# SINGLE FREQUENCY NETWORKS IN DIGITAL RADIO

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## ABSTRACT

Not too surprisingly, a Digital Radio Single Frequency Network (SFN) shares the same properties as a Digital Television SFN. For this reason some of this paper has been taken from [1]. The main differences between radio and TV SFN are due to the different S/N requirements and guard intervals. SFNs do offer significant potential advantages including better coverage, less interference, less power, higher reliability and a more efficient spectrum use. These properties are derived from basic propagation models. Potential problems that must be considered, and are specific to SFNs, are discussed. They all relate back to receiver performance. In addition, some basic discussion about how antenna patterns can be used to combat delay problems is included. The "hybrid" mode of HD Radio has some significant differences in its requirements for SFN distribution since both the digital and analog components must be considered. For a digital-only SFN overlaid on the coverage area of a hybrid FM station, there would still be analog implications to consider. Since hybrid transmission is likely to be the reality for many years to come, it raises special issues on which we elaborate later in the paper.

## GENERAL

According to Shannon the more energy the more information (bits) can be transmitted since the bit energy versus the noise power spectral density increases ($E_b/N$). All broadcasters know that the more power you transmit the better coverage you get. This has always been understood to mean more power into the same antenna. However, the same effect can be had by sending the extra power to another antenna. In a sense, one can argue that the SFN concept is nothing but more power in disguise. There is some truth to that opinion, but it will be shown that for practical propagation, SFNs should actually cover the same area with less power. The reason is that an SFN allows a more even distribution of the power. So, in theory, adding transmitters, i.e. building a Single Frequency Networks (SFNs) should always improve performance.

Single Frequency Networks (SFNs) are nothing new in radio; they have been around for a long time in analogue FM. However, performance has been less than stellar. This poor performance is not due to any inherent limitation in SFNs. In fact, it is because of the lack of equalizers in traditional FM receivers. At the moment the receiver can handle the multipath, SFNs offer many potential advantages. Since all digital systems such as HD Radio® and DRM® already have equalization, the old limitations are gone.1 This opens the door for SFNs. What SFNs have to offer are: flexible coverage, improved coverage, decreased interference, and higher reuse. Since all SFN systems are inherently the same, in particular for TV and radio, much of the theoretical background has been taken from [1].

To increase coverage in single transmitter system requires a combination of increased antenna height, increased output power, and/or a different antenna pattern. None of these options might be practical. In this case SFNs can offer an attractive option, easily extending coverage with the simple addition of lower-power transmitters at various sites throughout the desired coverage area. Among their many benefits, SFNs are more flexible in terms of coverage area, superior interference performance and inherently more fault-resistant. Another difference for a SFN or repeater may be control of interference to stations on the same or adjacent frequencies since lower power (than the primary "broadcast" transmitter) to fill areas of poor coverage. The focus is on HD Radio and DRM, but the same principles apply to all SFN systems. Three different cases of digital audio broadcasting (DAB) will be considered, of which the first two are very similar: digital-only HD Radio and DRM. The third being hybrid analog-digital version of the HD Radio system.

## MULTIPATH AND DOPPLER SHIFT

No receiver can distinguish between reflected signals from one transmitter versus several received signals from multiple transmitters. To the extent that a system can handle multipath, it is possible to design an SFN around it. Since analogue AM and FM receivers do not

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[1] "HD Radio" is an In-Band On-Channel (IBOC) DAB technology licensed by iBiquity Digital Corporation and approved by the FCC and National Radio Systems Committee. DRM (Digital Radio Mondial) is an open-source IBOC platform for shortwave, mediumwave/AM and longwave digital radio broadcasting approved by the ITU, IEC and ETSI.

have equalizers, how do they survive in a multipath environment? How do they function at all, since some multipath is always present? The answer lies in the narrow bandwidth in relation to the delay spread. The delay spread being the duration of the RF channel's impulse response. For most practical cases, the impulse response will have died down within 100 µs, often after only a few µs. The net effect is that the received signal will appear to fade in amplitude. I.e. there is no frequency selectivity, commonly referred to as "flat fading."

