Bob's TechTalk

Number 46
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How FM Stereo Works:
For last month's RF I wrote a *Heathkit of the Month* article on the AJ-14 Stereo FM Tuner. This tuner came out in mid-1965, not too many years after FM Stereo broadcasting became common. As I wrote the article, I realized it would be too long if I used the opportunity to also describe how stereo is broadcast so the two channels can be separated at the receive end. The solution was to write this separate technical article. Someone once said that *if you want to understand something, teach it*. During my research I gained a lot more insight into FM stereo multiplexing than I had when I began.

Commercial FM Transmission:
The commercial FM band runs from 87.8 to 108 MHz and and contains 101 channels, each 200 kHz apart. The channels are centered on odd tenths of a MHz. (88.1, 88.3, etc.) Channels that might interfere with local aircraft frequencies, and nearby channels that close to 10.7 MHz apart are not used. (Most FM receivers have a 10.7 MHz IF frequency and two strong signals 10.7 MHz apart may mix and cause interference in the receiver.) The channel at 87.9 MHz is reserved and not used as a normal FM station channel.

Frequency modulation is the process of sending information by modulating the carrier frequency of the broadcast energy. The amplitude is not modulated. The FCC defines 100% modulation on the FM broadcast band as a frequency deviation of ±75 kHz.

Pre-emphasis:
FM has an advantage for high fidelity radio transmission because most radio noise appears as amplitude variations which are ignored by the FM reception process. However, background noise is still a problem when transmitting and receiving high fidelity audio. Since this noise is more prominent at the higher audio frequencies the higher audio frequencies are "emphasized" by passing them through a high-pass filter prior to modulating the carrier to raise their signal-to-noise ratio. This filter has a knee frequency of 2.12 kHz representing a 3 dB boost, increasing 6 dB per octave; at 15 kHz the boost is about 17 dB.

At the receiver, after detection, the audio undergoes de-emphasis by passing it through a simple low- pass RC filter with a time constant of 75 µS (Europe uses 50 µS). This filter also has a knee (cutoff) frequency of 2.12 kHz and attenuates the high frequency audio signals back to their proper level.

Monaural FM Transmission:
Monaural Hi-Fi FM is transmitted with a frequency response of 50 Hz to 15 kHz. This is commonly referred to as the main channel carrying the baseband audio as shown in figure 1 in orange.

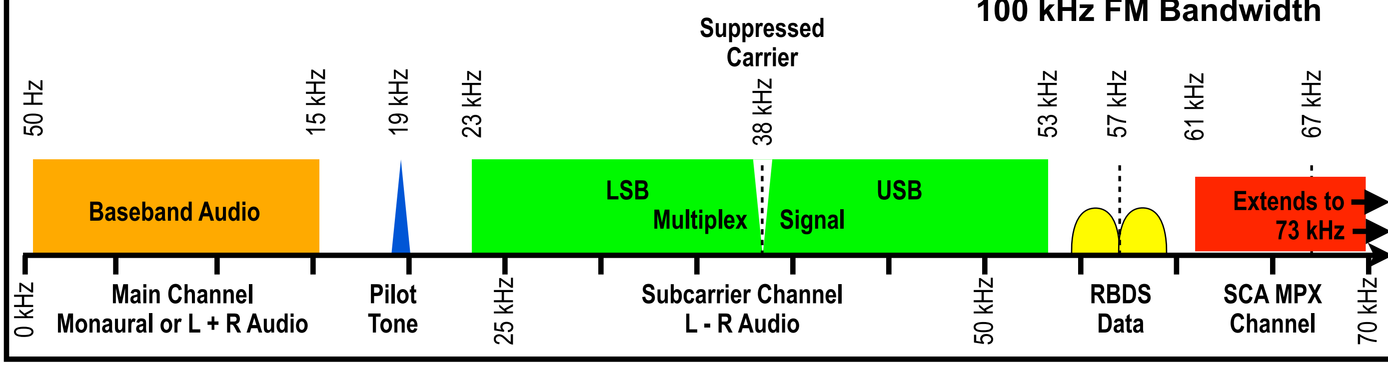


Figure 1: The first 70 kHz of the 100 kHz FM Bandwidth

Stereo FM Transmission:
Stereo FM requires the transmission of two channels. In order to accomplish this, a second channel is multiplexed on a subcarrier frequency of 38 kHz. This channel, shown in green in figure 1, is transmitted as a double-sideband suppressed-carrier signal (DSB). A pilot tone at 19 kHz, shown in blue in figure one, is also broadcast at a modulation level of about 10%. This tone has a 4 kHz guard buffer on either side, and is used during reception to sync the frequency and phase of a free-running 38 kHz oscillator that reinserts the carrier into the multiplexed DSB channel. It is transmitted in phase with and at exactly 1/2 the 38 kHz carrier.

