Using the Spectrum Analyzer as an Educational Tool for Mobile Communications

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Abstract— **Application of the spectrum analyzer for illustrating several concepts associated with mobile communications is discussed. Specifically, two groups of observable features are described. First, time variation and frequency selectivity of multipath propagation can be revealed by carrying out simple measurements on commercial-network GSM and UMTS signals. Second, the main time-domain and frequency-domain features of GSM and UMTS radio signals can be observed. This constitutes a valuable tool for teaching mobile communication courses.**

I. Introduction, setting and required equipment

Mobile communication courses require the students to grasp certain concepts that are abstract and often difficult to visualize. It is thus desirable for the teacher to provide a means to illustrate those concepts in a more concrete way. In this paper, use of the spectrum analyzer is described to achieve these goals in two specific areas:

- Illustration of multipath propagation effects; and
- Observation of the time and frequency structure of actual signals.

The spectrum analyzer is a relatively affordable instrument which is usually available for radio communication courses. Although normally employed for representing frequency spectra, it can also be utilized for time-domain observations.

There are two ways in which the spectrum analyzer can be used for the intended purposes:

- Practical laboratory work done by the students under supervision; or
- Classroom demonstrations carried out by the teacher.

The former has the advantage of greater student involvement as and more direct contact with the measurements. Classroom demonstrations, on the other hand, give the teacher more control; in this case student involvement can be achieved, to a certain extent, by means of questions and discussions guided by the teacher. Both options have been successfully applied by the author in mobile communication courses within Telecommunication Engineering degrees, at Universidad Autónoma de Madrid (2005–2009) and at Universidad Politécnica de Madrid (2010 to present date).

The following equipment is used for the measurements:

- Spectrum analyzer with frequency range up to 2.5 GHz; resolution frequency down to a few kHz; possibility to set zero frequency span; sweep time down to at least 5 ms, preferably 1 ms; trace averaging capability. Basic models usually fulfill these requirements amply.

If classroom demonstrations are to be done, the analyzer should allow connecting to a laptop computer for projecting the measurements on the classroom screen; and should preferably be of the portable type.

- Antenna: it can be easily built by attaching a rigid wire to the inner conductor at one end of a coaxial cable.
- Laptop computer with appropriate software for connecting with the instrument, in the case of classroom demonstrations.

Sections II and III respectively describe the two kinds of measurements referred to at the outset.

II. Propagation effects on GSM and UMTS signals

A salient feature of propagation in mobile communications is the existence of multiple paths. This phenomenon gives rise to time-varying and frequency-selective *fading*, i.e. time and frequency variations in the received signal power [1]. These two types of variations can be easily observed with a spectrum analyzer. They are dealt with separately in the following.

A. Time variations

The time variation of a channel is characterized by its *coherence time*. This is defined as the minimum time separation necessary to observe a significant change in the channel response, and corresponds to a displacement of a fraction of the wavelength, λ, by the mobile; typically $\lambda/2$ is considered as a reference.

The standard way to measure time variations in attenuation would be to transmit a sinusoidal wave and observe the received power. For greater realism, and to avoid use of a signal generator, signals transmitted from actual networks can be used. The two main candidate systems are currently GSM and UMTS[1]. The former is preferred for this measurement because of its small bandwidth, on the order of 200 kHz, which is lower than the coherence bandwidth of most propagation channels. A UMTS signal, with its 4-MHz bandwitdh, could easily experience frequency-selective fading. The consequent frequency diversity would result in smaller variations of the total received power.

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[1] All physical-layer features and propagation aspects of GSM signals to be observed apply also to the GSM-evolved technologies known as GPRS and EDGE. Similarly, the discussion of UMTS signals is equally applicable to HSDPA and HSUPA. Thus, throughout the paper, the terms "GSM" and "UMTS" should be interpreted in this broader sense, that is, as "GPRS/GPRS/EDGE" and "UMTS/HSDPA/HSUPA" respectively.

A requirement on the transmitted signal is that it should have constant power, so that the received power accurately reflects variations in channel attenuation. This is easily accomplished by using a GSM *beacon* carrier[2]. These are special carriers that are transmitted with fixed power (further details are given in Section III-B).

