal parameters. Values may be read by means of the *marker* (**Mkr**) function.

This measurement needs to be refined by restricting the frequency span to the neighborhood of the signal component of interest. For this purpose, *marker functions* (**Mkr ▶**) can facilitate instrument set-up:

- **(Mkr ▶) → Set To Peak**

which positions the marker on the highest level value of the trace. Since a single frequency is provided by the generator, the marker will be on the relevant peak, but at *full span* marker values will be somewhat inaccurate;

- **(Mkr ▶)** → **Set To Peak** → **Center = Marker Freq**

  which sets the spectrum analyzer centre frequency to the marker frequency value. This means the signal frequency is positioned at the centre of the instrument display;

- **(Span)** → **Manual Span** → **(⇓/⇑)**

  that allows to choose a suitable frequency span for a detailed analysis of the signal spectrum.

It may be noticed that, as the frequency span is narrowed, the instrument *resolution bandwidth* is also narrowed accordingly[4], resulting in a sharper peak for the measured component. This will also evidence marker position accuracy, that can be improved by repeating the steps above.

Following the generation of a sinusoidal signal, square waves and triangular waves can be generated so that it is possible to compare the visualized spectrum with the expected theoretical one.

2.3.2 AM and FM modulated signals

After visualizing pure waves, ti is possible to exploit the Modulate function of the AWG. To this aim, the first tests should be performed by exploiting the AM modulation function, where different types of modulating functions can be chosen. When choosing a sinewave as a modulating function, it is possible to study the effect of masking due to an excessively high value of RBW. This can be done by manually varying the resolution bandwidth: **(BW)** → **RBW: Manual**.

Following the AM modulation, the FM can be chosen. In this case, using the same setting applied for the PLL laboratory activity, it is possible to visualize the frequency sweep on the spectrum analyzer screen. Then, setting the shape of the modulating wave as Square, it possible to clearly visualize the shape of the modulating signal by choosing the Zero Span mode visualization: **(Span)** → **Zero Span**. Remember that the horizontal scale factor is dependent on the Sweep Time, and it can be then varied by varying its value: **(Sweep)** → **Sweep Time: Manual**.

---

[4] It should be remembered that *frequency span*, *resolution bandwidth* and *sweep time* are **interdependent controls**, that are managed by the instrument unless manual settings are selected. Then, span variations automatically produce adjustments in resolution bandwidth and sweep time values.

Chapter 3

Vector signal analysis of RF digital modulations

3.1 Presentation

This laboratory exercise is an introduction to the kind of complex test set-up that would be usually needed for characterization and compliance verification of electronic designs. The activity is a demonstration of the test activities enabled by the combination of a flexible radio-frequency (RF) signal generator and a digital IF spectrum analyzer featuring dedicated vector signal analysis (VSA) application software.

Instruments

- Agilent Technologies E4432B ESG-D Signal Generator;
- Agilent Technologies N9010A EXA Signal Analyzer with 89600 VSA software;
- Keysight MSOX 3024T.

3.2 Signal Generator

A basic functional diagram of the RF signal generator employed in this exercise is shown in Fig. 3.1. The instrument is provided with two sample memories, each one feeding a digital-to-analogue converter, so that two arbitrarily defined base-band signals can be generated. These are fed into a couple of mixers whose RF inputs are produced by a precision RF oscillator. The mixer whose RF input comes directly from the oscillator receives the *in-phase* (I) base-band signal, whereas the *in-quadrature* (Q) signal is mixed with an RF input that is phase-shifted by 90 degrees.

The resulting RF generator output is the recombination the two mixer outputs, as shown in Fig. 3.1. Auxiliary outputs allow to display the I and Q signals on an oscilloscope screen.

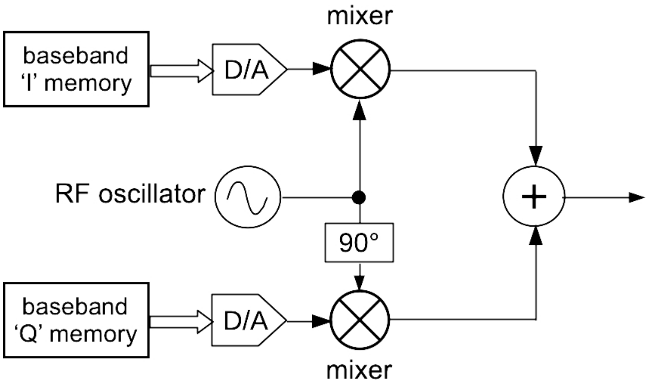


Figure 3.1: Basic functional diagram of a RF signal generator.

