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SUBJECT	Practicalities of Channel Spacing and Occupied Bandwidth		
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Introduction

The spectrum occupied by a modulated carrier depends on the modulation method being used. For an unmodulated carrier the bandwidth occupied is theoretically zero. Each type of modulation occupies a different bandwidth, which is largely determined by the modulating frequency (f_m).

Amplitude Modulation

In a double side band, full carrier system, known as AM, the occupied bandwidth (B) is given by the formula:

$B = 2 \times f_m$

Hence, with a modulating frequency of 3kHz the bandwidth occupied is 6kHz. It follows then that a receiver for AM requires an IF bandwidth of 6kHz.

Single Side Band

In an SSB, suppressed carrier modulation scheme the bandwidth occupied by the transmitted signal is given by:

$B = f_m$

The maximum modulating frequency is normally limited to 2.5kHz, hence the IF bandwidth required is 2.5kHz.

Pulse Modulation

In a pulse-modulated signal using a rectangular pulse the occupied bandwidth is the reciprocal of the pulse duration. Pulse modulation is commonly used with RADAR systems and in this case if the pulse is very short the receiver will require a very large bandwidth.

The bandwidth occupied is given by:

$B = 1/\tau$

Where τ is the pulse duration.

If the pulse duration is 1μs the bandwidth required is theoretically 1MHz. However, D.O. North in 1946 showed that the actual IF bandwidth required is 1.17 times the calculated. In practice in RADAR using a 1μs transmitted pulse we would require a receiver bandwidth of approx. 1.2MHz to encompass all the energy in the resulting echo.

Frequency Modulation

The case for FM is not as simple as the previous ones, because the signal generated can consist of many sidebands. The formula needs to consider both the modulating frequency and the frequency deviation. Carson in 1962 derived the basic equation, which is still valid today. This is known as "Carson's Rule".

$B = 2 \times (\Delta f + f_m)$

Where: Δf is the peak deviation.

For a FM transmitter with a peak deviation of 5kHz and a maximum modulating frequency of 3kHz the occupied bandwidth is 16kHz. In mobile radio FM systems we usually limit the maximum modulating frequency to 2.5kHz. In this case the bandwidth is reduced to 15kHz.

FM Broadcast

Armstrong in 1932 developed the use of frequency modulation for high fidelity broadcasting. (Major Edwin Howard Armstrong, paper published in the American IRE for 1932, laid down the principle of fm broadcasting still in use today). In the Armstrong system the maximum modulating frequency was limited to 15kHz. The peak deviation was limited to 75kHz. Using Carson's Rule we can hence calculate the occupied bandwidth as being 180kHz. In the early days the FCC in America had not allocated any spectrum for this new broadcasting system and it was firstly used in the portion of spectrum of 42 to 50MHz. Later a new band of 88 to 108MHz was set aside.

The occupied bandwidth being high it was considered impractical to pack in the stations too closely. The FCC decided that anything closer than 300kHz would cause interference. Hence, even today we are still using the 300kHz-channel spacing for fm broadcast transmitters.

Narrow Band FM

"*Narrow Band*" is a relative term, meaning nothing in particular except that that it is narrower than the broadcasting type. In the early days of fm radiotelephony the NBFM channel spacing chosen was 100kHz with a maximum deviation of 20kHz. Later this was reduced to 50kHz with a deviation of 10kHz, then 25kHz with a deviation of 5kHz and finally 12.5kHz with a deviation of 2.5kHz. Notice that each new system was a reduction to half of the previous system. The next logical system would be 6.25kHz if the needs should arise in the future. (NATO military equipment has recently adopted the 8.33kHz channel spaced system, which is 1/3rd that of a 25kHz system then in current use).

The occupied bandwidth of each these systems is as follows:

SPACING kHz	Bandwidth kHz
100	60
50	30
25	15
12.5	7.5

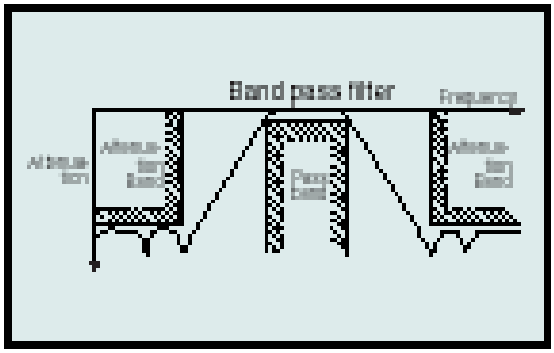
Using Carson's Rule we can determine the possible deviation and modulating frequency to fit within the bandwidth window.