In order to observe time variations in received signal power, the analyzer frequency span needs to be set to zero. This way, the horizontal axis in the graph directly represents time, instead of frequency. Using a sweep time of several seconds, time variations can easily be observed as the receiving antenna is moved around. It is best to use single-sweep mode, so that the trace remains on screen after the measurement.

Resolution bandwidth can be set to a value slightly larger than the GSM signal bandwidth, such as 300 kHz. Alternatively, a lower value can be applied to slightly reduce the perceived noise in the representation. The reason for this is that the signal's power spectral density is highest at the center frequency. If a spot with good GSM coverage can be selected, a 300-kHz bandwidth is recommended, as in this case the vertical axis has the straightforward interpretation of total received power of the GSM signal.

The burst nature of the GSM signal needs to be taken into account when selecting video bandwidth. Specifically, the signal is organized into 0.547-ms bursts separated by 30.5-μs guard intervals [2] (see Section III-B). Since the received power suddenly drops during guard intervals, whose duration is much smaller than the sweep time, the received power displayed on the screen takes the form of a band, reflecting the fast variations associated with the alternating bursts and guard intervals. The video bandwidth should be sufficiently small to remove this effect. However, too small a value would affect the power variations caused by fading, and thus must be avoided. A value of 100 Hz has been found to be adequate.

Several beacon carriers will typically be received at the measurement spot. Ideally the strongest one should be selected, so that the margin of powers that can be measured (which is limited by the noise power at the used resolution bandwidth) be as large as possible. The selection can be done by a quick analysis of the desired frequency band. Section III-B discusses how to distinguish beacon from non-beacon carriers.

Figure 1 shows the variations in received power from a beacon carrier in the 900-MHz band, in an indoor environment. During each measurement, which consists of a single sweep of 3 s, the antenna is moved at an approximate speed of 1 m/s. The familiar multipath fading pattern is observed, with steep minima and milder maxima (this is actually an artifact of the logarithmic scale), and with variations of 20–30 dB.

It can be checked that a significant variation in signal power corresponds to a displacement on the order of $\lambda/2$. In this case λ is approximately 0.3 m, represented by one horizontal division. Figure 2 is similar except that a beacon carrier in the 1800-MHz band is used, which gives twice as fast variations.

[2]The usual convention is followed in this paper, whereby a GSM signal transmitted on a given frequency is called a "carrier", even though it is a modulated signal and thus not strictly a carrier.
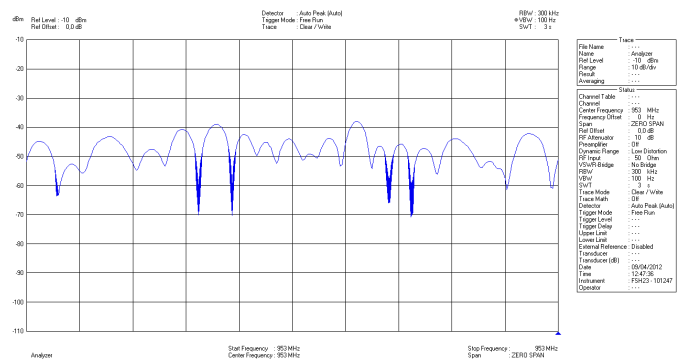

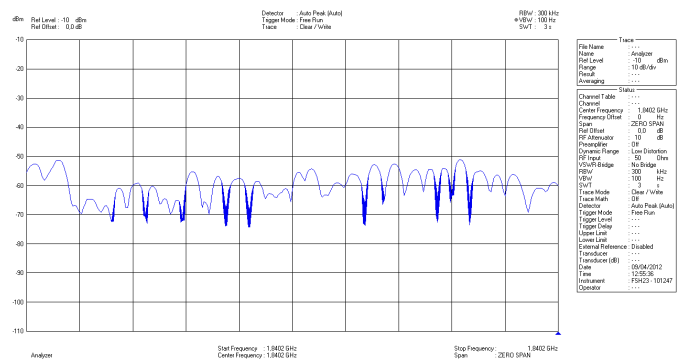Fig. 1.   Time-varying fading, GSM beacon carrier, 900-MHz band

Fig. 2.   Time-varying fading, GSM beacon carrier, 1800-MHz band

B. Frequency selectivity

Frequency selectivity of a channel is measured by its *coherence bandwidth*, defined as the minimum separation of two frequencies that experience significantly different attenuations. In order to observe frequency-selective fading, a wideband signal is required, with a bandwidth comparable or greater than the coherence bandwidth of the channel.

a) GSM signal: GSM signals very rarely experience frequency-selective fading, because coherence bandwidths are usually much larger than 200 kHz. This can be illustrated by placing the antenna at various positions, and observing how the spectrum on the screen moves up and down coherently, i.e. all frequency components experience the same fading, and no distortion occurs.

