Orthogonal Frequency Division Multiplexing

In last quarter's technical report, I mentioned that the next subject would be OFDM, or orthogonal frequency division multiplexing; so let's take on that subject. As in the 2nd quarter report investigating 8-VSB, my intent is to address this subject both in theory and by way of actual measurements. As you'll see, in many ways OFDM is a difficult concept to 'get ones arms around', but if we keep our traditional FDM methods in mind it will help. OFDM, as compared to 8-VSB, is perhaps more difficult to understand (at least for the author) -- in both theory and measurement.

Introduction.

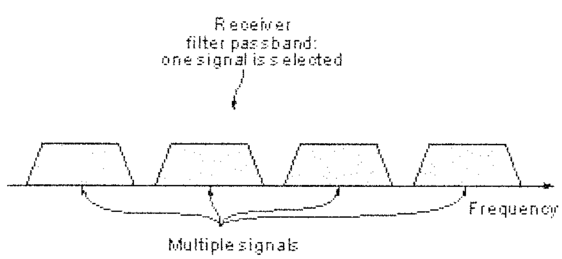
At the onset, it's important to understand that OFDM is a 'spectral management method' and not a type of *modulation*. An RF cable engineer who has been involved in the cable industry for any length of time understands that the HFC plant carries multiple signals *simultaneously* on a single coaxial cable (or fiber strand) using a technique known as frequency division multiplexing, or FDM. Let's briefly examine that concept before moving on to OFDM.

FDM

In FDM, each system carrier is assigned a separate specific frequency and amount of spectrum (bandwidth). At some point, typically in the headend; all of the separate carriers, subcarriers, etc. are combined onto a single coaxial cable before driving the input of a linear laser or coaxial amplifier. The combining (or separating) of these separate carriers requires a rather complex arrangement of passives and filters that we've come to commonly call a 'combining network'.

The frequency of most (but not all) carriers is typically mathematically related. For example, if one begins at channel 23, the frequency of the luminance carrier is 217.25 MHz, and each successively higher channel is normally (but not always) exactly 6 MHz higher in frequency. Aeronautical offset requirements may displace these frequencies by +12.5 or +25 KHz, but a basic 6 MHz incremental relationship exists for most carriers. And most 'channels', whether NTSC analog or QAM, occupy 6 MHz of bandwidth or RF spectrum in a US cable system. Other countries may have differing spectral allocations. Europe, for example, and as shown in a later diagram employs a bandwidth of 8 MHz per channel. FDM spectral *efficiency* is not nearly as good as desired, as the FDM method requires small amounts of open spectrum known as guard bands to ensure that carriers don't interfere with each other. And the NTSC format (within the allotted 6 MHz) makes poor use of spectrum from a power efficiency perspective.

The use of FDM also requires that any subsequent amplification be very linear, since if it is not, intermodulation products will be produced that typically land within spectrum being used, thus degrading the overall performance of those channels and information throughput.



Typical FDM Channel Spacing

OFDM

OFDM is a broadband multicarrier modulation method that offers superior performance and benefits over older, more traditional single-carrier modulation methods, and it is a better fit with today's high-speed data requirements and operation in the UHF and microwave spectrum. It was developed, at least conceptually, in the 1960s and 1970s. Originally known as multicarrier modulation, OFDM was extremely difficult to implement with the electronic hardware of that time, so it remained a research curiosity until semiconductor and computer technology finally made for practical implementation.

As stated earlier, the FDM technique is somewhat wasteful of spectrum, because to keep the modulated carriers from interfering with one another, you have to space them with guard bands (unused space between carriers). Even then, very selective filters at the receiving end often have to be employed to separate signals. What researchers discovered is that with *digital transmissions*, the carriers can be more closely spaced to one another and still remain separate, and that means less waste of valuable spectrum.

In OFDM, the serial digital data stream to be transmitted is split into *multiple slower* data streams, with each modulated onto a separate *subcarrier* in the allotted spectrum. The modulation (of each subcarrier) can be any form of modulation used with digital data, but the most common at present are binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and quadrature amplitude modulation (QAM). In the case of QAM, the QAM complexity can be whatever the communications system and PHY layer (cable, wireless, etc.) will allow i.e., 16-QAM, 32-QAM, and even 64-QAM. The outputs of all the subcarrier modulators are linearly summed (using a technique described later in this report), with the resultant combined signal then transmitted. This 'summed signal' can also be up-converted or amplified as needed. The following are basic illustrations.

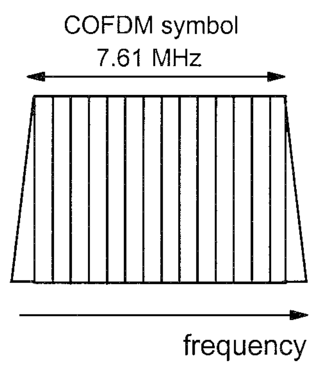
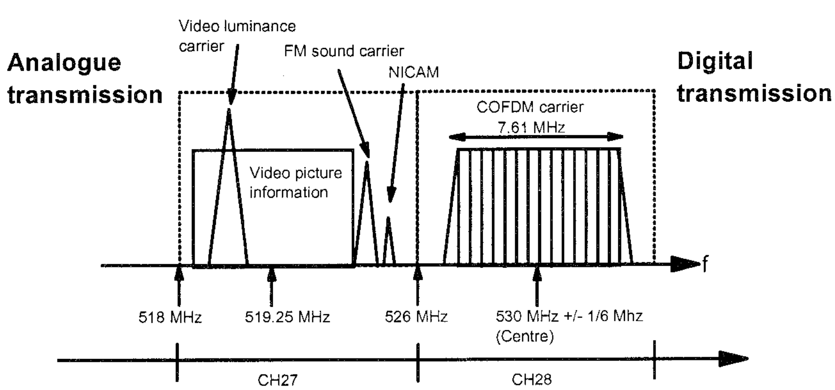


Illustration of a DVB-T COFDM signal of 8 MHz Bandwidth - Composite Signal with Subcarriers



European cable TV illustration showing spacing for analog (PAL) and digital (COFDM/QAM) signals

OFDM works best if hundreds or even thousands of parallel subcarriers are used. To implement that on the hardware side is a challenge even with modern semiconductor technology. In fact, it's really not accomplished as I've described thus far. Instead, the whole process is accomplished in computer hardware (or software) by using the fast Fourier transform (FFT) and the inverse FFT (IFFT).