As the channel-spacing gets progressively tighter the necessity is to reduce the deviation and modulating frequency to stay within the allocated IF bandwidth. At 25kHz-channel spacing the constraints are not too severe and a deviation of 5kHz with a full audio bandwidth of 3kHz gives a figure of 16kHz. In practice the AF is normally limited to 2.5kHz as the difference between 2.5kHz and 3kHz is not noticeable for speech.

Correlation between Occupied Bandwidth and Channel-Spacing

In the original Armstrong fm broadcasting the choice of 300kHz-channel spacing was as a result of the difficulty of making IF filters with sufficiently sharp cut-off. In a receiver for FM or PM we cannot use a flat-topped filter with a transition to maximum attenuation with a sharp corner. To do so would introduce excessive phase distortion as the signal transits the portion between the flat top and the skirts. We need to use a filter with a gradual roll-off from the pass band to the stop band; this shows a noticeably rounded corner and not a sharp corner. This means that the skirt selectivity is nowhere as good as a SSB or AM filter. In an SSB filter the skirts can be almost vertical, if it was possible to achieve this response. FM filters do not have such sharp "*shape-factors"* and figures of approx. 1.5:1 to 2.5:1 are more likely.

The typical filter is characterised by its 3dB and 60dB attenuation points. It is at these points on its response that the shape-factor value is determined.



Consequently a filter for FM has a bandwidth at the 60dB points that is quite wide, typical values are approx. 2 times the pass band width. So for a filter designed for 25kHz-channel spacing these values are 15kHz and approx. 30kHz. This places a limit on how closely the adjacent channels can be.

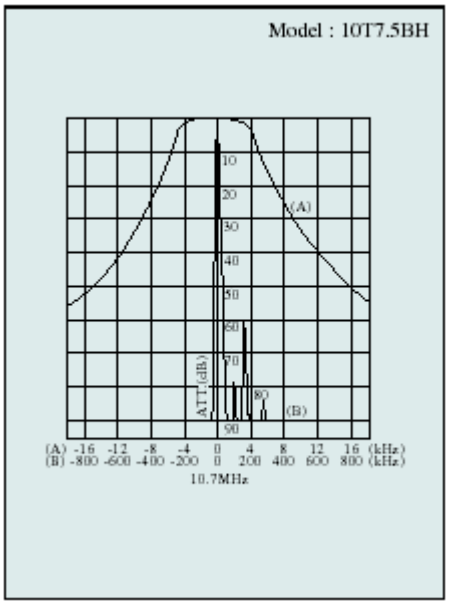
> If we go back to the original FCC specification for broadcasting FM we can see that the occupied bandwidth and the channel spacing are linked. In the FCC specification the ratio of channel spacing to bandwidth is 1.666:1, being 300kHz / 180kHz.

This "*magic number"* of 1.666 has been carried on down the years and is used for all later fm systems. For example, in a 25kHz channel-spacing system we can determine the maximum bandwidth the signal can occupy by dividing the channel spacing figure by 1.666. It gives a figure of 15kHz! Doing the same for a 12.5kHz system gives the answer of 7.5kHz. Hence, we have to choose between peak deviation and modulating frequency to stay within the allocated IF bandwidth.

Reduction of adjacent channel interference

In order to see why the channels are not spaced at the same value of the occupied bandwidth we now need to examine the properties of fm receivers. In an SSB system, because we can have filters with virtually instantaneous cut-off, we can pack stations every 2.5kHz or so without much danger of interference. With the rather sloppy shape of a filter for fm we cannot do this.

At the 60dB point on the filter skirts we are at a frequency which is offset from the filter center of approx. the occupied bandwidth figure. In other words in a 25kHz channel-spacing system the filter has a bandwidth of ±7.5kHz. Hence at a point corresponding to 15kHz from the center frequency of the filter we are at the 60dB point. At this point on the filter slope we have an attenuation of 60dB relative to the pass band figure.



Today the typical two-way radio fm receiver uses a filter with stop-band figures of approx. 90dB at a frequency offset from the center of one channel spacing. This is because the adjacent interference is a function of the strength of the unwanted signal. If the receiver is trying to hear a weak signal, of maybe 1μV, and the interfering adjacent channel signal is equivalent to a signal of 1mV, then this corresponds to a signal 60dB stronger than the wanted. Because of the filter attenuation it is attenuated to 1μV, but even so it will compete with the wanted signal. Hence, the greater attenuation we can achieve the better the receiver will be in discriminating between the wanted and unwanted adjacent channel signal.