In order to obtain a cleaner representation, trace averaging can be applied in the analyzer. In this case, however, the fading variations as the antenna is moved cannot be observed as easily, because it takes several seconds for the representation to settle after the antenna position has been changed.

Figure 3 shows an example measurement with trace averaging. The GSM signal spectrum is undistorted, as corresponds to flat fading.

b) UMTS signal: The situation is different with UMTS signals, whose 4-MHz bandwidth is usually enough to make frequency selectivity apparent. Due to larger signal bandwidth and lower power spectral density values, trace averaging is indispensable in this case.
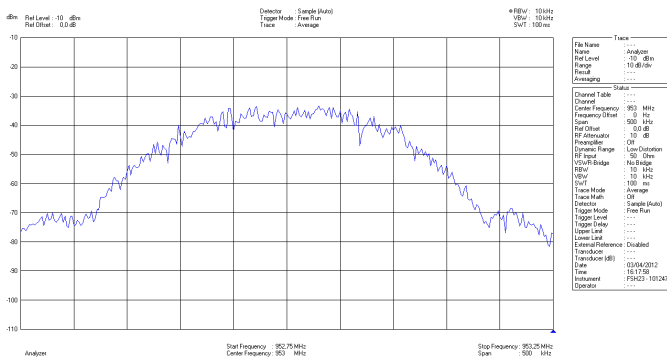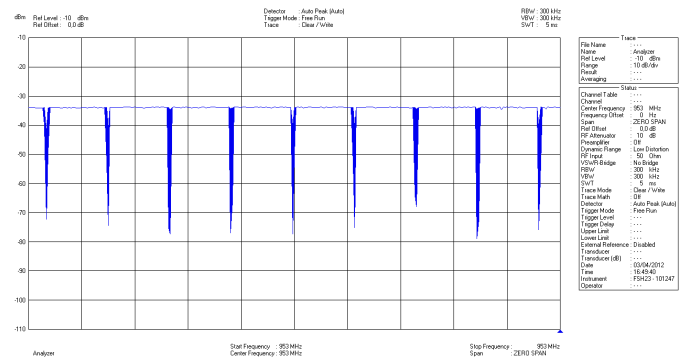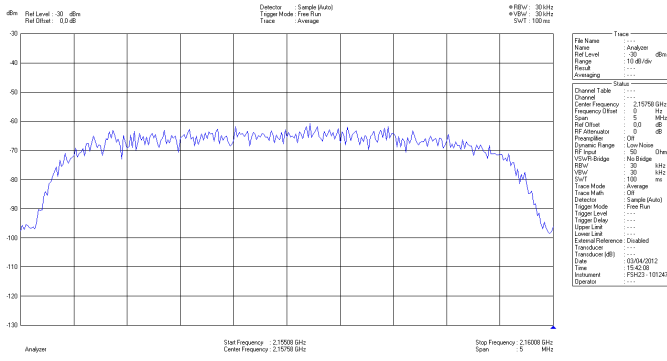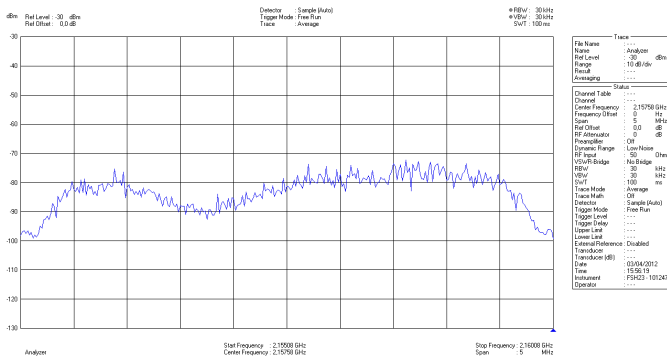
Fig. 3. Frequency-flat fading, GSM signal

(a) No observed frequency-selective fading

(b) Frequency-selective fading clearly visible

Fig. 4. Frequency-selective fading, UMTS signal

Testing several antenna locations, it is easy to find some where the signal spectrum is approximately flat, while at others frequency-selective fading is clearly noticeable. Figure 4(a) is an example of the former, while Figure 4(b) illustrates the latter, showing (linear) distortion on the spectrum. The measurement also provides a rough approximation of the coherence bandwidth of the channel.

