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My simple 8VSB tutorial a few months ago prompted a number of questions from readers concerning DTV pilot carrier frequencies. As I investigated the answers, it became clear they were quite complex, depending on a number of circumstances. This month I'll show you how to calculate the proper DTV pilot carrier frequency for a given channel, if you know the interference conditions. I'll also discuss some of the hardware methods available to meet the tighter frequency tolerances required by some of the offsets.

What is the Frequency?

DEFINING THE DTV CHANNEL FREQUENCY

You may not be able to immediately tell me the visual carrier frequency of a TV station on channel 44, but you can probably figure it out without too much effort. Channel 14 starts at 470 MHz, each channel is 6.0 MHz wide and channel 44 is thirty channels above channel 14. Therefore, the channel must start 180 MHz (30 x 6) above 470 MHz, or 650 MHz. The visual carrier is 1.25 MHz above the lower band edge and the sound carrier 4.5 MHz above the visual carrier, or 651.25 MHz and 655.75 MHz, respectively.

Now, without looking it up -- what is the pilot carrier frequency of your DTV assignment on channel 45? What is the frequency if you need to protect a co-channel DTV station? What is the offset to protect your lower adjacent channel NTSC station? What if do you need to do if there is an LPTV NTSC station on the channel below your DTV channel? What frequency tolerance is required?

I'll answer the easy question first. You might remember that the DTV pilot carrier is approximately 309 kHz above the lower channel edge. This is obtained by taking the bandwidth of the DTV signal -- 5,381.1189 kHz (the Nyquist frequency difference or one half the symbol clock frequency of 10,762.2378 kHz) -- and centering it in the 6 MHz TV channel. Subtracting 5,381.1189 kHz from 6,000 kHz leaves 618.881119 kHz. Half of that is 309.440559 kHz, the precise, standard pilot offset above the lower channel edge. The resulting channel 45 DTV pilot carrier frequency is 656.309440559 MHz. However, there is a good chance that won't be your actual DTV pilot carrier frequency! The reason is that co-channel and adjacent channel interference can be reduced significantly by using offsets.

DTV FREQUENCIES - SPECIAL OFFSETS MINIMIZE INTERFERENCE

Upper DTV channel into lower NTSC channel

The interference situations I mentioned in the earlier paragraph are not as easy to answer. Only one of the conditions mentioned in the question paragraph is covered in the FCC rules -- precision offset with a lower adjacent NTSC station, full service or LPTV. I'll cover that one first.

The FCC Rules, Section 73.622(g)(1), states that:

> DTV stations operating on a channel allotment designated with a "c" in paragraph (b) of this section must maintain the pilot carrier frequency of the DTV signal 5.082138 MHz above the visual carrier frequency of any analog TV broadcast station that operates on the lower adjacent channel and is located within 88 kilometers. This frequency difference must be maintained within a tolerance of ±3 Hz.

This precise offset is necessary to reduce the color beat and high frequency luminance beat created by the DTV pilot carrier in the lower adjacent NTSC channel. It was obtained using the following formula:

$$\text{Offset} = (455/2)*F_h + 95.5*F_h - 29.97 = 5{,}082{,}138 \text{ Hz.}$$

$$F_h = \text{NTSC horizontal scanning frequency} = 15{,}734.264 \text{ Hz.}$$

So, if the channel 44 NTSC station is operating with a zero offset, the Channel 45 DTV pilot carrier frequency must be 651.250000 MHz plus 5.082138 MHz or 656.332138 MHz., 22.697 kHz above the normal frequency. Of course, if the lower adjacent NTSC channel is offset plus or minus 10 kHz, the DTV frequency will have to be adjusted accordingly.

Note that full power stations are required to cooperate with lower adjacent NTSC Low Power TV (LPTV) stations within 32 km of the DTV station to maintain this offset:

The FCC Rules, Section 73.622(g)(2), states that:

> Unless it conflicts with operation complying with paragraph (g)(1) of this section, where a low power television station or TV translator station is operating on the lower adjacent channel within 32 km of the DTV station and notifies the DTV station that it intends to minimize interference by precisely maintaining its carrier frequencies, the DTV station shall cooperate in locking its carrier frequency to a common reference frequency and shall be responsible for any costs relating to its own transmission system in complying with this provision.

The FCC rules don't consider other interference cases where offsets help. The offset for protecting lower-adjacent NTSC signals takes precedence. If that isn't required, other offsets can minimize interference to co-channel NTSC or DTV signals.