A perusal of a data sheet for crystal filters will highlight this problem.

■ 10.7MHz, 21.4MHz Series

※ -40~+80°C(Available on request)

Model	Nominal Fre-quency (MHz)	Pole	Pass Band-width		Attenuation Bandwidth				Ripple	Insertion Loss	Terminating Impedance	Operating Temp. Range	Type	Weight
			(dB)	(kHz)	(dB)	(kHz)	(dB)	(kHz)	(dB)	(dB)	(Ω// pF)	*(°C)		(g)
10A7.5CA	10.7	6	3	±3.75	45	±8.75	65	±12.5	2	3.5	910// 25	–20~+70	D-152	23
10A15CA	10.7	6	3	±7.5	45	±17.5	65	±25	2	3	910// 25	–20~+70	D-152	23
10A30CA	10.7	6	3	±15	45	±35	65	±50	2	3	910// 25	–20~+70	D-152	23
10A7.5DA	10.7	8	3	±3.75	70	±8.75	90	±12.5	2	4	910// 25	–20~+70	D-152	25
10A15DA	10.7	8	3	±7.5	70	±17.5	90	±25	2	3.5	910// 25	–20~+70	D-152	25
10A30DA	10.7	8	3	±15	70	±35	80	±50	2	3.5	910// 25	–20~+70	D-152	25
10B7.5DA	10.7	8	3	±3.75	70	±8.75	90	±12.5	2	4	910// 25	–20~+70	D-153	25
10B15DA	10.7	8	3	±7.5	70	±17.5	90	±25	2	3.5	910// 25	–20~+70	D-153	25
10B30DA	10.7	8	3	±15	70	±35	80	±50	2	3.5	910// 25	–20~+70	D-153	25
10P7.5DA	10.7	8	3	±3.75	70	±8.75	90	±12.5	2	4	910// 25	–20~+70	D-100	32
10P15DA	10.7	8	3	±7.5	70	±17.5	90	±25	2	3.5	910// 25	–20~+70	D-100	32
10P30DA	10.7	8	3	±15	70	±35	80	±50	2	3.5	910// 25	–20~+70	D-100	32
21C7.5DC	21.4	8	3	±3.75	65	±9	90	±12.5	2	4.5	470// 15	–20~+70	D-162	12
21C12DC	21.4	8	3	±6	65	±14	90	±20	2	4	470// 15	–20~+70	D-162	12
21C15DC	21.4	8	3	±7.5	65	±17.5	90	±25	2	4	470// 15	–20~+70	D-162	12
21C30DC	21.4	8	3	±15	65	±35	80	±50	2	4	470// 15	–20~+70	D-162	12

This table is reproduced from a crystal filter manufacturer's data sheet. If we consider the first model in the table – 10A7.5CA. Here we can see that it is a 6 pole filter for 12.5kHz-channel spacing and has a bandwidth of ±3.75kHz at the –3dB points (a total bandwidth of 7.5kHz) and an adjacent channel attenuation of 45dB at ±8.75kHz offset and 66dB at an offset of ±12.5kHz. This is not good enough for most applications and so we would need to select a filter with more poles to get a steeper skirt slope. If we examine the figures for an 8-pole filter, model 10B7.5DA, we can see it has a much steeper skirt slope.

The 10B7.5DA has a bandwidth at –3dB points of ±3.75kHz and an attenuation of 70dB at an offset of ±8.75kHz and 90dB at an offset corresponding to the channel spacing of 12.5kHz.