Unfortunately, sending the left channel on the main channel and the right channel on the subcarrier channel presents a serious problem; people listening on a monaural receiver would only hear the left channel, and miss much of the content. The solution is to transmit the sum of the left and right channel on the main channel and the difference between the left and right channel on the subcarrier channel.

For stereo reception, the main and subcarrier channels are added to get the left channel and subtracted to get the right channel. Mathematically:

$$(L + R) + (L - R) = L + R + L - R = 2L$$

and:

$$(L + R) - (L - R) = L + R - L + R = 2R$$

Thus, a person hearing the monaural channel will hear both audio channels, though in monaural. *Remember this concept because it comes into play later on in a very interesting way*.

Typical waveforms:
Figure 2 shows a sample of channel waveforms that will be used throughout this article, and how they combine. Figure 2a represents two cycles of a 200 Hz., 10-volt peak sine wave being transmitted on the **left channel**; figure 2b represents seven cycles of a 700 Hz., 7-volt peak sine wave being transmitted on the **right channel**. In figure 2c the top two waveforms

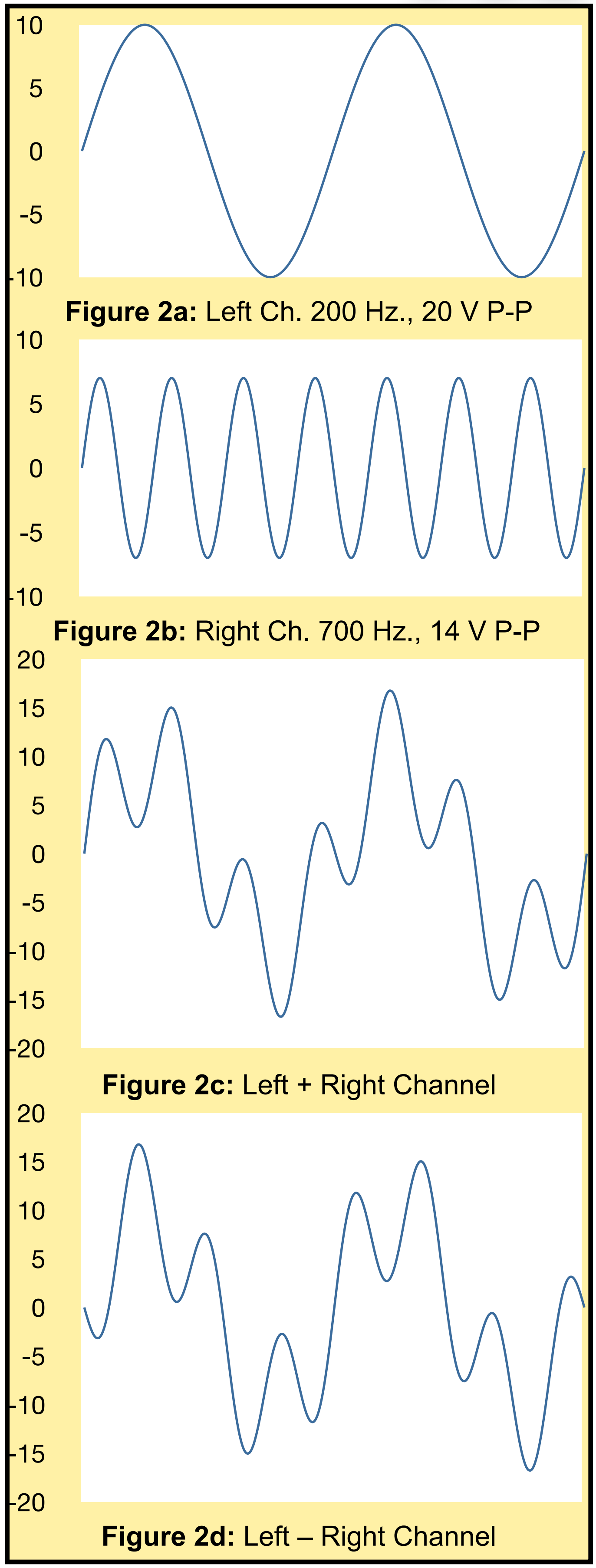


Figure 2a: Left Ch. 200 Hz., 20 V P-P

Figure 2b: Right Ch. 700 Hz., 14 V P-P

Figure 2c: Left + Right Channel

Figure 2d: Left – Right Channel

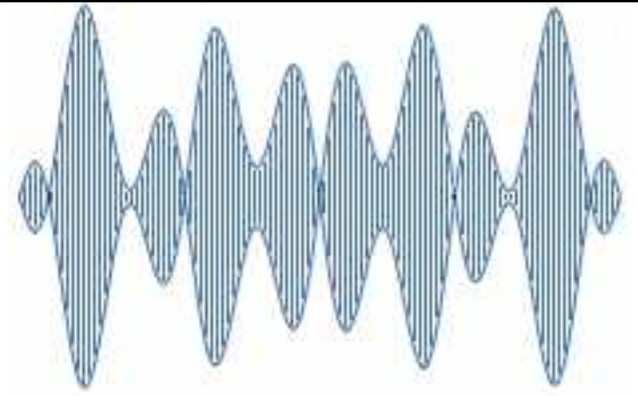


Figure 3: Fig. 2d (L – R) as a DSB signal

have been added showing the **sum of the two channels (L + R)** and in figure 2d the second waveform has been subtracted from the first waveform showing the **difference between the two waveforms (L - R)**. The horizontal axis represents 10 milliseconds of time in each waveform of figure 2.