Figure 3.2: Front panel of the Agilent Technologies E4432B Signal Generator.

The arbitrary waveform generation feature allows the creation of a variety of signals. In particular, most of the signals associated with the digital modulation formats employed in wireless communications can be generated according to the closely-specified descriptions provided by communication standards.

The Agilent Technologies E4432B signal generator provides a choice of predefined, internally generated signals for a number of wireless standards, as well as the possibility to select from a wide range of modulation formats, change the settings of modulation filters, etc.. Importantly, software generation of signals allows to also introduce signal **impairments** in a controlled way. In this context, therefore, arbitrary waveform generation supports the extensive test of wireless communication devices, in particular of receivers, up to their expected performance limits.

The front panel of the generator employed in the laboratory is presented in Fig. 3.2. The two most prominent keys allow the setting of:

- **Frequency** – that is, the RF **carrier** frequency. This means the output signal spectrum will be **centered at** the frequency set by this control. Carrier frequencies for the signals of interest listed below would range from about 900 MHz to the 2.4-2.5 GHz ISM band although, in practice, any value could be set on the generator. Signal bandwidth, of course, depends on the shape of the modulating I-Q signals;

- **Amplitude** – this is actually the output **power level**, given in dBm.

Numerical values can be entered through the keypad on the front panel.

IMPORTANT WARNING

Never exceed **-30 dBm** for the generator Amplitude.

NOTE – Remember that a **RF On/Off** key is located on the front panel, close to the N-type output RF connector. To prevent damage to the spectrum analyzer or to any other device connected to the generator, it is advisable to set the RF output to **Off before** any change of setting is made on the generator.

The **Mode** key on the front panel recalls the main menu for the choice of digital modulation formats. Main menu items are associated to soft keys at the side of the display, in particular:

- **Bluetooth** – allows to configure a Bluetooth RF signal, which employs frequency modulation (FM). As the frequency-hopping feature is not enabled on the generator, the carrier frequency remains constant;

- **Other formats** – provides a choice of different modulation formats employed in a number of telecommunication standards like GSM, NADC, EDGE, TETRA, etc. For this exercise, the following will be considered:
  - **GSM** – this is the well-known second-generation European and world standard. Gaussian minimum shift key (GMSK) modulation is employed, resulting in a channel bandwidth of about 300 kHz and constant signal power level;
  - **EDGE** – Enhanced Data rates for GSM Evolution was a GSM development providing higher data transmission bit rates through a different modulation scheme;

3.3 Signal Analyzer

The measuring instrument employed for this activity is an Agilent Technologies N9010A EXA Signal Analyzer with a 9 kHz to 3.6 GHz input frequency range. It is fitted with a vector signal analysis software tool suite (currently marketed as Keysight PathWave 89600 VSA) that processes the sampled I-Q outputs of the spectrum analyzer digital IF stage, providing additional functions for modulation domain, frequency and time analysis of digitally modulated signals.

The main spectrum analyzer set-up options are usually grouped under three main multiple-choice functions:

- a *frequency* (**FREQ**) key, that provides access to *centre* frequency, *start* frequency and *stop* frequency settings;

- a **SPAN** key, that provides access to various settings, including determination of the span width (for a **given** centre frequency), selection of the *zero span* mode, etc.;

Figure 3.3: Front panel of the Agilent Technologies N9010A Signal Analyzer.

- an *amplitude* (**AMPTD**) key, which allows to configure the vertical scale factor and reference level, the input attenuator setting, etc. – **Note**: manual setting of the input attenuator is **for experienced users only** – **DO NOT** modify the attenuation setting.