Co-channel DTV- NTSC

If you remember the pre-Grand Alliance debates about DTV transmission, you may remember that one of the advantages touted for the 8VSB system was its ability to work well in an environment with NTSC signals. The performance of the 8VSB receiver's NTSC rejection filter and its clock recovery performance will be improved if the DTV station's carrier is 911.944 kHz below the NTSC visual carrier. In other words, if the NTSC station is not offset, the DTV pilot carrier frequency will be 338.0556 kHz above the lower channel edge instead of the normal 309.44056 kHz. As before, if the NTSC station is operating with a 10 kHz offset the DTV frequency will have to be adjusted in the same direction. The formula for calculating this offset is:

$F_{pilot} = F_{vis(n)} - 70.5*F_{seg} = 338.0556$ kHz (for no NTSC offset)

where:

F_{pilot} = DTV pilot frequency above lower channel edge

$F_{vis(n)}$ = NTSC visual carrier frequency above lower channel edge:
= 1,250 kHz for no NTSC offset (shown above) or
= 1,240 kHz for minus offset
= 1,260 kHz for plus offset

F_{seg} = ATSC data segment rate
= symbol clock frequency / 832
= 12,935.381971 Hz.

Note that in this case the frequency tolerance is plus or minus one kHz. More precision is not required.

Co-channel DTV- DTV

There is one final case to consider. If two DTV stations share the same channel, interference between the two stations can be reduced if the pilot is offset by one and a half times the data segment rate. This ensures the frame and segment syncs of the two signals don't line up. With this offset, they will alternate and be averaged out in the receiver.

The formula for this offset is simple:

$$F_{offset} = 1.5*F_{seg} = 19.4031 \text{ kHz}$$

where:

F_{offset} = offset to be added to one of the two DTV carriers

F_{seg} = 12,935.381971 Hz. (as defined above)

This results in a pilot carrier 328.84363 kHz above the lower band edge, provided neither DTV station has any other offset.

SUMMARY: DTV FREQUENCY

Table of DTV Pilot Carrier Frequencies

Table 1 summarizes the various pilot carrier offsets for different interference situations. Note that if more than two stations are involved the number of potential frequencies will increase. For example, if one DTV station operates at an offset because of a lower adjacent NTSC station, a co-channel DTV station may have to adjust its frequency to maintain a 19.403 kHz pilot offset. If the NTSC station operates at an offset of plus or minus 10 kHz, both DTV stations should compensate for that. As you can see, this may get complicated in some markets! Cooperation between stations will be essential in order to reduce interference.

TABLE 1 - DTV Pilot Carrier Frequencies for Two Stations

Normal offset above lower channel edge: 309.440559 kHz

	DTV Pilot Carrier Frequency Above Lower Channel Edge			
Channel Relationship	**NTSC station Zero Offset**	**NTSC station + 10 kHz offset**	**NTSC station - 10 kHz offset**	**DTV Station No Offset**
DTV with lower adjacent NTSC	332.138 kHz +/- 3 Hz	342.138 kHz +/- 3 Hz	322.138 kHz +/- 3 Hz	
DTV co-channel with NTSC	338.056 kHz +/- 1 kHz	348.056 kHz +/- 1 kHz	328.056 kHz +/- 1 kHz	
DTV co-channel with DTV	+ 19.403 kHz above DTV	+ 19.403 kHz above DTV	+ 19.403 kHz above DTV	328.8436 kHz +/- 10 Hz

Frequency Tolerances

How difficult will it be to maintain the DTV carrier frequency? The tightest specification is for a DTV station with a lower adjacent NTSC station. If both NTSC and DTV stations are at the same location, they may simply be locked to the same reference. If there is interference with a co-channel DTV station, the NTSC station should be stable within 10 Hz of its assigned frequency. The co-located DTV station carrier should be 5.082138 MHz above the NTSC visual carrier (22.697 kHz above the normal pilot frequency). The co-channel DTV station should set its carrier 19.403 kHz above the co-located DTV carrier.

While it is possible to lock the DTV station's frequency to the NTSC station, I don't consider that the best option if the two stations are not at the same location. It makes more sense to maintain the frequency of each station within the necessary tolerances. Where co-channel interference is a problem, that will be the only option. Oscillator frequency tolerance is generally expressed as an exponent -- so many parts per billion, for example. Given a worst case example of a UHF station (NTSC or DTV) on channel 69, the frequency stability required to meet the +/- 3 Hz tolerance will be 3.7 x 10e-9 or 3.7 parts per billion. If two stations are involved and the oscillators are not locked to a common reference, each must maintain its frequency within half that range, or 1.8 x 10e-9.

Hardware Options for Tight Frequency Control

Thumbing through a magazine with ads for oscillator manufacturers, the most stable oscillator I found was the MTI model 260. That OCXO (oven control crystal oscillator) can achieve stability of 5 x 10e-11 per day or 3 x 10e-10 per year (30 parts per billion) at oscillator frequencies up to 30 MHz. This is good enough short term, but would have to be monitored and adjusted throughout the year. Long term it would not meet the +/- 10 Hz or 12.5 x 10e-9 requirement for co-channel DTV stations.

A rubidium standard is much better and will meet our worst case requirements. The Novatech Model 2950AR is advertised at $3,995 and is specified to a stability of better than 5 x 10e-10 (0.5 parts per billion) per year. Temex advertises rubidium atomic clock modules, at various frequencies, with a life of 15 years and stability of 1 x 10e-10 per month. See the web resources at the end of the column for more information on these standards.