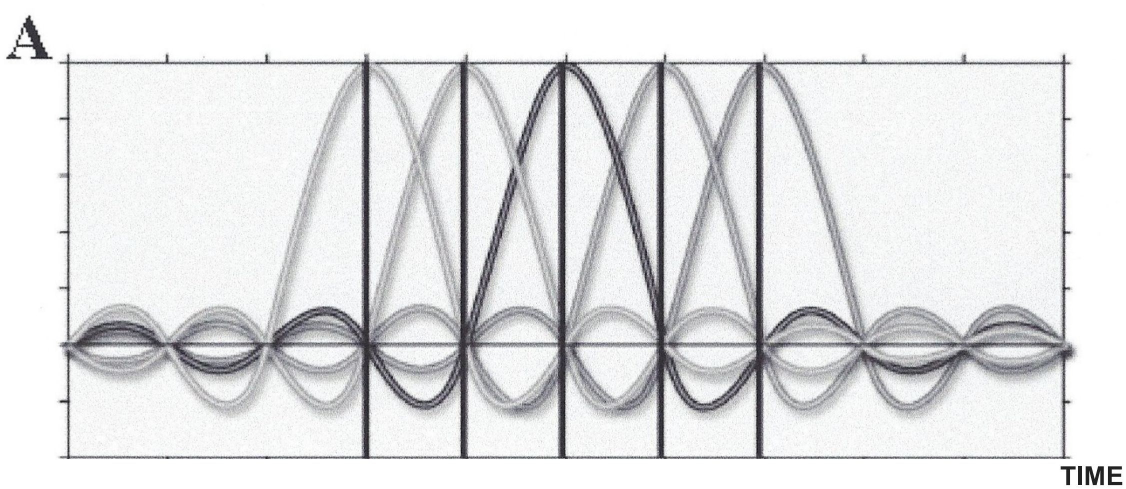
Some Painless Math

The FFT is a variation of the discrete Fourier transform (DFT). Fourier, as you might remember from your college (or military in my case) math days, was a French mathematician and physicist who discovered that any complex signal could be represented by a series of harmonically related sine waves added together. For example, a perfect square wave (time domain) is actually a sine wave with an infinite number of odd harmonics present with the fundamental (sine wave) signal (frequency domain). He also developed a mathematical series to prove it. The math is difficult, and early computers could 'work' it only very slowly. In the 1960's, Cooley/Tukey developed the 'fast Fourier transform', or FFT, as a way to greatly speed up the math and make Fourier analysis more practical.

From a practical perspective and for our interest in this analysis, the FFT estimates the spectral content (harmonic content) of a time-domain sequence of digital signal samples (think oscilloscope), and the results of the FFT are frequency-domain samples (think spectrum analyzer). And the IFFT is a process to convert frequency-domain samples back to time-domain samples. For clarification purposes, the Fourier transform is *not* the same as the Inverse Fourier transform. To think that they're the same is a bit like thinking that multiplication and division are the same.

Now back to how this is applied in the OFDM method, all the individual subcarriers with their respective modulation in digital format can be subjected to an IFFT mathematical process, creating *a single composite signal to be transmitted*. The FFT at the receiver reverses the process, and 'separates' all the subcarriers to recreate the original data stream.

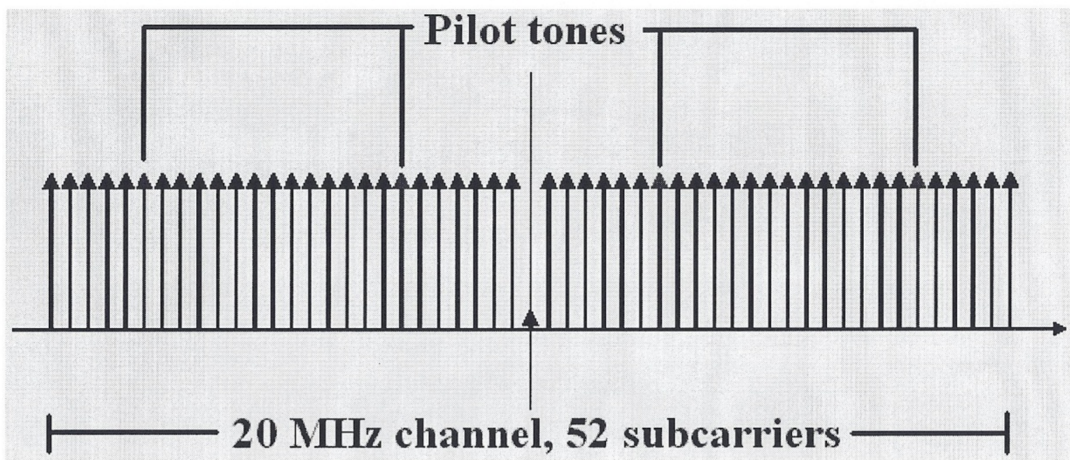
How does the OFDM process keep the individual modulated carriers from interfering with one another? This is where the term "orthogonal" comes in. At a very basic level, orthogonal simply means 'at a right angle to'. The subcarriers are created so they are orthogonal to one another, thereby producing little or no interference to one another despite their close spacing. In design terms, it means that if you space the subcarriers (from one another) by an amount equal to the reciprocal of the symbol period of the data signals, the resulting 'sin x/x' frequency response of the signals is such that the *first nulls occur at the subcarrier frequencies on the adjacent channels*. Orthogonal subcarriers all have an integer number of cycles within the symbol period. With this arrangement, the modulation (whatever type it may be) on one channel will not produce 'inter-symbol interference' (ISI) in adjacent channels. The following diagram illustrates this nulling process.