Further to this, several other front panel keys provide access to more specific set-up menus. When parameters are involved:

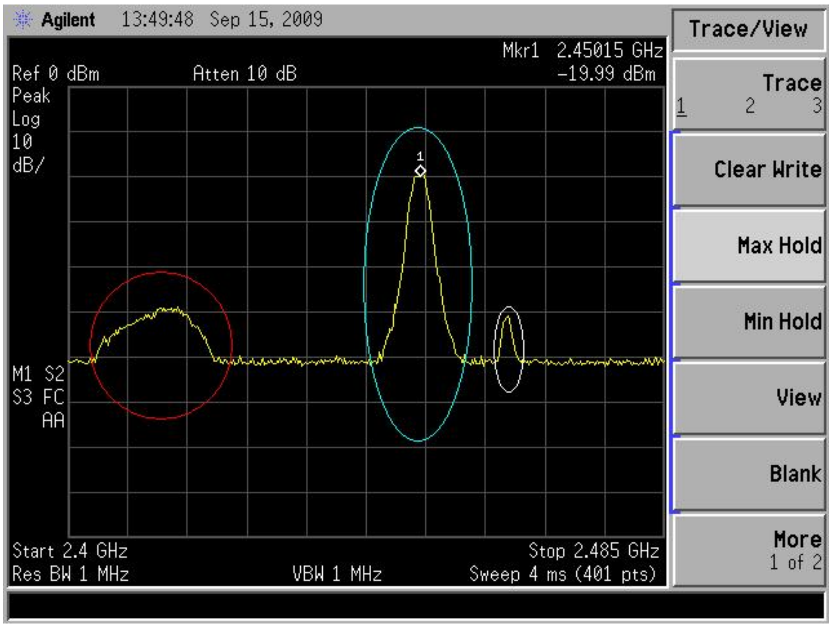
- a **knob** allows to vary the numerical value of parameters from any instrument set-up menu;
- a **keypad** with numerical keys allows direct input of parameter values, as well as ($\Uparrow$) and ($\Downarrow$), keys enabling stepwise parameter variation according to an instrument-defined sequence.

WARNING
The instrument **Preset** deletes any previous instrument setting. After the *preset* routine is completed, the input attenuator is set to a safe value and the spectrum analyzer is configured for **full span** analysis. Thus, any particular choice of *frequency* and *span* setting (as required, for instance, when a specific signal source is monitored), is **lost**.

Mode selection

The **Mode** front panel key allows the selection of different instrument operating modes, from spectrum analyzer, to basic I-Q analyzer, up to full-function VSA. Operating modes for this activity are:

- **Spectrum analyzer** – this mode is employed for preliminary selection of the signal of interest. In general, this would mean picking out one from a group of signals in a certain frequency interval (Fig. 3.4). Although in this exercise the signal carrier frequency is known, being indicated on the signal generator, it is advisable to measure it as the peak position of the spectrum analyzer cursor. This measured value will have to be entered into the VSA application software to correctly analyze modulation features.