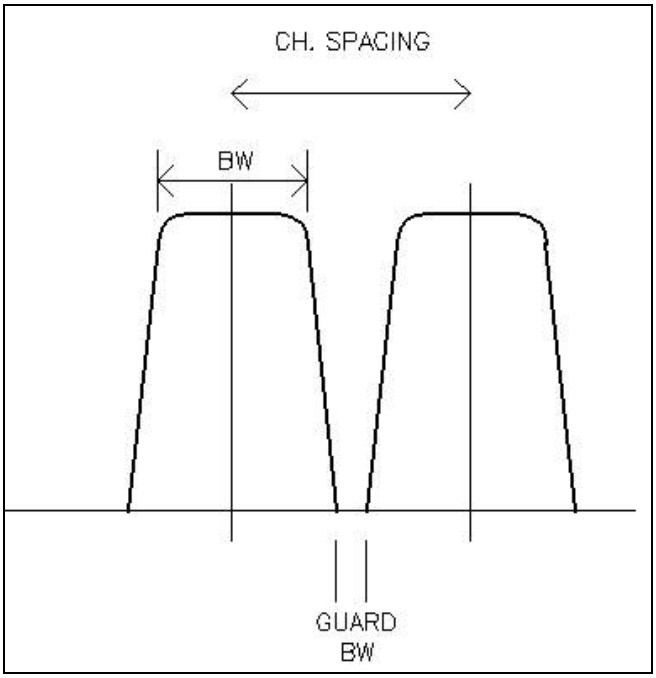
Another problem facing the use of the newer narrow channel spacing is the frequency accuracy of the transmitter and receiver. For 12.5kHz-channel spacing equipment the accepted norm for this figure is a maximum of 1kHz error in either the transmitter or the receiver. Assuming a scenario where the transmitter and the corresponding receiver are both at the limit of this specification.

Let us assume that the transmitter is transmitting exactly +1kHz off the designated channel. We will assume that the receiver is also 1kHz off frequency. If the receiver was +1kHz of the designated channel then no error exists. However, if the receiver is -1kHz then the total error is equivalent to 2kHz. As the IF filter is only 7.5kHz wide this represents an error of 2/7.5 = 26.6% and means only about 75% of the filter bandwidth is available to pass the wanted signal, which is excessive and will cause severe distortion on the received signal. Today the 12.5kHz-channel spacing limits have been tightened to a more respectable figure of 500Hz.

For speech transmissions the distortion is not of too much consequence as the human brain is very good at filling in the missing details caused by the distortion. The same cannot be said for data systems where an error of as little as 1bit is sufficient to render the received data corrupted. Hence, in 12.5kHz equipment for data (packet radio etc) the frequency setting accuracy is extremely critical. The causes of the error can be due to many factors; battery voltage variation and ambient temperature cause a slow drift in the oscillator frequency. Gross errors could be due to an error in setting up the equipment with an inaccurate frequency standard etc.

Guard Band

Because of the possibility that one or more transmitter or receiver may be slightly off frequency the *frequency planning* for channel spacing contains a small unused portion between each channel known as a *Guard Band*. In practice this is quite small, in 12.5kHz-channel spacing it is of the order of 2kHz to cater for the maximum accumulated error. Hence, if the diagram were drawn of two adjacent designated frequencies with the IF filter responses superimposed the picture would look like this:



Note: If the receiver IF filters were too wide at the skirts then it would be necessary to increase the channel spacing to prevent adjacent channel interference. This is wasteful in spectrum and hence the onus is on the equipment manufacturer to utilise a sufficiently narrow skirt filter to allow maximum packing in the allocated band.

Pre-emphasis and De-emphasis

Finally to complete the story let us look at pre-emphasis and de-emphasis. These two techniques are complimentary and normally the transmitter uses pre-emphasis and the receiver de-emphasis.

Pre-emphasis is the artificially boosting of the high audio frequency components at the expense of the low frequency ones. The need for pre-emphasis came about because of the problems with fm broadcasting. In fm broadcasting the highest audio frequency is 15kHz to allow high fidelity music to be transmitted. In speech transmissions the upper limit is only about 4.5kHz because little energy is contained in the upper portion of the audio spectrum. Consequently AM broadcast transmitters normally roll-off the audio frequency above approx. 4kHz to conserve bandwidth. The channel spacing for AM broadcasting stations is now set at 9kHz, so approx. 4kHz audio is the most any station can reasonably transmit.

In the early fm broadcasting tests it was noted that when a signal was weak the receiver IF amplifiers were not fully limited and hence not fully quieting the signal. The resultant high frequency audio noise was objectionable. The human ear has a rather non-linear response to different audio frequencies. The ear and brain combination is far more sensitive to high frequencies and less sensitive to low frequencies. The audio bandwidth of the fm broadcast system is limited to 15Hz at the low end and 15kHz at the top end. Armstrong devised a scheme whereby the higher audio frequencies would cause a much greater frequency deviation than the lower end of the audio spectrum. The slope of the response was settled on as +6dB/octave as being the best compromise. What pre-emphasis does is provide more deviation for the higher frequencies and less than normal at the lower end. (As an aside, in AM broadcasting it is common to use the opposite technique at the transmitter, here the low audio frequencies are artificially boosted with *bass-boost* to give a more realistic *music tone*).