The GPS (Global Positioning System) satellites provide a more stable reference. Hewlett-Packard's HP 55300A GPS Telcom Primary Reference Source and HP 58503 GPS Time and Frequency Reference Receiver provide a reference signal with an accuracy of 1 x 10e-12 (0.001 parts per billion!). In the event the GPS signal is lost, they will maintain an accuracy of better than 1 x 10e-10 per day (0.1 part per billion), well within our requirements.

I'll have more specifics on this hardware in a future column. Stations may have to modify their NTSC exciters for greater stability. One of these standards combined with a Direct Digital Synthesizer may be the easiest way to do this.

Phase noise

One other specification should be kept in mind when considering the frequency source. The ATSC recommended operating parameters state the transmitted signal's phase noise at 20 kHz should be at least -104 dBc/Hz. Not all frequency synthesizers will meet that requirement.

Conclusion

I hope I've cleared up some of the confusion surrounding DTV frequencies. From my reading of the FCC rules, it appears the only frequency offset required is the one to protect lower adjacent NTSC channels. However, if all stations are going to enjoy maximum interference free coverage, we should voluntarily work together to take advantage of the improvement precision offsets can provide. I welcome your comments.

Additions and Corrections

DIGITAL MICROWAVE

In my NAB review column in May I mentioned a display at NAB that showed a narrow band digital signal and an analog FM video signal combined in the same microwave channel. I credited this to Microwave Radio Communications. Rick Hollowell, their Director of Broadcast Products, emailed me to tell me that wasn't Microwave Radio's demonstration. They were showing a digitally encoded analog signal and an ATSC Grand Alliance 19.39 Mbps signal digitally multiplexed up to 45 Mbps for transmission over their microwave equipment. This was part of their Model Station HDTV demonstration.

I apologize for the confusion. Who was showing the hybrid analog / digital solution? I plan to take another look at digital microwaves in a future column, comparing the tradeoffs between data rate and reliability for different modulation methods.

8VSB versus COFDM

Gary Sgrignoli, Staff Consulting Engineer at Zenith Electronics Corporation, called to comment on last month's table comparing 8VSB and COFDM. He took issue with the 24.2 ms channel equalizer update period listed for 8VSB. In the data directed mode, the equalizer can be continuously updated. The frame sync is not required. Zenith's receiver chip set can switch between using the frame sync, which allows reception closer to threshold and the data directed mode, which offers better performance with moving ghosts. The chip set looks at the incoming signal and, under microprocessor control, decides which method to use.

Gary also pointed out that the multipath delay tolerance is a receiver implementation issue for 8VSB receivers, not a system issue. The tolerance can easily be extended to 50 microseconds if manufacturers use a bigger / longer filter.

Finally, Gary noted that the C/N (carrier to noise ratio) for COFDM and 8VSB can't be compared directed since ATSC and DVB used different methods to arrive at the threshold. DVB looked at the error rate after trellis decoding but before Reed-Solomon error correction. The ATSC test looked at the data after Reed-Solomon error correction. Since MPEG-2 is based on packets, the ATSC tests measured segment errors per second. DVB focused on bit error rate.

Ron Economos (mailto:re@optivision.com) sent me a link to a report on Australia's tests of 8VSB and COFDM. See the list at the end of the column. According to a Dow Jones news article, Australia decided to use the DVB-T, COFDM based system.

That's all for this month. Special thanks to Gary Sgrignoli for taking the time to explain the various offset options for DTV stations. I've taken the liberty of restating some of his formulas in an attempt to make them easier to understand. If I failed, or if you find an error, blame me, not Gary! As always, I welcome your comments. Email me at dlung@transmitter.com or try to telephone me at Telemundo, (305) 884-9664, after 6:30 PM eastern time, please. I've been very busy recently, so it may take a while for me to respond to you. Thanks for your patience.

FOR MORE INFORMATION:

Australian Department of Communications and the Arts - Communications Lab

http://www.commslab.gov.au/lab	Communications Lab Index
http://www.commslab.gov.au/lab/rep/rep/9804/9804_001.htm	Tests of DVB-T and ATSC

Hewlett-Packard GPS Frequency Reference Products

http://www.tmo.hp.com/tmo/datasheets/English/HP55300A.html	HP 55300A data sheet
http://www.tmo.hp.com/tmo/datasheets/English/HP58503A.html	HP 58503A data sheet

MTI-Milliren Technologies Inc. - Precision Quartz Crystal Oscillators

http://www.mti-milliren.com/	Home page
http://www.mti-milliren.com/html/260.html	Ultra-stable crystal oscillator data specs

Novatech Instruments Inc. - Frequency Standards and Direct Digital Synthesizers

http://www.eskimo.com/~ntsales	Home page
http://www.eskimo.com/~ntsales/m2950ar.html	Model 2950A Rubidium freq. standard

Temex - Rubidium Frequency Standards

http://www.tekelec-temex.com	Home page
http://www.tekelec-temex.com/temex/product/crystal/rac.html	Rubidium standards

Doug Lung's RF Technology Page

http://www.transmitter.com	Home page
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