Number of Subcarriers

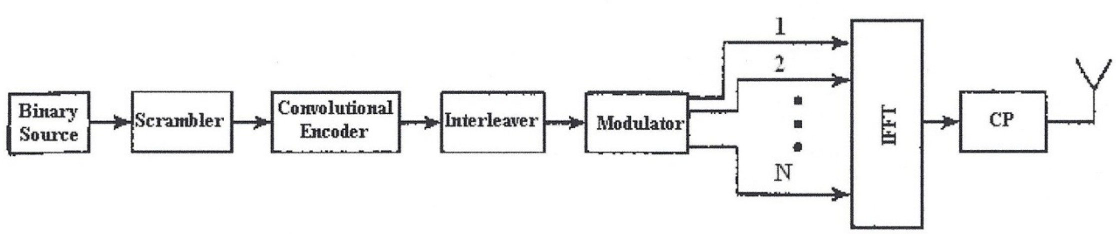
As already mentioned, the high-speed serial data to be transmitted is divided up into many, much lower-speed, serial data signals. OFDM sends these lower-data-rate signals over multiple subcarriers. This makes the bit or symbol periods longer, so multipath time delays have less of an effect. The more subcarriers used over a wider bandwidth, the more resistant the overall signal is to multipath phenomenon. This means one can use the higher RF spectrum with fewer concerns about the effects of multipath. An even greater advantage is that one can use them in mobile situations where the transmitter, receiver, or even both are moving and undergoing changing environmental conditions, all the while retaining good signal reliability.

The number of subcarriers within an OFDM 'channel' are typically very high. For example, in the European terrestrial high-definition broadcast system (8 MHz bandwidth), the number of discrete OFDM carriers can range from 1705 in what is known as 2K mode to 6817 in 8K mode. These subcarriers can be used for data (with a variable number of bits per symbol depending on the modulation method in use), TPS (transmission parameter signaling), and pilot carriers for synchronization at the receiver. Wi-Fi LAN systems utilize a varying number of subcarriers depending on the standard. For example, 802.11g, at 6 Mbps, OFDM, BPSK modulation employs 52 active subcarriers including 4 pilots. See the following diagram for illustration.



Wi-Fi 802.11b/g Subcarrier Arrangement in a 20 MHz OFDM Channel.
Pilot carriers are used for monitoring path shifts and Inter-Carrier Interference (ICI)

The overall structure of the OFDM transmitter is now illustrated in the following diagram.



After modulation, "N" carrier streams (at 1/N of the original rate) are fed to the N-point IFFT.
After the IFFT process, cyclic prefix (CP) is added at the beginning of the symbol. More on this in a moment.

Strictly speaking, the 'convolution encoder' (3rd stage above) is not part of OFDM, but is often employed in applications where deep fading could occur or where very low S/N may exist. When employed, the method is termed COFDM, or *coded* orthogonal frequency division multiplexing.

Advantages of OFDM

One primary advantage is spectral (or bandwidth) efficiency. What this means is that you can transmit more data faster in a given bandwidth in the presence of noise as compared to other spectral management techniques. The measure of spectral efficiency is bits per second per Hertz, or bps/Hz. For a given amount of spectrum, different modulation methods will yield widely varying maximum data rates *for a given bit error rate (BER) and noise level*. Simple digital modulation methods like amplitude shift keying (ASK) and frequency shift keying (FSK) are simple to implement but make poor use of spectrum. BPSK and QPSK are better. QAM is very good but affected by noise and low signal levels, and code division multiple access (CDMA) methods are very good as well. But none is better than OFDM (with a higher order modulation format) when it comes to getting the maximum data capacity out of a given channel. It actually comes close to the so-called Shannon limit that defines theoretical channel capacity, C, in bits per second (bps) as:

$$\mathbf{C = B \times Log_2 (1 + S/N)}$$

Here, B is the bandwidth of the channel in Hertz, and S/N is the power signal-to-noise ratio. With spectrum increasingly scarce and expensive; spectral efficiency has become the Holy Grail in wireless systems, but increasingly in wired systems as well such as HFC.

OFDM is highly resistant to the multipath problem experienced in high-frequency wireless. Very short-wavelength signals normally travel in a straight line (line of sight) from the transmit antenna to the receive antenna. The problem is that trees, buildings, cars, planes, hills, water towers (and even people) can sometimes reflect some of the radiated signal. These reflections are copies of the original signal that arrive at the receive antenna with some amount of delay. If the time delays of the reflections are in the same range as the bit or symbol periods of the data signal, then the reflected signals can add to or subtract from the direct signal and create cancellations or other anomalies.

Disadvantages of OFDM

Like any other spectral management method, OFDM has its disadvantages. The overall coding/decoding process is quite complex, making it more expensive to implement, and its complexity is avoided unless absolutely necessary. OFDM is also sensitive to carrier frequency variations. To overcome this problem, all OFDM systems transmit pilot carriers (as shown in a previous diagram) along with the data subcarriers for synchronization at the receiver. Another disadvantage is that the OFDM signal has a high peak-to-average power ratio. As a result, any amplification of the complex OFDM signal must be very linear. This means greater inefficiency in a RF *power* amplifier and greater power consumption, which has implications for applications such as terrestrial broadcast television, where high transmit EIRP levels are required.

At the design level, the two major challenges associated with OFDM are ICI, or inter-carrier interference; and ISI, or inter-symbol interference. How these problems are dealt with from a design perspective is beyond the scope of this technical report. In brief summary and as an example, frequency shift due to the Doppler effect can cause ICI; and a ‘guard time’ is introduced that helps to maintain orthogonality of the subcarriers. And when large signal delays are encountered ISI results. ‘Cyclic prefix’ works to counteract this phenomena.