The wave form of figure 2c is transmitted on the main (baseband) audio channel. The waveform of figure 2d is mixed in a balanced modulator with a 38 kHz carrier signal and is transmitted as the multiplexed subcarrier channel. Figure 3 shows the (L – R) signal of figure 2d as it appears as a 38 kHz DSB signal.

At the transmitter, the (L + R) audio, the 19 kHz pilot tone and the 38 kHz (L - R) subcarrier band are all combined and transmitted. There are other signals that may also be combined and transmitted above the (L - R) subcarrier band that are not directly associated with the stereo signal. These will be discussed later.

Stereo FM Reception:

Should you be listening to a stereo transmission on a monaural FM radio, the signal recovered from the FM detector contains all the transmitted signals, however, since only the main band (L + R) audio is of interest, the others are filtered out right after the FM detector.

Stereo reception recovers the main audio channel signal as well as the 19 kHz pilot tone and the 38 kHz (L - R) subcarrier channel. The pilot tone is transmitted in phase with the suppressed carrier used to modulate the subcarrier tone. Some phase shift may have occurred during transmission, and in early stereo HI-FI FM tuners a PHASE control was often incorporated to allow the user to manually adjust the phase for best left and right channel separation.

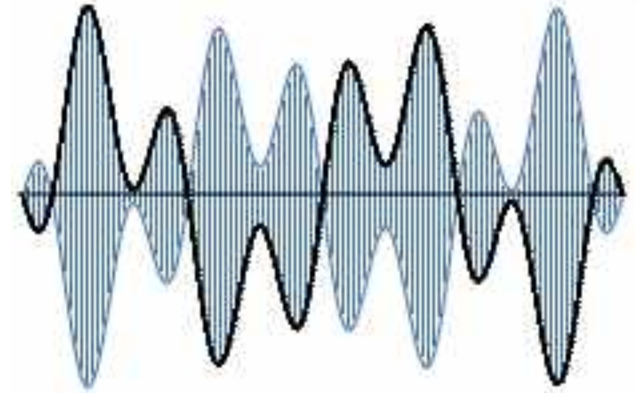


Figure 4a: Highlighting + [Plus] (L – R)

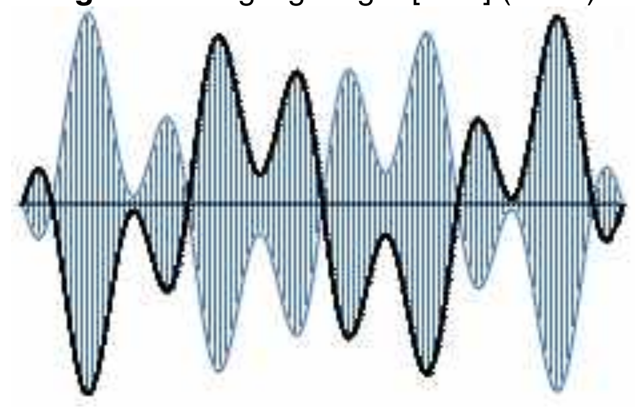


Figure 4b: Highlighting – [Minus] (L – R)

The recovered 19 kHz pilot tone is used to sync a free running oscillator in the FM receiver to 38 kHz in exact frequency and phase with the 38 kHz oscillator used to modulate the DSB (L – R) subcarrier, and is used to accurately recover that subcarrier signal.