Agilent 13:49:48 Sep 15, 2009

Mkr1 2.45015 GHz
-19.99 dBm

Ref 0 dBm Atten 10 dB

Peak
Log
10
dB/

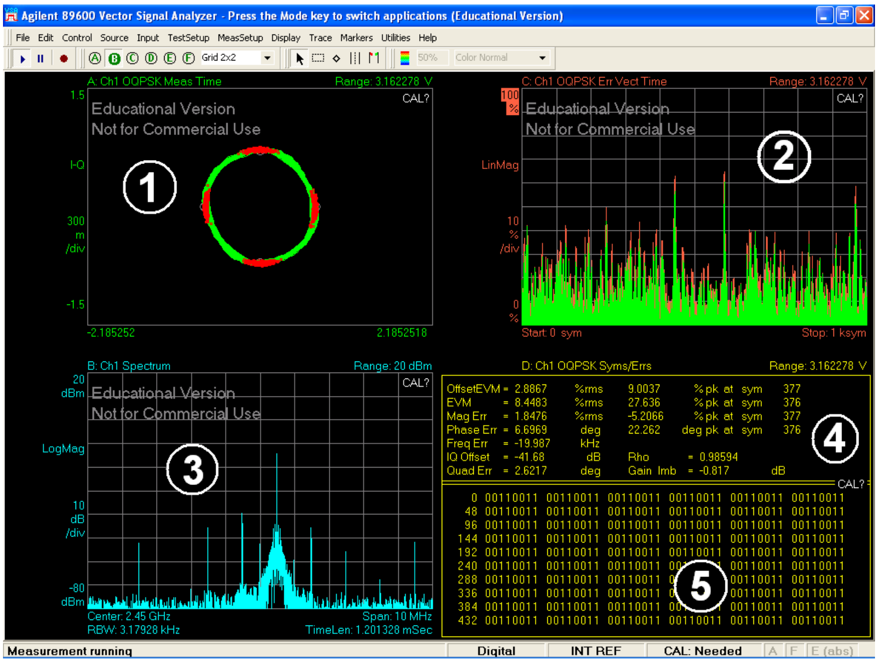
M1 S2
S3 FC
AA

Start 2.4 GHz Stop 2.485 GHz
Res BW 1 MHz VBW 1 MHz Sweep 4 ms (401 pts)

Figure 3.4: Locating the frequency band of interest. The cursor reading is reported on the top right corner of the display.

- **89600 VSA** – this mode is employed for modulation domain analysis of the signal of interest. For this form of analysis it is common to employ a multi-trace display, like the 2 × 2 array shown in Fig. 3.5. The VSA **MeasSetup** menu allows to activate and configure a demodulator (**MeasSetup** → **Demodulator** → **Digital Demodulator**).

  For simplicity the predefined configuration for the modulation format of interest can be recalled directly by following the menu path: **MeasSetup** → **Demodulator** → **Digital Demodulator** → **Demodulator Properties** → **Preset to Standard**. A broad choice of telecommunication standards is provided and further variations can be introduced by specific settings.



```
OffsetEVM =  2.8867     %rms     9.0037       % pk  at  sym    377
EVM       =  8.4483     %rms     27.636       % pk  at  sym    376
Mag Err   =  1.8476     %rms     -5.2066      % pk  at  sym    377
Phase Err =  6.6969      deg     22.262     deg pk  at  sym    376
Freq Err  =  -19.987     kHz
IQ Offset =  -41.68       dB     Rho        =  0.98594
Quad Err  =  2.6217      deg     Gain  Imb  =  -0.817        dB

  0  00110011  00110011  00110011  00110011  00110011  00110011
 48  00110011  00110011  00110011  00110011  00110011  00110011
 96  00110011  00110011  00110011  00110011  00110011  00110011
144  00110011  00110011  00110011  00110011  00110011  00110011
192  00110011  00110011  00110011  00110011  00110011  00110011
240  00110011  00110011  00110011  00      1  00110011  00110011
288  00110011  00110011  00110011  0          00110011  00110011
336  00110011  00110011  00110011  0          00110011  00110011
384  00110011  00110011  00110011  00      1  00110011  00110011
432  00110011  00110011  00110011  00110011  00110011  00110011
```

Figure 3.5: Four-screen VSA presentation showing: vector diagram (top left); error vector versus time (top right); spectrum (bottom left); decoded binary values (bottom right).

Chapter 4

Time and frequency measurements with a universal counter

Instruments

- Hewlett-Packard 5316B Universal Counter;
- Hewlett-Packard HP 54654 demonstration board;
- Arbitrary Waveform Generator;
- Oscilloscope;
- Multimeter.

4.1 Introduction

In this exercise, a *universal counter* is used to determine the duration, period, or frequency of various signals generated by means of an Arbitrary Waveform Generator and provided by a Hewlett-Packard HP 54654 demonstration board. To correctly set up the measurement, a preliminary evaluation of the characteristics of the instrument, as well as of the signals through the oscilloscope may be necessary.

Knowing some information about the measurement setup and the measured signals will also be necessary for the subsequent evaluation of the uncertainty associated with the measurements provided by the *counter*.

4.2 Hewlett-Packard 5316B Universal Counter

The Hewlett-Packard 5316B *counter* has two input channels (labeled 'A' and 'B') with a bandwidth of 100 MHz, whose input impedance is formed by the parallel of a 1 MΩ resistor and a capacitance of about 50 pF. The corresponding settings concern the coupling mode (AC or DC, with AC coupling as the default configuration) and the possibility of inserting an attenuator (through **ATTN** button) to reduce the amplitude of the input signal by a factor of 20.