In the case of analog stereo FM, however, the effects of multipath can occur before flat fading is significant. For example, delays of only a few microseconds between the direct and reflected paths can cause audible distortion and crosstalk if the amplitude ratios are small (e.g., less than 20 dB). This is because analog stereo is sensitive to sideband distortions farther from the channel center than with monophonic FM modulation, and is analogous to wideband data modulation requiring more equalization against multipath than narrowband data.

If the bandwidth of the signal increases, the fading will become more and more frequency dependent. In the time domain, the effect of non-flat fading is inter symbol interference (ISI), i.e. the bits/symbols start to overlap each other. It is intuitively clear that a small amount of overlap should be fine, but significant amounts will blur the signal. In a digital broadcast system with its higher bandwidth and need for high data rates, intersymbol interference does become a problem.

There are two basic approaches to combat multipath propagation/ISI. One is to design a signal that is robust to reasonable multipath. The second is to have an equalizer in the receiver. Quite often a combination of the two is used, starting with the latter. Since the RF channel can be modeled as time a varying filter, the job of the equalizer is to continuously find the inverse filter and apply it to the received signal. The main problem is generally in the estimation of the filter. This has been, and still is, an area of active research.

The second approach is to use a signal that is inherently immune to multipath. With this respect OFDM signals have become extremely popular. They are used in HD Radio and DRM as well as some digital television systems. An OFDM system with N carriers can be thought of as consisting of N narrowband transmitters each transmitting a part of the signal. The resistance to multipath is based on two properties, a guard interval and the use of orthogonal carriers. The actual signals consist of CW carriers, whose phase and amplitude are kept fixed during the symbol time. To make them orthogonal, the spacing must be a multiple of the inverse of the symbol time.

Assuming that the channel impulse response is shorter than the guard interval, the guard interval between the symbols ensures that the intersymbol interference period is longer than practical delay spread. For this reason, many OFDM systems can work in different modes, allowing the user to choose different guard intervals. The frequency response caused by the RF channel will only cause a fixed phase and amplitude offset to each carrier, resulting in each carrier seeing “flat” fading, making them easy to detect. It is worth noting that applying a matched filter to each carrier yields an optimum linear detector, equivalent to taking the FFT on the received signal. This gives the OFDM signal an additional advantage of signal processing with reduced complexity – resulting in lower cost receivers.

As with all systems, there are trade-offs; the guard interval results in a decreased throughput. An OFDM system without guard interval using an equalizer would have a higher throughput. It should also be noted that it is possible to add an equalizer to an analogue FM receiver, given the decreasing cost of processing power (DSPs and FPGAs), which would make analogue SFNs much more tempting.

## DOPPLER SHIFT

Doppler shift will occur if the impulse response changes over time, for example by the receiver being in a moving car. The net effect is that a reflected signal can be slightly offset in frequency

$$f = f_c \frac{1}{1 + v / v_c}$$

v Speed of object

$v_c$ speed of light $3 \cdot 10^8$ m/s

In an SFN system when moving away from one transmitter towards the other, the frequency difference between the two signals will be

$$f = f_c \frac{1}{1 + v / v_c} - f_c \frac{1}{1 - v / v_c} \approx f_c \frac{2v}{c}$$

For a car on a freeway, worst case, this would be about

100MHz((2·100km/h)/(3·$10^8$ ))=2/3·100/3.6=22Hz.

In an OFDM receiver without equalizer, the two signals, after taking the FFT, will appear as having a 22Hz offset. This destroys the orthogonality between the carriers. An alternative view of this degradation is as intersymbol interference in the frequency domain. The question is: how much interference this will cause and might it cause problems? Assuming that the receivers do a simple FFT of the signal, then the time limited carriers will have a sin(πx)/πx type of spectra, where each carrier would be found at x=1,2,3.... etc. For FM HD radio with a 363.4Hz carrier spacing, a 22 Hz offset will result in the n'th carrier leaking into the first by

$$\varepsilon_n = \sin((\pi 22/263.4 + n)/(\pi(22/363.4 + n))$$
$$n = \pm 1, \pm 2, \pm 3, ...$$

Since the different carriers are assumed uncorrelated, the power will be

$$\sum |\varepsilon_n|^2 \approx 1.1 \cdot 10^{-2} \Rightarrow SDR = 40dB$$

Hence, Doppler shift is not a problem. If someone would be driving really fast, say 200km/h (125mph), the Doppler shift could reach 44 Hz, and the SDR would be 14 dB. For a QPSK signal, this is still acceptable. Note that this assumes that the car is driving on a straight line from one transmitter to the other; in reality this is somewhat unlikely.