Let's go back to the DSB signal of figure 3. Looking closely at figures 4a and 4b, both of which are just figure 3 highlighted, we see the waveform amplitude contains the (L – R) signal of figure 2d as both the + (L – R) signal (4a) as well as the inverted – (L – R) signal (4b). The black line in figure 4a is the locus of points when the phase of the 38 kHz carrier

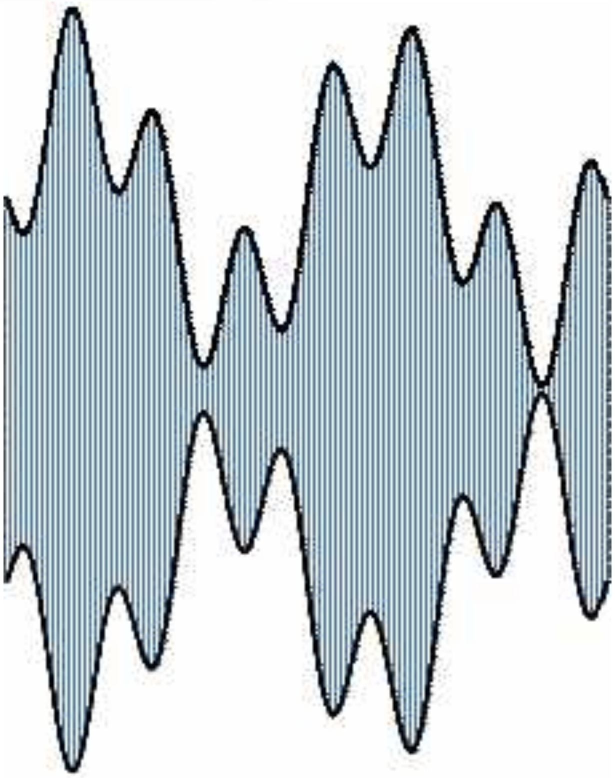


Figure 5: Figure 3 with the 38 kHz carrier reinserted (shown for clarification).

wave is at 90° (i.e. at its most positive point), and the black line in figure 4b is the locus of points when the phase of the 38 kHz carrier is at -90° (i.e. at its most negative point). [See Sidebar for more on degree notation]. Note that in figures 4a and 4 b the (L - R) subcarrier channel phase inverts with relation to the 38 KHz carrier each time the highlighted line crosses the X-axis.

Figure 5 shows for clarification the figure 3 waveform with the 38 kHz carrier reinserted. Note that the + (L - R) waveform is riding on the top points of the carrier (90° phase) and the – (L – R) waveform is riding on the bottom points of the carrier (–90° or 270° phase).

The signals coming out of the FM detector, after the 19 kHz pilot tone is recovered, and any other signal information not related to recovering the stereo channels are removed, are the DSB signal of figure 3 and the main channel audio (L + R). However, in reality the 38 kHz DSB signal of figure 3 is actually riding on top

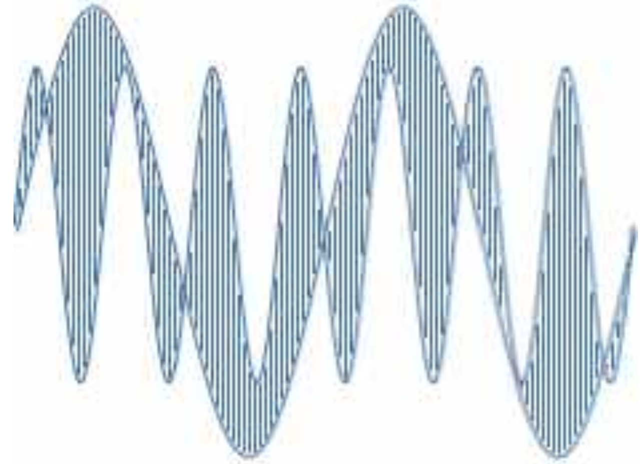


Figure 6a: This is what Fig. 3 looks like riding on top the main channel (L + R) signal.