Today’s Applications

OFDM has been adopted as the spectrum management method of choice for practically all new wireless technologies presently in use or under development, and is increasingly employed in ‘wired’ systems as well. For example, the (switched-circuit) telephony system developed by ADC (Homeworx™) some years ago employs OFDM for both downstream and upstream spectral management, with an underlying modulation scheme of 32-QAM (or 4-QAM).

What are other technologies that use OFDM? The list is long and impressive. It is used for digital radio broadcasting—specifically Europe’s DAB and Digital Radio Mondial, and it is used in the U.S. HD Radio system. It is used in commercial TV broadcasting like Europe’s DVB-T and DVB-H. You will find it in *wireless* local-area networks like Wi-Fi; the IEEE 802.11a/g/n standards are all based on OFDM. The wideband wireless metro-area network (MAN) technology WiMAX uses OFDM. And, the new 4G cellular technology standard known as Long-Term Evolution (LTE) uses OFDM.

Other examples of OFDM use in *wired* systems are BPL, or 'broadband over power lines'. One of the first successful and most widespread uses of OFDM was in dial-up (data) modems connected to twisted pair telephone lines. ADSL and VDSL, used for Telco high-speed Internet access, employ a form of OFDM known as discrete multi-tone (DMT). Finally, this list is far from complete, since we've not examined OFDM use in satellite or military applications.

My point is that if you haven't begun your investigation till now, it's time to begin in earnest, as this spectral management technique will continue to see wider deployment in both wireless and wired systems in the coming years, as spectrum becomes more scarce and valuable and as we continue our 'digital migration'.

Practical Improvements for OFDM?

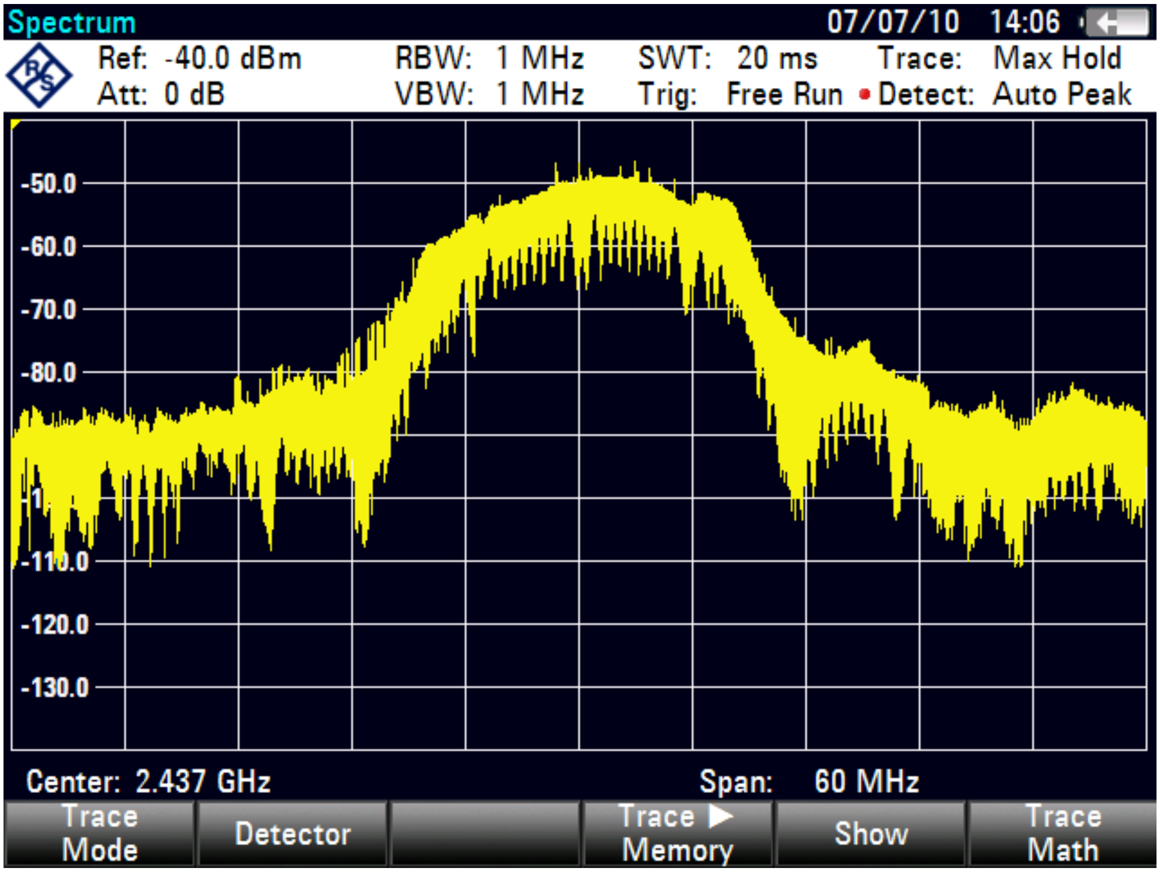
The only practical improvement to OFDM at present is on the wireless side and makes use of MIMO, the 'multiple-input multiple-output' antenna technology. It is currently used in 802.11n Wi-Fi and in the forthcoming LTE (Long Term Evolution) cellular technology. MIMO techniques are beyond the scope of this article, but there are tutorials available on this subject if you desire to learn more.