It follows that multiple transmitters in an DAB SFN can have quite a bit of frequency offset. As a rough estimate, 10 Hz. By comparison, the ATSC digital television SFN standard calls for transmitters to be within 1 Hz of each other. The reason lies with the receiver equalizer, which needs to track the two carriers, and in many receivers this happens on a rate of a few Hz. With today's easy access to good frequency references (GPS), it is relatively easy to lock two transmitters to within one Hz.

## HD RADIO RECEIVER PERFORMANCE

As in the normal multipath case, the receiver will work just fine, as long as signals delayed more than what the equalizer can handle will be below the signal to noise threshold - taking some fading margin into consideration. Note that the transition is smooth, so that if a receiver can handle 100 us of delay, it won't immediately break down at 101us. Theoretically, what really matters is the bit energy ($E_b$) relative to the power spectral density of the noise ($N_0$). Since signal to noise (S/N) is more commonly measured, it is practical to relate the two. Since the HD Radio carriers are QPSK, one can approximate the S/N needed by relating back to QPSK performance. In turn, QPSK can be seen as two orthogonal BPSK signals, so it is possible to relate back to BPSK performance. Turns out that Eb/No for an OFDM carrier is the same as the S/N of the signal. Half of the QPSK signal energy and half the noise energy is in the I channel and the other half in the Q channel. The bit error becomes

$$P_B = Q\left(\sqrt{2S/N}\right)$$

For an SNR of 5 dB, the BER is already down to 10e-6, so the signal is inherently robust.

The HD Radio waveform has a guard interval of about 156 µs, out of a total length of 2.9 ms. If there is a multipath delay of 78µs, there will be little overlap within the "core" symbol, and very little ISI. For a multipath delay of 156 µs, the overlap will be 78 µs, where the overlapping signal is gradually decreasing due to the pulse shaping. Hence the S/N due to the overlap will be $10\log_{10}(2900/78)$=16dB. Since this is a good S/N ratio for QPSK, it seems that multipath delays of up to the guard interval of 156 µs, should be acceptable. Ideally it should be less than 78 µs.

Should one allow for a fading margin? Definitely, the different paths will fade independently so a 10 dB fading margin should be sufficient. This only affects delayed signal paths that are beyond 78 µs. For a delayed signal of 156 µs, the S/N will be 6dB taking the fading margin into consideration, which is an acceptable interference level.

## DRM RECEIVER PERFROMANCE

The DRM signal has a guard interval of more than 2 ms, as listed in Table 1, or about ten times that of HD Radio. The standard allows for 4-QAM (QPSK), 16-QAM and 64-QAM. The S/N requirement in QPSK mode will be the same as for HD Radio. The other modes will require higher S/N ratios of 6 dB and 12 dB relative the QPSK mode.

Table 1 DRM, different modes

| Robustness mode | Duration $T_u$ | Carrier spacing $1/T_u$ | Duration of guard interval $T_g$ | Duration of symbol $T_s = T_u + T_g$ |
|---|---|---|---|---|
| A | 24 ms | $41^{2/3}$ Hz | 2,66 ms | 26,66 ms |
| B | 21,33 ms | $46^{7/8}$ Hz | 5,33 ms | 26,66 ms |
| C | 14,66 ms | $68^{2/11}$ Hz | 5,33 ms | 20 ms |
| D | 9,33 ms | $107^{1/7}$ Hz | 7,33 ms | 16,66 ms |

As compared to HD Radio, the guard and symbol time are both about five to ten times greater. The advantage is that this OFDM signal can handle larger delay spread. The down side is that it is more sensitive to Doppler shift.

## SFN IMPLEMENTATION ISSUES

The problems one is likely to encounter are the same as in TV [1]. Implementing a SFN does take care since there are several potential problems. Simply feeding the same AES data streams to two different transmitters will not work. For an SFN system to work the transmitted signals must be essentially identical and within an appropriate time interval. There are at least three things that can break an SFN system: Timing errors, frequency offset, and non-identical data.