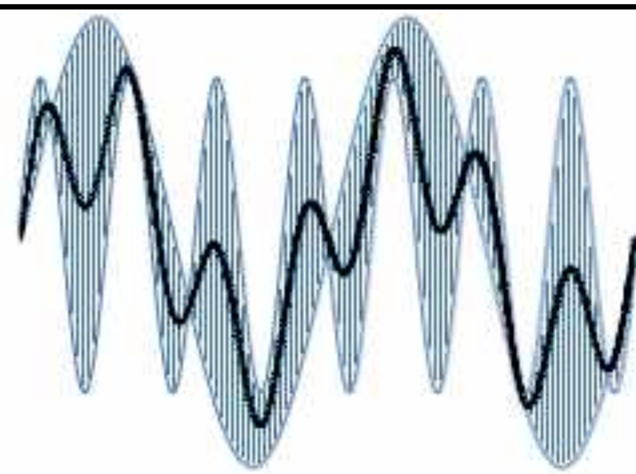


Figure 6b: This is Fig. 6a highlighting the main channel (L + R) signal.

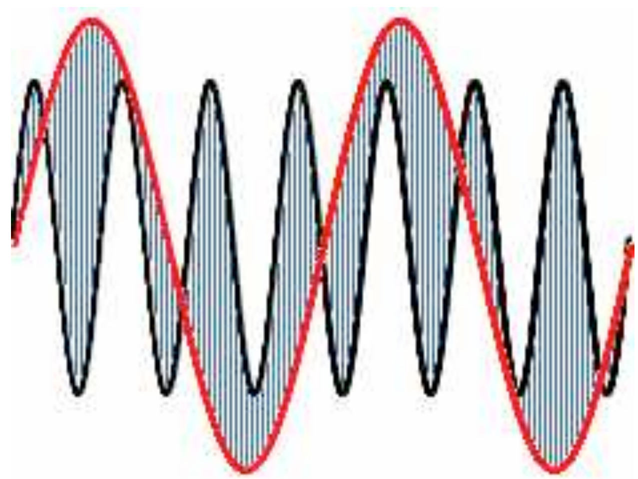


Figure 6c: This is Fig. 6a highlighting the Left channel (Red) and the Right channel (Black).

of the main channel audio as shown in figures 6a and 6b.

Go back to the two equations we introduced earlier. The DSB carrier which has (L – R) as its 90° waveform is riding on top (adding to) the main (L + R) audio channel resulting in:

(L + R) + (L – R) = 2L (Red in Fig. 6c)

And – (L – R) as its –90° (or 270°) waveform resulting in:

(L + R) – (L – R) = 2R (Black in Fig. 6c)

Figure 7 shows what figure 6 would look like if the 38 kHz carrier was reinserted. (Yes, that is the left channel on the top of the waveform and the right channel on the bottom of the waveform!)

However it is not actually necessary to reinsert the carrier; instead, it is only necessary to feed the signal of figure 6a into two switching transistors. One switch turns on momentarily each time phase of the 38 kHz oscillator is at the 90° phase point, charging a capacitor to the momentary level; thus recovering the left channel. And the other switch turns on each time the 38 kHz oscillator is at the –90° (270°) phase point, charging a separate capacitor and recovering the right channel. These switches each charge a capacitor that follows the recovered waveform for its channel. The audio channels are each then filtered to remove any residual 38 kHz signal, de-emphasized and output to separate left and right channel amplifiers.