Wi-Fi Measurements

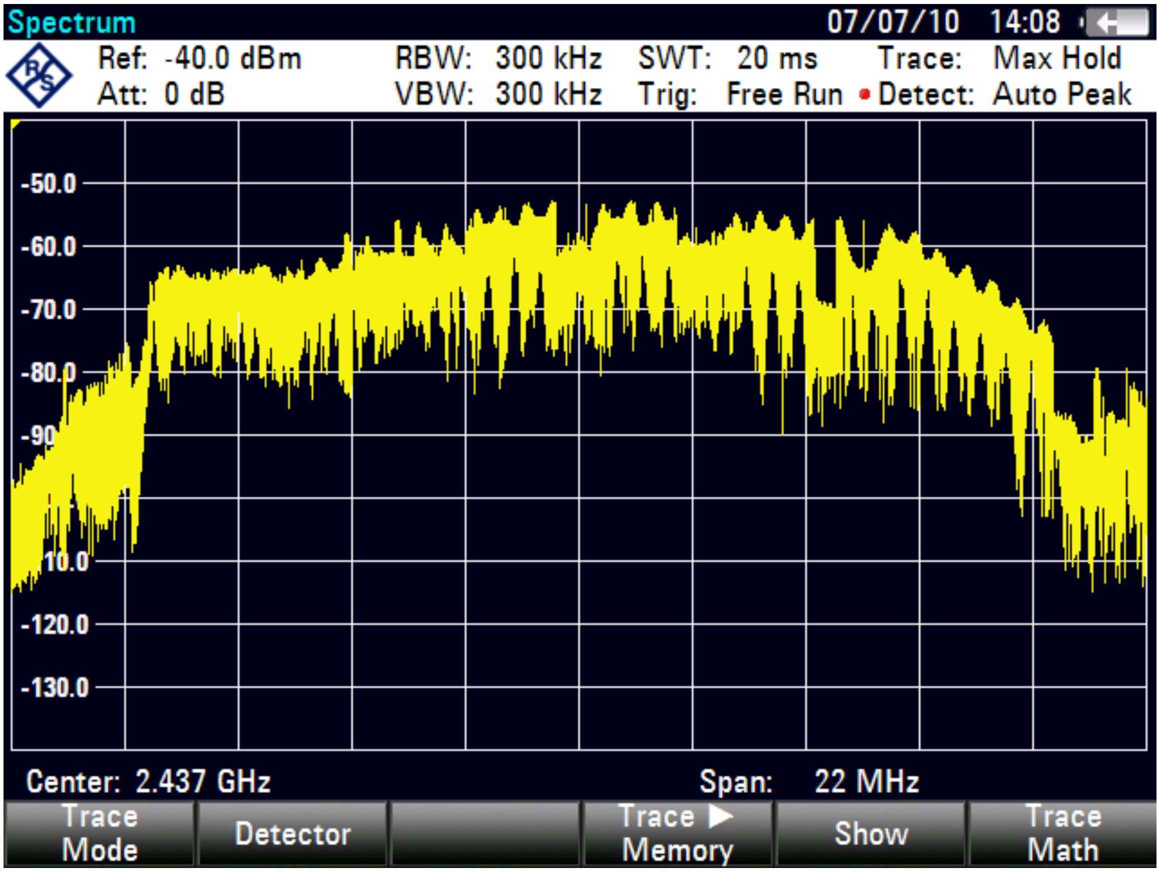
The following measurements were taken by monitoring a standard wireless router (WiFi system) operating in 802.11g mode at the CSEI office.

The IEEE standard 802.11g operates in the 2.4 GHz ISM band. It provides a maximum raw data rate throughput of 54 Mbps, however this translates to a practical throughput of just over 24 Mbps. Although the system is compatible with 802.11b, the presence of a 'b' participant on the network significantly reduces network speed. 802.11g employs several modulation schemes. For speeds of 6, 9, 12, 18, 24 36 48 & 54 Mbps, OFDM/QPSK is employed. Lower speeds (associated with a 'b' participant) may force utilization of CCK, DBPSK, or DQPSK+DSSS modulations.

The following waveforms were captured using a Rohde Schwarz FSH8 series analyzer and an Aaronia calibrated log-periodic antenna (tripod mounted) with a flat frequency response from 400 MHz to 6 GHz.