In an SFN system most receivers will receive only one dominating transmitter. Dominating in the sense that the other signals are sufficiently weak to not interfere. The only receivers that will experience multiple signals are those where the signals from the different transmitters are within the SNR range of the various systems, e.g., 10-15 dB. Outside this range, the other transmitters can be treated as noise, as shown in Figure 1. Signals from other transmitters outside this range can be used by a receiver with a good equalizer, but it doesn't have to. In an OFDM system, all the signals arriving within the guard interval will be used by the receiver. These signals will be used by the OFDM receiver without any need for an equalizer.

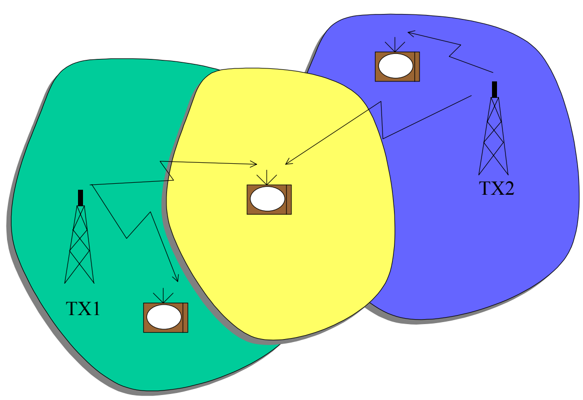


**Figure 1** Areas served by the different transmitters

In an SFN system there will always be areas where the signals from two or more transmitters are very close in amplitude, within a dB or less. This will result in some frequencies being notched out. There is nothing that can be done about this. However, it will not break the system; the error correction will handle it (within reason). The problem with signals close in amplitude is less of an issue in OFDM since OFDM receivers do not care if the channel is minimum phase or not. As long as the delayed signal in an OFDM signal are within the guard interval, they will be correlated and will make the RF channel appear to have a more uniform frequency response. A worst case is two signals of equal amplitude with a delay of 75-150 µs, which will result in notches in the frequency response every 13-7 kHz. For HD Radio's 363 Hz frequency spacing, there is more or less a 50% chance that a particular carrier is significantly attenuated.

## FREQUENCY ERRORS

It was shown earlier that any frequency offset between carriers in an OFDM system results in ISI in the frequency domain. Further more, this frequency offset can be seen as a Doppler shift. As long as the frequency offset is within the Doppler shift bound, the system will work. For both HD Radio and DRM this limit is a fairly generous 20Hz (approx). In systems that do use equalizers, the Doppler shift can be tracked out providing the equalizer can be made to track the channel. In OFDM systems without equalizers, the general case, it is not possible to track it out.

## DATA AND SYNCHRONIZATION ERRORS

Ideally, the different transmitters will transmit exactly the same signal. One way to achieve this is by distributing the actual RF signal using repeaters. If not, the individual transmitters must perform identical modulation. If the individually modulated signals are not the same, the receiver will obviously not work. This is a problem unique to SFN systems. The studio to transmitter link, STL must be error free; if not, this becomes a separate problem.

It might seem that this would be all. However, not all digital transmission standards are deterministic. For example, the input data is often processed in blocks, but where to start is left up to the modulator. Trellis coders might have random initial states, as in the ATSC digital TV standard. Or, if an error occurs in a trellis coder, it might propagate forever. In this case the system is, in some sense, unstable. Furthermore, any training and synchronization sequences must be inserted at exactly the same point. These types of problems are also unique to an SFN. One way to achieve synchronization is to insert some symbol in the data stream. An alternative is to send all, or part of, the modulated data to the transmitter. This simplifies things but might require more bandwidth in the STL.

Data synchronization only becomes a problem if SFN applications were not considered at the system design phase. Once one is aware of the problems of data synchronization, they are easily circumvented at the time of the standard setting.

## DELAY AND TIMING ERRORS

The theory behind signal delay is exactly the same for both radio and TV SFNs. This and the following sections up until "Less Interference in SFNs" summarize results found in [1]. For the SFN to work the time offset as seem by the receiver must be within the bounds of the equalizer. The time difference between the signals from two different transmitters depends on two factors: the time offset between the transmitters, and the receiver's position relative to the transmitters. If the delay is longer than what the equalizer can handle, there will be problems. Similarly, if the receiver already sees a delayed signal from one transmitter, adding a second or third transmitter etc., which introduces very little extra delay, can potentially put the equalizer over the edge.