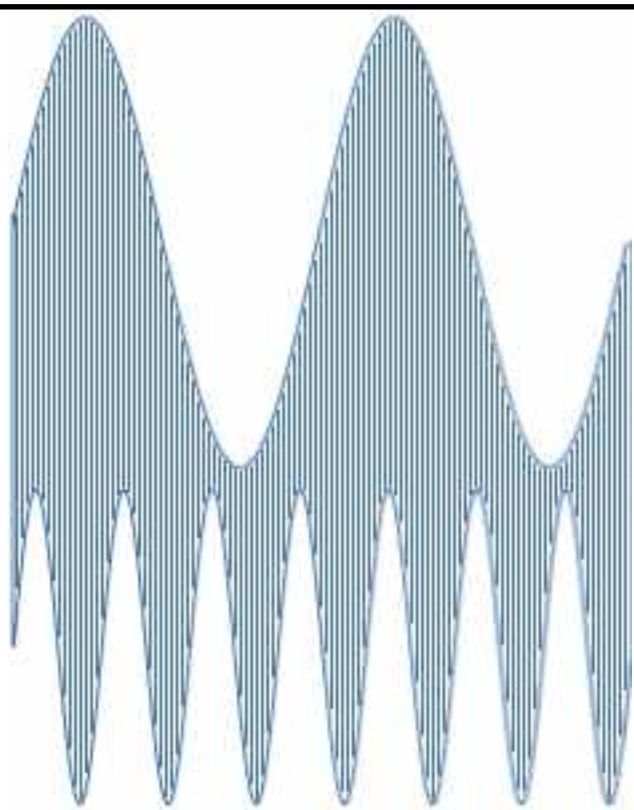


Figure 7: This is what figures 6 would all look like if the 38 kHz carrier was reinserted.

Other FM Subcarrier Signals:
Additional signals may be transmitted on the FM carrier, whether transmitting monaural or stereo signals. The one most talked about is the SCA (Subsidiary Communications Authorization) signal. Another less known signal is the RBDS (Radio Broadcast Data System - sometimes just RDS). This is used more heavily in Europe and Latin America but is growing in the US.

SCA: (Shown in red in figure 1 - at 67 kHz)
Monaural FM stations can transmit up to three SCA channels on FM modulated subcarriers. Subcarrier frequencies are typically located at 41 kHz, 67 kHz and 92 kHz, with 67 kHz being the most common. These channels have various uses. The most common use was once for commercial-free music (so-called "elevator music") for use in stores and offices; Musak used to be a big user of this service, but now uses a different system. Many states have book reading for the blind and visually handicapped offered on SCA channels, often in conjunction with PBS stations. An SCA channel may also send telemetry data from the remote transmitter to the station location to monitor transmitter parameters.

Stereo FM stations cannot use subcarriers below a frequency that would interfere with the high end of the 38 kHz multiplex band (about 54 kHz) so are usually limited to two SCA channels at most.

The arithmetic sum of the modulated SCA subcarriers may not exceed 20%, and subcarriers above 75 kHz may not exceed 10%. Thus the audio frequency response is not hi-fi; it is often not even as good as an AM broadcast station when more than one SCA subcarrier is in use. Still the channels are good for voice and for data. SCA is broadcast as a subcarrier using FM on its subcarrier. On 67 kHz an audio bandwidth of 4 to 6 kHz is typical.

The FCC has remained quite lenient on SCA standards since they were first introduced. Teletype and slow-scan TV can be used. More information may be found here:

http://www.fcc.gov/encyclopedia/broadcast-radio-subcarriers-or-subsidiary-communications-authority-sca

RBDS: (Shown in yellow in figure 1)
This signal is transmitted on a subcarrier at 57 kHz. (The third harmonic of the pilot tone). It has a narrow bandwidth and transmits only data at a rate of 1187.5 bits per second (bps) After error correction and framing overhead the data rate is reduced to 730 bps., or about 100 ascii characters per second. This data can be used for sending a variety of different information. Each type has a two or three letter code associated with it: Some of the codes are:

- AF (Alternate Frequency) - When used with a mobile receiver designed for the AF function, the receiver can switch to an alternate station that is broadcasting the same program material when the mobile gets out of range of the current station.
- CT (Clock Time) - this data can be used to synchronize the car clock.
- PS (Program Service) - An eight-character static data string of the station's call letters.
- RT (Radio Text) - sixty-four characters of text that can be used as desired by the station; often used to transmit the name and/or artist of the current song.
- PTY (Program Type) - Thirty-one pre-defined codes (news, sports, talk, oldies, top 40, country, etc.) Code 31 signifies an "Emergency" broadcast.

There are five other types, mostly involving traffic reporting and information, encoded station ID and "region specific" programming.

Radios that utilize these features are slowly coming on the market - mostly for automotive use. Integrated circuit manufacturers such as ST Microelectronics, Philips (now NXP), and Silicon Labs are producing RDS chipsets for incorporation into radios.