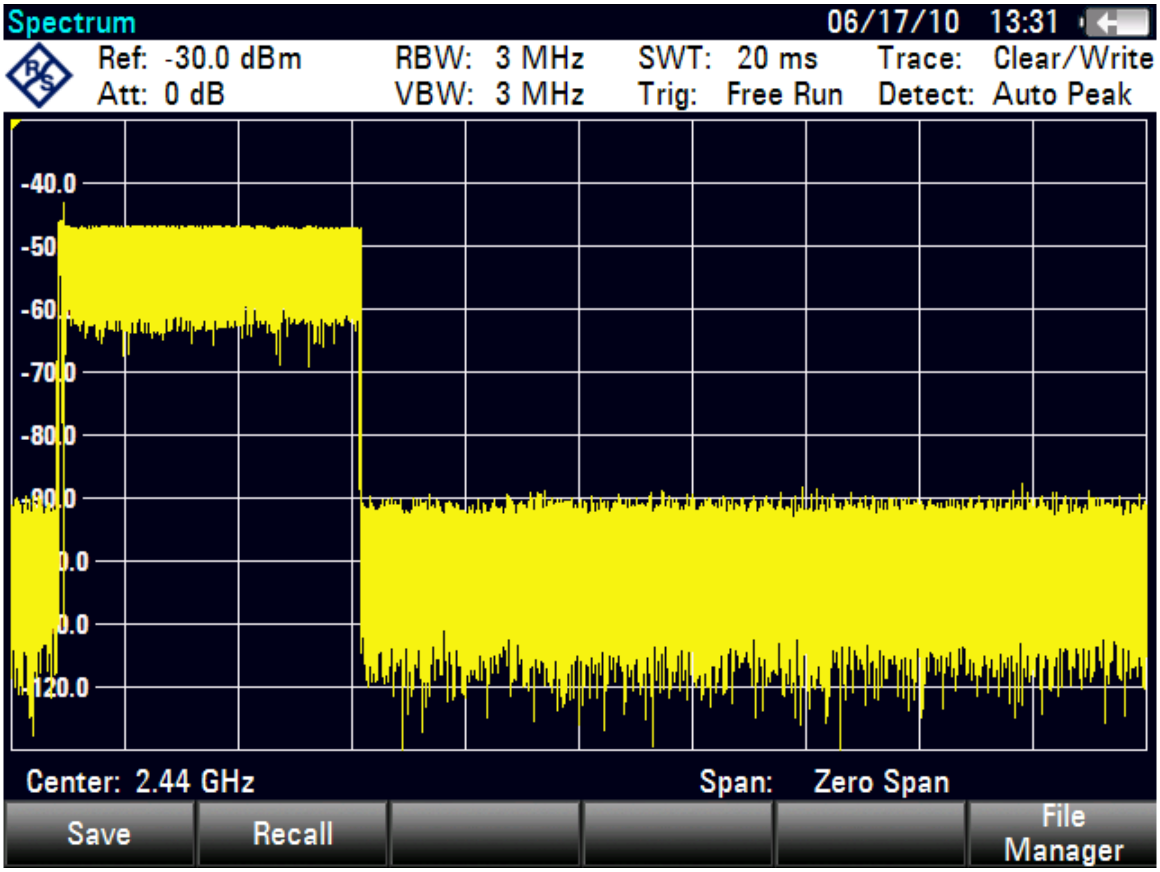


Spectrum analyzer in peak-hold, centered on Wi-Fi (802.11g) CH6 at 2.437 GHz. I've widened the span to 60 MHz to illustrate the high degree of adjacent spectral energy. Actual channel BW is 20 MHz.



In this waveform, the center frequency is kept the same (CH6 at 2.437 GHz); however the span is narrowed to 22 MHz, with the actual channel bandwidth at 20 MHz. Individual subcarriers are difficult to capture on a standard analyzer due to the speed at which they are 'integrated' – depending on LAN traffic requirements, so once again peak hold is employed to illustrate the individual orthogonal subcarriers.

The spectral energy "mask" is now more apparent. An accurate average power level measurement often requires the use of software routines in the spectrum analyzer.

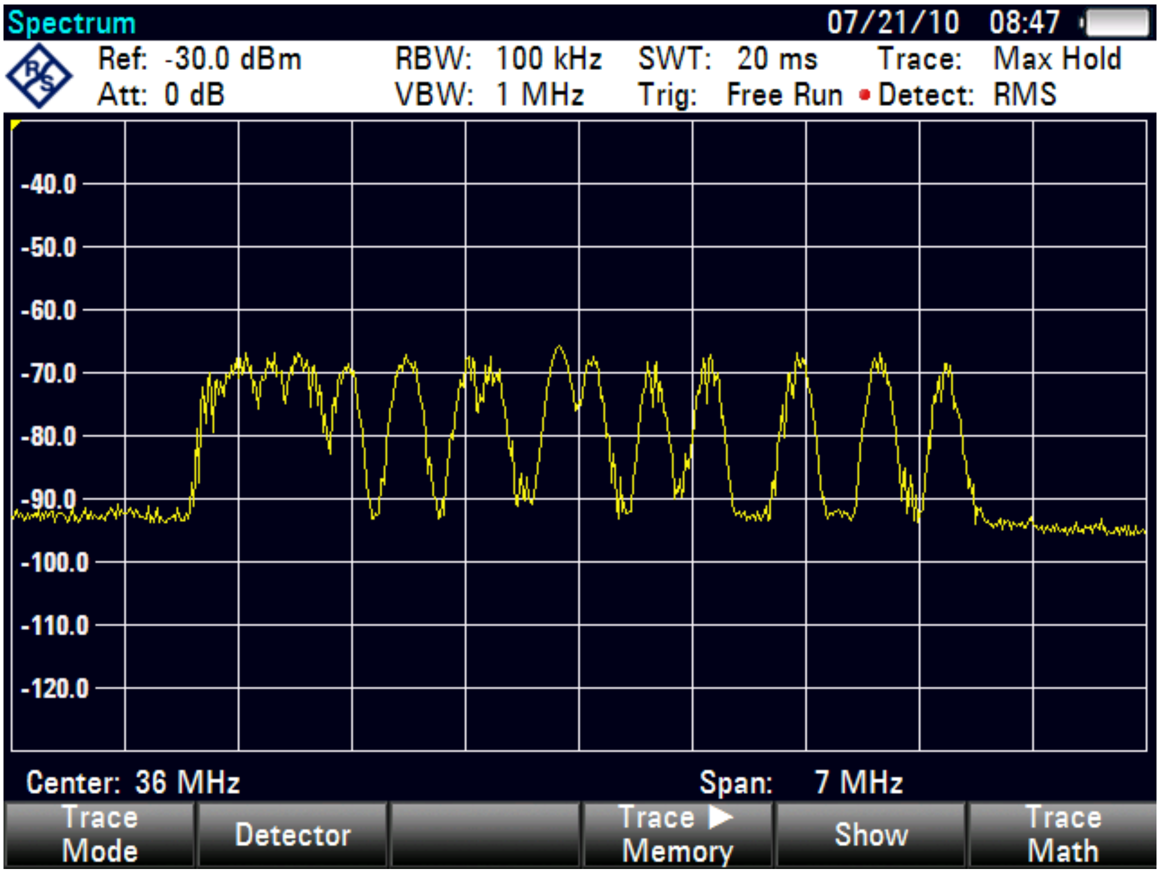


This final WIFI analyzer screen capture illustrates data transmission with the analyzer in zero span mode.