The two channels send signals to two trigger circuits, of which it is possible to adjust the threshold level or the sensitivity. A selector allows to choose whether to vary the trigger threshold level or the width of its hysteresis band, keeping the threshold fixed at 0 V. In addition to this, another selector allows to choose the reference slope (***slope***). Finally, it is possible to dedicate both trigger circuits to channel 'A' only ('COM A' button on the instrument panel) while keeping their respective adjustments independent, so as to be able to identify different points of the same signal (for example, a rising edge and a falling edge).

The duration of the *gate time* used for the measurements is also adjustable and the measurement functions of the *counter* are selected using a series of keys.

The detailed specifications of the instrument are found in the Appendix.

4.3 HP 54654 demonstration board

Test Point	Description
1	Square wave, fundamental frequency $\sim$ 500 kHz, $\sim$ 3.7 V peak-to-peak amplitude.
2	Square wave equal to the previous one, delayed by a fraction of a period.
3	Impulse train with a repetition period of approximately 28.6 μs and 3.7 V peak-to-peak amplitude.
5	Periodic impulse with del 6.6 % duty cycle, 28.2 ms duty cycle, 3.7 V peak-to-peak amplitude.
6	Periodic impulse of 325 ns duration, 6.4 ms period.
8	Triangular wave, 1.2 V peak-to-peak amplitude, average value $\neq 0$, $\sim$ 1.6 s period.
11	Sine wave with noise, 1.1 kHz frequency, 1.4 V peak-to-peak amplitude.
13	Sinusoid similar to the previous one; it is possible to vary the phase shift with respect to this one by acting on the potentiometer placed near the measurement point.
14	Amplitude modulated signal; frequency of the carrier $\sim$260 kHz, frequency of the modulating signal: $\sim$1.1 kHz.

The circuits on the HP 54654 board provide 14 different types of signal, accessible through measurement points located on the side of the board itself. Next to each point is a graphical illustration of the relative signal trend. There are also two points for connection to the ground. The board is powered by a 9 V battery. Correct power supply is indicated by the lighting of a red LED.

A button located near the battery holder allows to activate or deactivate the power supply.

The features of the signals used in this exercise are briefly summarized in the table above.

NOTE: an attenuating probe reduces the amplitude of the acquired signal by a factor of 10. It is possible to compensate for this effect by setting an appropriate ***probe factor***, which varies the indication of the vertical scale factor: the relative command is part of the group of commands relating to the vertical channels (CHANNEL). Some instruments automatically recognize the presence of a probe and modify the scale factor accordingly, without the intervention of the operator.

4.4 Measurements on the AWG-generated signals

The first measurements will focus on signals generated by means of an Arbitrary Waveform Generator (AWG). These measurements will focus on investigating the features of the *counter*, comparing the measured values with the ones achievable with other instruments.

For the first measurements, a sine wave will be generated by means of the AWG. Starting from a sine wave of known frequency the following aspects have to be investigated on the *counter*:

- Measure the frequency investigating the effect of the *gate time* on the resolution by changing its duration, from low too high values. The *gate time* can be varied using the corresponding knob;

- Check the minimum and maximum value of the *gate time*: this can be visualized by clicking on the Blue button, which activates the secondary functions of the other buttons, and then choosing the *gate time* measurement by clicking on the corresponding button;

- Analyze the variations of the resolution for different frequency values (remembering the bandwidth of the instrument, choose frequency values of different orders of magnitude);

- Analyze the impact of the trigger level (which can be varied using the knob of the corresponding channel) on the counting by varying the amplitude of the signal (remember that you can visualize the value of the trigger level, which is provided as an output at the **Trigger out** connector, by means of an oscilloscope). When triggering occurs, the LED close to the knob starts blinking anytime that triggering occurs;

- Identify the maximum and minimum value of the sensitivity by varying the amplitude of the generated sine wave. To this, you have to select the **Sensitivity** function by clicking on the button close to the knob. Now, by rotating the knob you can vary the width of the hysteresis bandwidth. Remember that, when the peak-to-peak amplitude value of the generated signal is lower than the hysteresis bandwidth, counting does not occur anymore. Note that, by rotating the knob to the maximum value you are setting the lowest sensitivity, while when rotating it to to the minimum value you are setting the maximum sensitivity.