A slope of +6dB/octave means that for an audio frequency of 1kHz the deviation will be one unit. At 2kHz audio frequency the deviation will be twice that at 1kHz and so on. The transition point was chosen as 1kHz. So the deviation occurring at the upper end of the audio spectrum of 15kHz was much higher than at 1kHz. Because the audio was artificially *treble boosted* it to some extent over rides the noise from a weak signal and was less objectionable. But the audio output was now very *tinny* and sounded unnatural as it contained too much treble content. To correct this another audio-processing network was required in the receiver to bring the audio back to a *flat response*.

This second audio shaping network was *de-emphasis*, which produces a corresponding equal and opposite response of –6dB/octave. (If the original audio signal was first passed through a pre-emphasis network and then through a de-emphasis network it would emerge unchanged, if the networks both had the same 6dB/octave slope).

The audio signal exiting the fm receiver demodulator, prior to de-emphasis, is therefore frequency shaped. If a deviation of 1kHz causes say, an audio voltage of 1V p-p, then a deviation of 2kHz will cause the signal to be 2V p-p. Most fm and ALL PM receivers require de-emphasis, if only from the Signal to Noise aspects. If the 6dB/octave de-emphasis is removed and an SINAD measurement is made of the sensitivity it will show the receiver is now approx. 9dB less sensitive.

If we now go back to Carson's Rule we can calculate the occupied bandwidth for different audio frequencies. To make the explanation simpler let us assume we are using a *packet radio data transmission* that uses two audio tones to denote the mark & space characters. Let us choose a tone of 1kHz for the low tone and a 2kHz tone for the high tone. (In practice we would normally select a non-harmonically related tone of 1.8kHz or 2.2kHz for the high tone, but for the purpose of

the explanation we will use 2kHz. Bell 202 is the standard used by AX-25 packet radio, and it uses tones of 1.2kHz and 2.2kHz).

Let us define our peak deviation as being 2.5kHz for simplicity.

When the low tone is transmitted the deviation will be half that of when the high tone is transmitted because of the +6dB/octave pre-emphasis. Hence, when the low frequency tone is sent we will have a deviation of 1.25kHz. When the high tone is sent we will have a deviation of 2.5kHz. Now using Carson's Rule we can determine the occupied bandwidth for each case.

Low tone = 2 (1.25 + 1) = 4.5kHz BW which will fit within the 7.5kHz IF BW
High tone = 2 (2.5 + 2) = 9kHz BW which is greater than the IF bandwidth.

As we only have a maximum receiver bandwidth of 7.5kHz we must reduce the deviation to the point where the occupied bandwidth is less than 7.5kHz.

However, we would not normally choose the two tones to be harmonically related and the high tone would be better chosen at 1.8kHz.

So our occupied bandwidth calculations now look like:

High tone = 2 (2.5 + 1.8) = 8.6kHz which is still excessive, hence we must reduce the deviation more.

Assume we use a peak deviation of 2kHz.

High tone = 2 (2 + 1.8) = 7.6kHz BW which is just about perfect.

Then our low tone will occupy: (The deviation will now be 1/1.8 x peak deviation because of the +6dB/octave slope = 1.1kHz).

Low tone = 2 (1.1 + 1) = 4.2kHz BW

At the receiver the signal exiting the demodulator will be vastly different AC levels, but after passing through the de-emphasis network will become the same amplitude. In a data system the audio tones would then be *squared-up* in a hard limiter stage to be fed to the digital processing circuitry, which detects the tone frequencies and hence decides if it is a one or a zero character. Hence, any slight differences in the audio levels is not of great concern. It is the use of a *squarer circuit* that makes the use of non-harmonically related tones essential.

This worked example explains why when using packet radio data the peak deviation must be reduced to stay within the allowable bandwidth.

IARU Region 1 choice of IF bandwidth

The stated IF bandwidth of the IARU Region 1 for NBFM is 12kHz. This is very different from the accepted international standards for 12.5kHz channel spacing equipment of 7.5kHz. Knowing Carson's Rule and with the basic parameters as laid down we can see why this is so.

The peak deviation in the IARU Region 1 system is given as 3kHz. Similarly the recommendation for the maximum audio (modulating frequency) is also 3kHz. Using Carson's Rule we can calculated the required bandwidth.

B = 2 (3 + 3) = 12kHz.