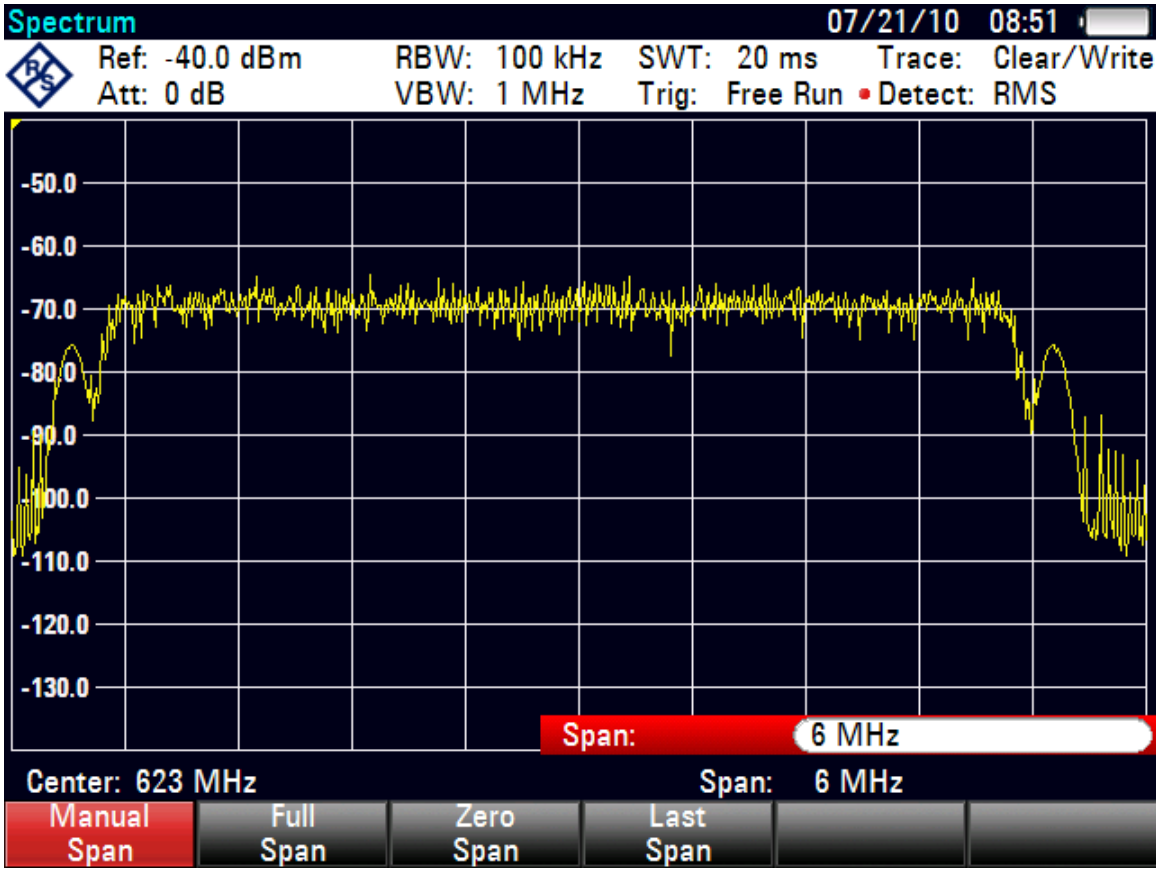
OFDM on a HFC Network

The following waveforms were captured in an HFC system using the ADC Homeworx™ telephony system. Downstream and upstream transmissions employ 6 MHz spectral allocations; however, only 5 MHz is utilized for the subcarriers, with a .5 MHz guard band placed on each side. Homeworx employs COFDM and normally 32-QAM, however the Homeworx™ system is unique in that it can switch from 32-QAM to 4-QAM while maintaining orthogonal multiplexing if plant conditions warrant it. 32-QAM provides for a 2.5X throughput increase, or if using 4-QAM a 10 dB S/N advantage.

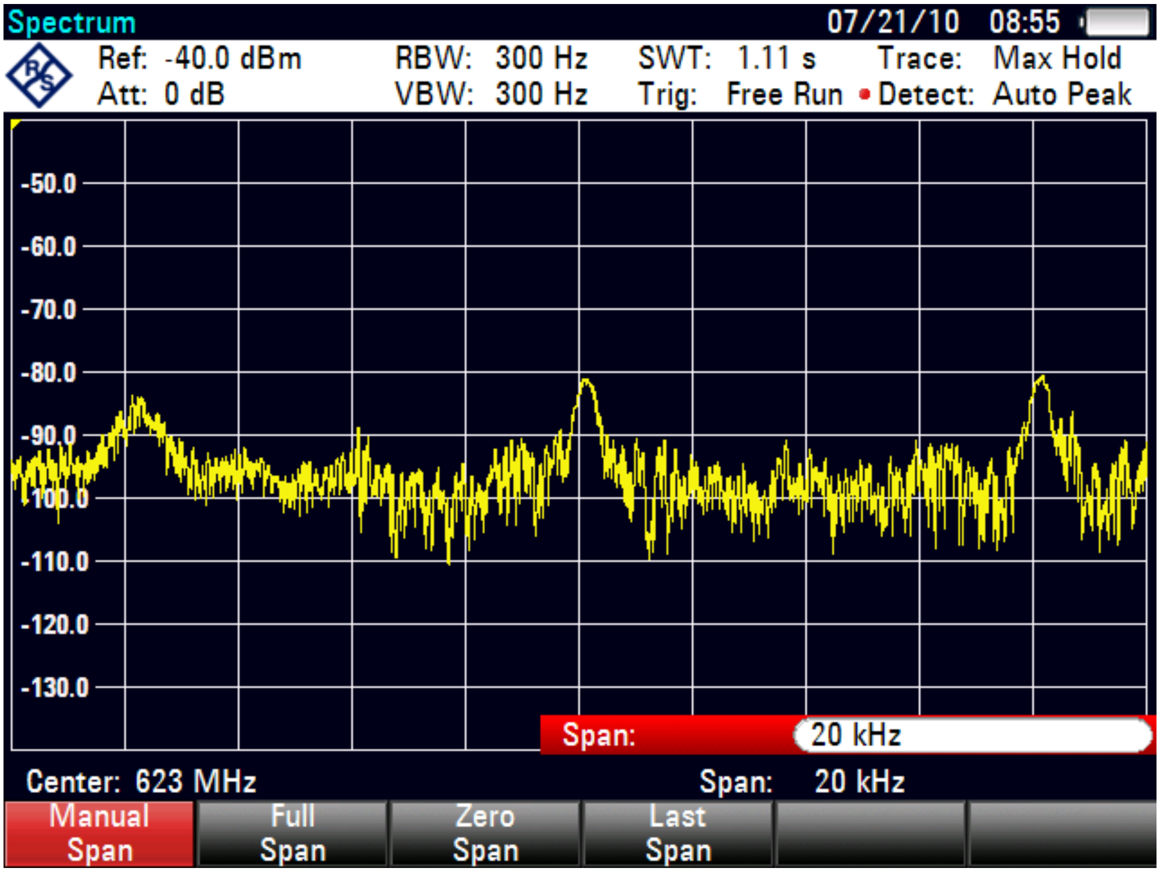
In this particular system, the downstream carrier is centered at 623 MHz and the upstream is centered at 36 MHz.