III. TIME-DOMAIN AND FREQUENCY-DOMAIN CHARACTERISTICS OF GSM AND UMTS SIGNALS

As is well known, GSM is a FDMA/TDMA system, whereas UMTS is a FDMA/DS-CDMA system [1]. The spectrum analyzer can be used to observe time-domain and frequency-domain, but not code-domain, characteristics of sig-

Fig. 5. Frame in a GSM beacon carrier

nals. Consequently, both types of features can be observed in GSM signals, whereas only frequency aspects can be revealed in UMTS signals. In the following, frequency aspects of both types of signals are dealt with first, and then the time structure of GSM signals is discussed.

A. Frequency-domain features of GSM and UMTS signals

Observation of the spectra of these signals is rather straightforward. Examples can be seen in Figures 3 and 4(a) above. In addition, specific parameters can be measured such as total received signal power, adjacent channel power ratio, or occupied bandwidth for a given percentage of signal power.

B. Time-domain features of GSM signals

GSM signals are organized into *frames* of period $T_f = 4.615$ ms, each consisting of 8 *time-slots*. A time-slot is occupied with a *burst* that lasts $T_b = 0.547$ ms followed by a *guard interval* of $T_g = 30.5$ μs [2]. GSM carriers can be classified into beacon or non-beacon. In a beacon carrier, time-slots without traffic are filled with "dummy" bursts, so that some transmitted signal is always present; and transmitted power is constant, i.e. no power control is permitted. These two features allow the mobiles to use beacon carriers for attenuation measurements (this is the reason why beacon carriers were used in Section II-A).

a) Time-slot and frame structure: The frame structure of GSM signals can be revealed using a similar approach as that used in Section II-A; that is, setting zero frequency span, resolution bandwidth of 300 kHz and single-sweep mode, in order to inspect the instantaneous power variations of the signal. The video bandwidth is not critical, and can be left equal to the resolution bandwidth. Using a sweep time on the order of T_f, frames and slots can be identified in the signal. Figure 5 shows an example graph for a beacon carrier. A lower sweep time allows a closer examination of bursts and guard intervals, as shown by Figure 6. Their duration can be approximately measured from the graph.

Repeating the procedure with a non-beacon carrier gives the result in Figure 7. The distinctive non-beacon features can be seen: some time-slots are empty (owing to absence of traffic); and power levels may be different (owing to power control). This may be used to raise some issues with the students and
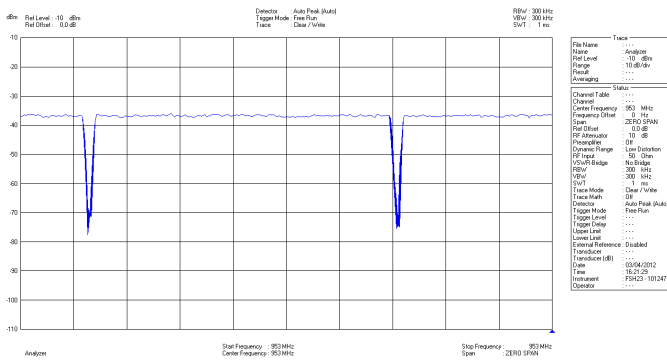
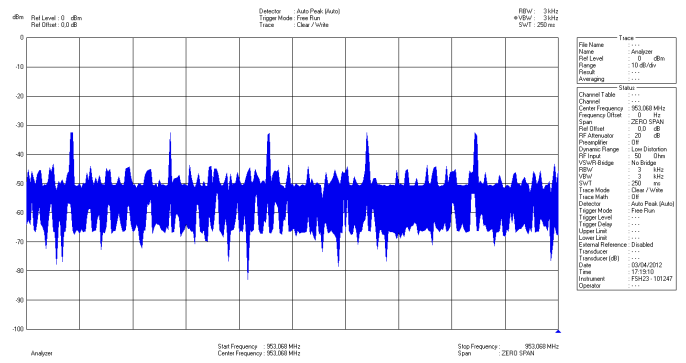Fig. 6. Time-slots in a GSM beacon carrier