An IF bandwidth of 12kHz is in fact an internationally recognised standard, but it is for 20kHz channel spacing and not the stated spacing of 12.5kHz as laid down in the IARU Region 1 VHF

Hand Book. So it is apparent that somewhere along the way the parameters were incorrectly defined.

20kHz is not a commonly recognised channel spacing today, it was in use by the USA in the past but has long since been superceded by the later 10kHz-channel spacing. 10kHz channel spacing gives an occupied bandwidth of 10/1.666 = 6kHz which is more consistent with AM transmissions than the frequency inefficient types such as FM or PM.

Very few, if any, European countries have ever used a channel spacing of 20 or 10kHz, the vast majority have used the 50kHz, 25kHz and the 12.5kHz common today. Commercial two way radio equipment likely to find its way onto the surplus market and able to be purchased by amateurs will almost certainly be either 25kHz or 12.5kHz today.

So we are left with a quandary if we persist with the standard laid down by the IARU Region 1 VHF Manual.

Appendix

The derivation of FM Broadcasting stations channel spacing.

The allocation of spectrum is performed by the ITU. The coordination of the channel frequency is done in Europe by the European Broadcasting Union (EBU). In other parts of the world the national legislator allocates channel frequencies based on various criteria. In North America the FCC allocates the stations channel frequency.

Below is a simplified example of how the fm broadcasting channels are allocated.

Center Frequencies

While most countries use frequencies ending in .1, .3, .5, .7, or .9, some use .0, .2, .4, .6, and .8. Still others use .15, .35, .55, .75, .95, or .05, .25, .45, .65, .85 instead. Some, like Italy, allow a station on any 50kHz boundary where it can be squeezed in. This offset helps to prevent co-channel interference, and take advantage of FM's capture effect and receiver selectivity.

USA Bandplan and Channel Numbering

In North America, each channel is numbered from 200 (87.9MHz) to 300 (107.9MHz) in increments of 1 (0.2MHz). 87.9MHz, while technically part of TV channel 6 (82.0~88.0MHz), is used by two class D stations in the U.S. as channel 200. Portable radio tuners generally go down to 87.5, in case they are taken abroad. Automobiles are unlikely to go overseas, but usually tune down to 87.7, so that TV channel 6 audio on 87.75 can be received (although at a somewhat lower volume).

In the USA, the center frequencies of 88.1 though 91.9 are reserved for non-commercial stations only, e.g., religious or educational. The center frequencies 92.1 through 107.9 may contain either commercial or non-commercial stations.

Originally, the FCC devised a band-plan where stations would be assigned at intervals of 4 channels, or 800 kHz separation, for any one geographic area. Thus, in mid-Missouri, stations might be at 88.1, 88.9, 89.7, etc., while in the St.Louis area, stations might be at 88.3, 89.1, 89.9, 90.7, etc. Certain frequencies were designated for Class A only (see FM broadcasting), which had a limit of 3000 watts ERP and an antenna height limit for the center of radiation of 300 feet height above average terrain (HAAT). These frequencies were: 92.1, 92.7, 93.5, 94.3, 95.3, 95.9, 96.7, 97.7, 98.3, 99.3, 100.1, 100.9, 101.7, 102.3, 103.1, 103.9, 104.9, 105.5, 106.3, and 107.1. On other frequencies, stations could be Class B (50kW, 500 feet) or Class C (100kW, 2000 feet), depending on which Zone they were in.

In the late 1980s (exact year, anyone?), the FCC switched to a "band-plan" based on a distance separation table using currently operating stations, and subdivided the class table to create extra classes and change antenna height limits to meters. Class A power was doubled to 6kW and the frequency restrictions noted above were removed. Basically, as of late 2004, a station can be "squeezed in" anywhere as long as the location and class conforms to the rules in separation table (http://www.fcc.gov/mb/audio/spacing/).

The basic formulas determining radio channels for North America as mentioned is as follows:

(MHz − 47.9) * 5 = ch#
(ch# / 5) + 47.9 = MHz

Deviation and Bandwidth

Normally, each channel is 200kHz (0.2MHz) wide, and can pass audio and sub-carrier frequencies up to 100 kHz. Deviation is up to 200kHz total, or ±100 kHz, but is typically limited to 150kHz total (±75 kHz) in order to prevent interference to adjacent channels on the band. Stations in the U.S. may go up to 10% over this if they use stereo or other sub-carriers, increasing total modulation by 1% for each 2% used by the sub-carriers.