Lines of constant time difference turn out to be hyperbolas as seen in Figure 2.

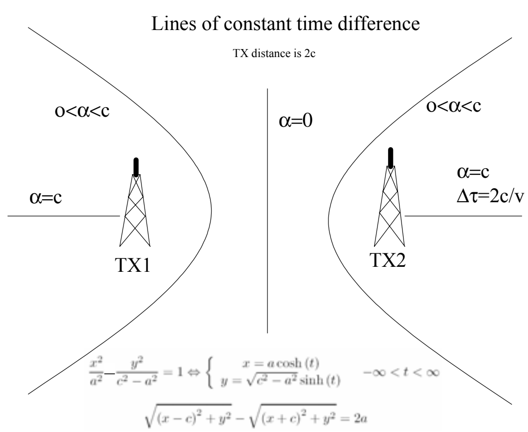


**Figure 2** Lines of constant delay.

Given to transmitters at coordinates +/- c (see figure 2) the lines of constant delays are:

$$y = a \cdot \cosh(t)$$
$$x = a \cdot \sqrt{c^2 - a^2}\,\sinh(t)$$

where a is the distance difference, which directly relates to the time difference through $\Delta\tau = a / v_c$.

In an SFN the delays are only important in relation to the signal strength ratio. This can be calculated assuming omni antennas and that the signal attenuation depends on the distance raised to some power α (propagation constant). Setting the signal ratio from the two transmitters in Figure 1 constant and solving gives:

$$\frac{P_{TX1}}{P_{TX2}} = \frac{\left(\sqrt{(x-c)^2 + y^2}\right)^\alpha}{\left(\sqrt{(x+c)^2 + y^2}\right)^\alpha} = p^\alpha$$

$$\left(x - c\frac{1+p}{1-p}\right)^2 + y^2 = c^2\frac{4p}{(1-p)^2}.$$

This is the equation of a circle centered at (c((1+p)/(1-p)),0) with radius c((2√p)/(1-p)). The circular shape does not depend on the attenuation constant α, but the actual signal ratio on the circle does. The higher the attenuation, α, the higher the signal ratio for a given circle, Figure 2.

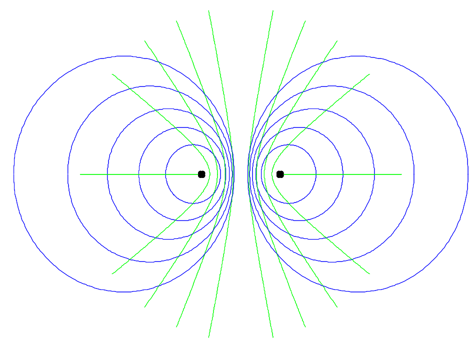

**Figure 3** Circles showing constant signal ratio and hyperbolas showing equal delay. The two transmitters at ±c.

In reality the curves of constant signal ratio will depend on the actual propagation and antenna pattern and could be quite different from circles. The important point is that the curves are generally different from the curves of constant delay. If the HD Radio receiver can handle 78µs of delay this distance is about 24 km (15 miles), and for 156µs the distance is 48 km (30 miles). For DRM, the same figures are in above 200 km (125 miles).

Far away from the transmitters, the signal strength from the two transmitters will be almost the same. If the distance between the two transmitters is such that the delay is beyond what the receiver can handle one will get a "dead zone" behind the two transmitters, Figure 4.

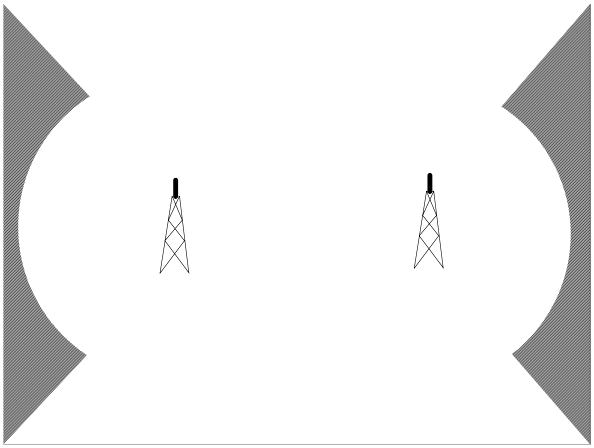

**Figure 4** The shaded region shows the area where no reception is possible in an SFN with two transmitters, if the distance between the two is too long.