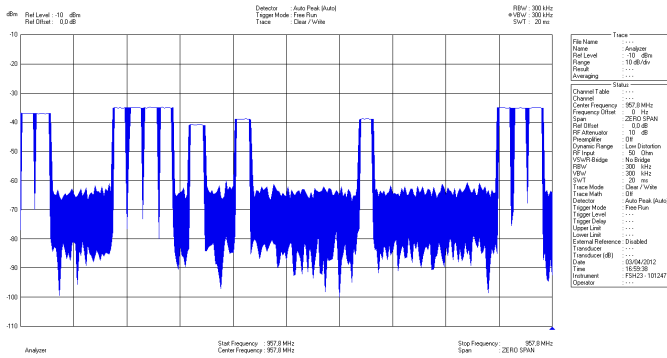Fig. 8. FCCH multiframe structure (GSM beacon carrier)

Fig. 7. Frames in a GSM non-beacon carrier

motivate discussion. For example, it may be asked why the empty time-slots are not the same in consecutive frames.

It should be added that even in a frequency-domain view of all signals present in a GSM band, beacon and non-beacon carriers can be distinguished. Non-beacon carriers tend to flicker, that is, they appear or disappear according to whether a burst is present when its spectral position is swept by the analyzer or not. Beacon carriers are stable, and usually have higher power, due to the absence of power control.

b) FCCH channel structure: GSM base stations transmit a special channel known as FCCH (frequency-correction channel), which consists of sinusoidal bursts of a fixed frequency, and is used by the mobiles as a frequency and time reference. The FCCH is present on the first time-slot of certain frames of each beacon carrier (this is another distinctive feature of beacon carriers). As happens with every channel in GSM, the FCCH shares its time-slot with other channels by time-multiplexing, following a *multiframe* structure. For this channel, the applicable multiframes (there are two different versions) have a period of 51 frames, numbered from 0 to 50; and FCCH occurs in frames 0, 10, 20, 30 and 40 [2]. This gives a time separation of 10 or 11 frames between consecutive FCCH bursts, depending on their location within the multiframe.

The FCCH bursts have all their bits equal to 0. With the differential binary GMSK modulation used in GSM, this results in a sinusoidal burst with frequency value $f_0 + R/4$, where f_0 is the carrier frequency and $R = 270.833$ kb/s is

the bit rate. This simple structure permits the mobile to easily detect this channel (in fact, it is the first channel that a GSM mobile should detect). Likewise, it allows for its observation on a spectrum analyzer. The approach is as follows. Since the FCCH consists of bursts of frequency $R/4 = 67.7$ kHz above the carrier frequency, and is the only channel with that feature, its appearances can be detected using zero frequency span, single sweep, and a filter with very low resolution bandwidth centered at the indicated frequency. Each FCCH burst will produce a higher output level than any other channel's bursts. A sweep time slightly larger than $51T_{\rm f} = 235.4$ ms should be used, so that five consecutive FCCH bursts can be detected.

Figure 8 shows an example graph with a resolution bandwidth of 3 kHz (this is the minimum value allowed by the spectrum analyzer used). The highest peaks in the trace correspond to FCCH bursts. It can be seen that the first four bursts have a time separation of approximately $10T_{\rm f} = 46.2$ ms, whereas the separation between the fourth and the fifth is approximately equal to $11T_{\rm f} = 50.8$ ms (a horizontal division corresponds to 25 ms).

IV. CONCLUSION

Use of the spectrum analyzer has been discussed for illustrating time-domain and frequency-domain aspects of multipath propagation and of the structure of radio signals in current mobile communication systems.

APPENDIX: EXAMPLE OF LABORATORY HANDOUT

An example laboratory handout (in Spanish) along the lines described in this paper is available at `http://oa.upm.es`.

REFERENCES

[1] J. M. Hernando, *Comunicaciones Móviles*, 2nd ed.   Centro de Estudios Ramón Areces, 2004.

[2] M. Mouly and M.-B. Pautet, *The GSM System for Mobile Communications*.   Published by the authors, 1992.