The following measurements have the main purpose of comparing the resolution of the *counter* with the one achievable with the other instruments. Starting from the multimeter, compare its bandwidth with the one of the *counter*, identifying the maximum measurable frequency with the multimeter. To do this, you should connect the AWG in parallel to the multimeter and to the counter. Then, by increasingly varying the frequency of the generated signal, you should identify the maximum value for which the multimeter can provide an accurate frequency measurement. Note that this may also depend on the signal amplitude.

4.5 Measurements on the HP 54654 demonstration board

4.5.1 Frequency and period measurements

These measurements exploit one input of the *counter*. You can check how the instrument settings and some characteristics of the signal influence the accuracy of the result: in particular, the duration of the *gate time* and the *trigger* setup. Hint: connect in parallel the board to the counter and to the oscilloscope so that you can have a visual feedback of the signal which is generated by the board.

- ***Measurement point 1***: determine the signal frequency and evaluate the uncertainty with two different gate time values ($<$ 100 ms and $>$ 5 s).
- ***Measurement point 8***: measure the signal period;
- ***Measurement point 13***: measure the signal period;
- ***Measurement point 11***: measure the signal period and compare it with the value measured at point 13. Evaluate the effect of inserting the filter at 100 kHz and varying the gate time duration.

"Tricky" signals

- ***Measurement point 3***: try to measure the signal period: is it possible?
- ***Measurement point 14***: try to measure the signal period: is it possible?

4.5.2 Time interval measurements

Appendix - HP5316B Universal Counter technical specifications

Frequency (channel A)

Range:

0.1 Hz to 100 MHz

LSD Displayed:
10 Hz to 1 nHz depending upon gate time and input signal. At least 7 digits diplayed per second of gate time.

Resolution:
for $FREQ < 10$ MHz: $\pm LSD \pm 1.4 * (trigger\ error)/(gate\ time) * FREQ$
for $FREQ \geq 10$ MHz: $\pm LSD$

Accuracy:
$\pm Resolution \pm (time\ base\ error) * FREQ$

Period

Range:
10 ns to 10^5 s.

LSD Displayed:
100 ns to 1 fs depending upon gate time and input signal. At least 7 digits displayed per second of gate time.

Resolution:
for $PER > 100$ ns: $\pm LSD \pm 1.4 * (trigger\ error)/(gate\ time) * PER$
for $PER \leq 100$ ns: $\pm LSD$

Accuracy:
$\pm Resolution \pm (time\ base\ error) * PER$

Time Base

Frequency	10 MHz
Aging Rate	$< 3 \times 10^{-7}$ / month
Temperature	$< 5 \times 10^{-6}$, 0 to 50 ^{o}C
Line Voltage	$< 1 \times 10^{-7}$ for ±10% variation
Oscillator Output	10 MHz, 50 mV p-p into 50 Ω
External Frequency Standard Input	1, 5, 10 MHz, 1 V rms into 500 Ω, or rear panel; 6 V rms maximum

Least significant Digit (LSD) displayed

:

Frequency:	$(2.5 \times 10^{-7}/gate\ time) * FREQ$,	for $FREQ < 10$ MHz
	$2.5/gate\ time$,	for $FREQ \geq 10$ MHz
Period:	$(2.5 \times 10^{-7}/gate\ time) * PER$,	for $PER < 100$ ns
	$(2.5 \times 10^{-7}/gate\ time) * PER^2$,	for $PER \geq 100$ ns

Trigger error

:

$$\frac{\sqrt{(120 \cdot 10^{-6})^2 + e_n^2}}{\text{input slew rate in V/s at trigger point}}, \text{ seconds rms} \tag{4.1}$$

Typical, where e_n^2 is the rms noise voltage of the input for 100 MHz bandwidth.

All the above calculations should be rounded to nearest decade (i.e. 5 Hz will become 10 Hz and .4 ns will become .1 ns)