Depending on the systems, this area, assuming that it exists, might be so far away that it is outside the desired coverage area. In which case it doesn't matter. The antenna pattern can be used to combat this problem, which will be covered later.

## TRANSMITTER SPACING

This is probably the most important issue and depends on the multipath properties of the OFDM signal; and, if present, the abilities of the equalizer. The previous section provides a lower bound on the transmitters spacing. It is obviously desirable to find the maximum spacing. Taking into account that the system can handle some harmful interference (i.e., long delays beyond a certain level) as long as it is below x dB, a less conservative estimate can be found:

$$d = 2c = y_{\mu s} 300 \frac{10^{x/(10\alpha)} + 1}{10^{x/(10\alpha)} - 1} m$$

where $y_{\mu s}$ is the allowable delay in μs, α is the signal attenuation and x is the acceptable interference level in dB. Using x=15dB, α=3, and y=78μs, then c=24km (14 miles). So the maximum distance between the transmitters is 48km (28 miles), about twice the distance predicted by using $y_{\mu s}$300. For a more detailed derivation see [1].

## POWER CONSUMTION IN SFNS

It turns out [1] that the power consumption in an SFN relative to a single transmitter system depends entirely on the signal attenuation α. For free space propagation (α=2) they are equivalent, for an α greater than 2, the SFN will need less power [1]. The greater α is the more advantageous an SFN becomes. For an SFN with N transmitters the ratio will be

$$\frac{P_{\sin gle}}{P_{SFN}} = N^{\alpha/2-1}.$$

Note that if α>2 the overall power consumption in an SFN will decrease as the number of transmitters increase.

## LESS INTERFERENCE IN SFNS

This is an important property of an SFN. The main reason for this is that the ratio between the closest transmitter and the interferer is greater in an SFN. The calculations are a bit more involved. The interested reader is referred to [1]. In essence, the more transmitters used in the SFN and the higher that the propagation constant (α) is, the more advantageous an SFN becomes.

## TX ANTENNA PATTERNS

The antenna patterns can be used to minimize areas of harmful multipath. If one of two identical transmitters changes its output power, then the area between the two where the signals are within ±x dB will decrease, and move towards the transmitter with the lower power. As an example: assume two transmitters have the same output power and omni antennas, let the distance between them be d=2c and let α=3. Then the region where the signals are within 15 dB of each other occurs at distance of 0.519c from each transmitter. In this case, then the signals are within 15 dB in the interval -0.5c to 0.5c, or about 50% of the distance. If the signal from the second transmitter is 30 dB weaker, this interval becomes 0.5c to 0.95c or 25% of the distance, Figure 5.

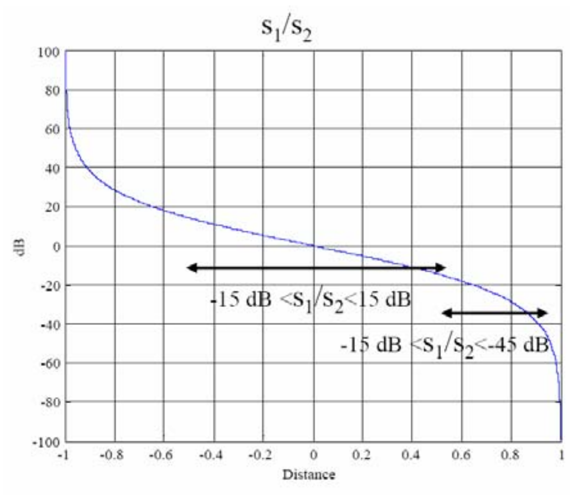


**Figure 5** The ratio $S_1/S_2$ for α=1 with one transmitter at -1 and one at +1.

The same effect can be had if the transmitters that are away from the center use a directional antenna, where the front to back ratio of the antenna provides the power difference. This will decrease the area of harmful interference, i.e., signals outside the guard interval/equalizer range, allowing wider transmitter spacing. Note that the delay between the transmitters must be changed so that zero delay between the received signals occurs in areas where the two signals are of equal magnitude.