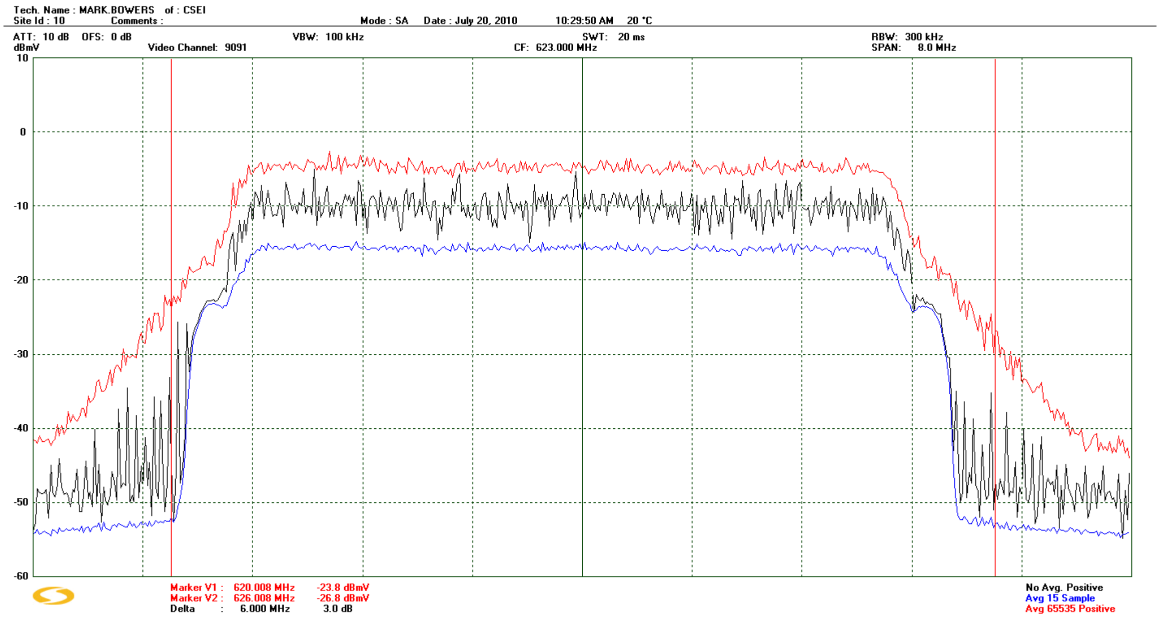
Upstream telephony subcarriers can be seen. Peak-hold on the analyzer is employed to capture 'some' of the telephony traffic.



The downstream 6 MHz COFDM carrier is shown. Individual subcarriers are just barely visible at this span and resolution bandwidth. As already noted, only 5 MHz of spectrum is utilized for the subcarriers, with a .5 MHz guard band placed on the upper and lower sides. 240 – DS0 circuits can be dynamically allocated within this 5 MHz of spectrum.



The same downstream COFDM carrier is shown (as in the previous waveform), but with the span and resolution bandwidth sufficiently narrowed, subcarrier spacing at 8 KHz can be clearly seen.



This final spectrum analyzer waveform was taken with a Sunrise Telecom AT2500 series analyzer. While the analyzer resolution bandwidth does not allow for the viewing of individual subcarriers, it does an excellent job of illustrating the overall spectral (power density) mask assigned to the COFDM signal. The red trace is peak-hold, black is real-time, and blue represents an average of 15 trace samples. Markers placed at the 6 MHz spectral slot boundaries show why the guard bands are necessary, as spectral energy clearly extends well beyond the 5 MHz allocated to the orthogonal subcarriers.

Conclusion

As stated in the beginning of this newsletter, in many ways OFDM is a difficult concept to understand and certainly to measure. Care must be taken when setting OFDM RF levels on a HFC system, as the average power level of the carrier will vary depending on the amount of traffic being carried. In general, most OFDM carriers are set to lower (than we are accustomed to) average power levels in the HFC network as compared to QAM, often in the -20 dBc range relative to analog! The extremely rugged nature of the signal allows for the levels to be set in this range, and it's a necessary safety precaution to prevent laser clipping as varying traffic levels change the average power level seen by the laser(s).

The ability of the OFDM system to operate under extremely adverse conditions is why it was adopted for use in BPL systems and often for telephony. The author has personally seen instances where the ADC Homeworx™ system continued to operate downstream of amplifiers that had almost completely failed. In those instances, video and cable modem services were no longer functional, however customers were still able to initiate phone calls downstream of the amp failure, often calling to report the outage in their area!

Beyond it's S/N advantages, its extreme spectral efficiency at a time of increasing scarcity of available spectrum will drive it's continued and increased use well into the future, in both wireless and wired applications.

The 4th Quarter Technical Report examines wireless links, how they are designed and implemented, along with some actual measurements an operational 11.2 mile 2.4 GHz wireless link.

Take care and best regards.

Mark Bowers
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