Summary:
Broadcasting multiple multiplexed signals on a single 200 kHz wide FM carrier requires some serious considerations. Any spurious or harmonic content from any of the signals can result in interference with another component of the composite transmission. Once the signals are combined, any significant nonlinearities, or restrictions on the bandwidth can cause undesired interaction. High feedline SWR, a transmitting antenna with too-narrow of a bandwidth, a failing transmitting tube and many other items can be troublesome to sending a clean composite signal. Yet with good engineering practices thousands of FM stations throughout the world transmit not just a stereo signal but also RDBS information, an SCA channel for public or private consumption and a subsidiary SCA channel that telemeters transmitter information back to the studio!

There is a lot more going on at that FM station you are tuned into than one imagines. The process allowing stereo to be sent so it can be detected easily when users listening on monaural receivers shows some good thought in implementation. A similar process had to be developed when color TV was developed.

Some links that might be useful if you want to look further into stereo FM broadcasting or some of the other signals that may be on the FM carrier are shown in table I.

73, from AF6C

A paper *Introduction to FM-Stereo-RDS Modulation* by Liang Ge, EK Tan and Joe Kelly of Verigy is available here:

https://www.advantest.com/cnsmprod/groups/public/documents/file/fm-stereo-rds.pdf

A paper *Subsidiary Communications and Stereophonic Broadcasting* by T.R. Humphrey and L.E. Hedlund of McMartin Industries covering SCA can be found at:

http://www.americanradiohistory.com/Archive-NAB-Engineering/NAB-6th-Edition/SCA-NAB-engineering-Handbook-6th-Edition.pdf

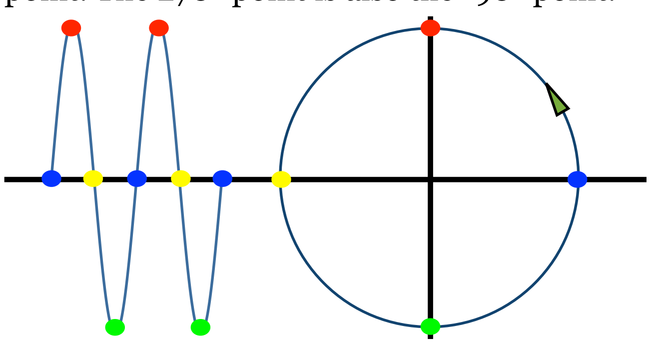
Further technical information on RBDS may be obtained from Silicon Labs technical note AN243 which can be obtained on the Internet at:

http://www.silabs.com/Support%20Documents/TechnicalDocs/AN243.pdf

Lot's more sites of varying technical levels can also be found: Search **FM Stereo Broadcasting Theory** on your favorite search engine.

TABLE I - Links

Sine Wave Degrees:
The figure contains two cycles of a constant amplitude sine wave next to a 360 degree circle. Going from left-to-right on the sine wave, and counter-clockwise on the circle, we start at 0° (blue dot). One-quarter way around the circle we reach the 90° point (red dot). One-halfway around the circle we reach the 180° point (yellow dot). Three-quarters way around the circle we reach the 270° point (green dot). And after another quarter of the way around the circle we return to the 0° point. The 270° point is also the -90° point.



If we go around the circle again we create the second sine wave, etc.

Note that each positive peak of a constant sine wave represents the +90° point and each negative peak represents the -90° point.

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But What's This Have to Do With Ham Radio?
Many hams are interested in learning about everyday radio. The AM mode of ham radio was superseded, starting in the 50s, by SSB. If you compare figures 3 and 5, as well as figures 6a and 7, you see two examples of a benefit of double-sideband suppressed-carrier (DSB) transmission over the double sideband with carrier (AM) transmission. Both are transmitting the same signal at the same level but if you consider the size of all that 'blue' in the figures represents power, you quickly realize that DSB uses less power to transmit a complex signal level. Thus, if you increase the power of the DSB signal to that of the AM signal, your level is higher.

If after suppressing the carrier to get a DSB signal you also filter or phase out one of the sidebands you get a single-sideband suppressed-carrier (SSB) signal and you gain additional efficiency over AM.

A 1KW AM signal 100% modulated contains 1,000 watts in the carrier and 250 watts in each sideband - effectively a 250 watts of 'intelligence'. A 1KW SSB signal has effectively 1,000 watts of 'intelligence' in one sideband.

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This article is based on the TechTalk article that originally appeared in the March 2015 issue of RF, the newsletter of the Orange County Amateur Radio Club - W6ZE.