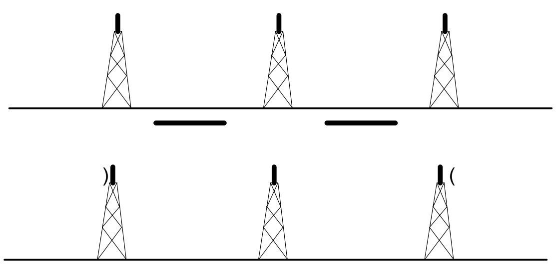

**Figure 6** The effect on the area where equalization is needed, thick line, for omni and directional antennas.

If directional antennas are used, as shown in Figure 6, it is probably better to delay the signals in the two outlying transmitters by the propagation delay. This approach may eliminate the underscored "dead zone" by using an antenna with a front-to-back ratio equal to the S/N ratio plus a suitable fading margin (15 dB for HD Radio), Figure 7, but this comes at the price of lower signal strength in the area between the antennas. Adding a third transmitter between the two as shown in Figure 6 can solve this problem. Another alternative is to use four transmitters on a circle with directional antennas and a fifth transmitter in the center using an omni directional antenna. In this case, the antenna gain in the directional antennas must be sufficiently low outside ±90deg in addition to a good front to back ratio. Other configurations are obvious.

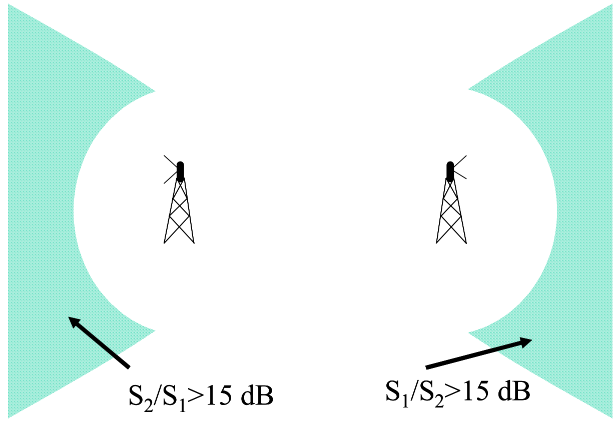


**Figure 7** Using directional antenna with sufficiently high front to back ratio to eliminate the "dead zone."

## OTHER POTENTIAL ADVANTAGES

There are two potential advantages of interest: S/N ratio improvement and diversity. The first one is based on the fact that the sum of two identical signals with independent noise results in a 3 dB S/N ratio gain. In an OFDM system, any signal arriving within the guard interval will improve the signal to noise ratio and is in theory helpful. In a system using equalizers, the S/N ratio gain might not happen due to the equalizer itself adding more gain to parts of the spectrum where the signal is weak. This tends to result in a noise gain. The second advantage is that multiple signals provide diversity. If the receiver sees two signals that are fading independently, the probability that both signals are drowned by the noise is significantly lower than for a single signal. For example, if the probability that one signal is below the noise level is 5%; the probability that both are below the noise level is only 0.25%. However, this assumes the two signals to be independent, which is not the case for OFDM signals when the delay is shorter than the guard interval.

Antenna diversity at the receiver would help, but is only realistic for some receiving situations, such as car radios. A fixed radio receiver would benefit from a directional antenna. Such an arrangement would allow the receiver to change the ratio of the two signals. For a portable receiver, this is unrealistic.

## PLANNING AND IMPLEMENTATION

An challenge to designing SFNs is controlling the interference between the transmitters. One must predict the signal strength from each transmitter as well as the relative propagation delay times across the desired coverage area. When signal strengths are similar *and* differential delay times exceed a critical value, multipath interference is predicted. The objective is to minimize these areas of multipath or move them to relatively unpopulated places.

In designing SFNs, multipath can be controlled by transmitter site selection, antenna radiation pattern, output power, and modulation time offsets. The site selection is the most powerful, so careful planning of the system is important. Changing sites once the system is built may be expensive or prohibited. Optimizing the antenna radiation pattern and signal delay are possible once the sites are established. Output power should be established once the site is chosen since a 5-10 dB power increase usually requires extensive re-engineering of the other transmission parameters. A power decrease results in a waste of installed transmitter capacity.

No system, SFN or not, will provide 100% coverage. As with all broadcast systems, there will be a tradeoff between coverage and cost. The multipath requirement is the same as for a single transmitter system (i.e., it depends on the system and to some extent what margins are used).

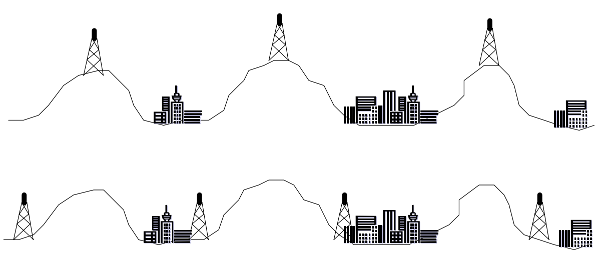

**Figure 8** Top: Site location that will increase multipath. Bottom: Site location that will decrease multipath.

In the SFN site selection process the trick is to use the terrain to one's advantage. Figure 8 shows two ways to achieve coverage in a hilly area, with most of the population living in the valleys. With the transmitters placed on the top of the ridges, the risk of excessive multipath is significant. Moving the transmitters down into the valleys eliminates most of the multipath.

Repeaters (also known as boosters) can be used to implement SFNs and they do have one advantage: since the repeater merely repeats the data modulation, the transmitted RF signals will be identical. Even for a broadcast system that can not easily be synchronized due to non-deterministic modulation, repeaters can be used to create an SFN. Repeaters have at least one short coming: their interconnection link adds delay. This is a serious issue since it is often desirable to have zero delay right between the two transmitters. One can employ synchronized transport networks and GPS frequency standards, but the costs may outweigh the coverage benefits offered by the repeater.


**Figure 9** KCSN(FM) primary analog coverage area (part); green is 60-70 dBu. This Longley-Rice coverage prediction shows a sharp cutoff of coverage to the south. Central Los Angeles is in the lower right of the map.

The planning of repeaters, boosters and single frequency networks is greatly aided by computer analysis. Computer models can evaluate the field strength ratios and propagation time differentials of the transmitters at millions of local points, a process that would be nearly impossible by hand. Interactive analysis of the location and severity of multipath zones permits the engineer to choose transmission sites and other parameters necessary to optimize a SFN design.

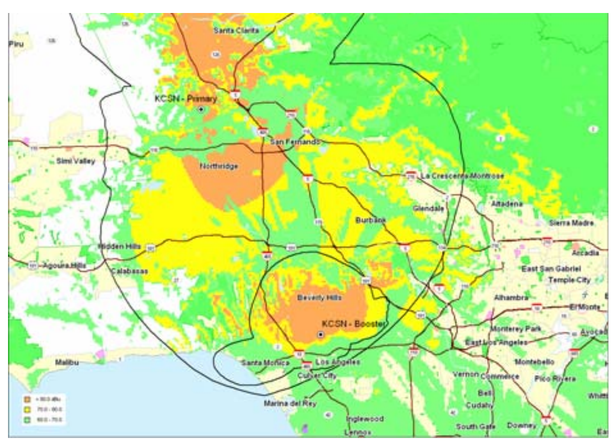


**Figure 10** Combined KCSN primary and booster coverage with F(50,50) 60 dBu contours overlaying Longley-Rice field strength prediction.

As a case study of SFN design, NPR Labs wanted to evaluate the performance of the first HD Radio single frequency network, built by public radio station KCSN(FM), Northridge, California [5]. This station experiences terrain shadowing effects, caused by the Santa Monica Mountain range that extends along an east-west line in the southern part of their coverage area. This effectively shields Santa Monica, Beverly Hills and Hollywood from service, as shown in Figure 9.

KCSN designed and built a hybrid (analog FM and HD Radio) booster on a building in south Beverly Hills with a directional antenna array aimed northward. This filled in signal in the shielded area, but avoided coverage extension beyond the 60 dBu service contour. The predicted coverage with the booster added is shown Figure 10.

The KCSN booster and primary transmitter are fed by time-synchronized STLs, so that digital audio is delivered to the inputs of the analog and HD Radio transmitters with differential delay of $\pm 2$ μS. GPS is used at both transmitters to control operating frequencies.

To evaluate multipath intersymbol interference NPR developed computer software to model KCSN's two-transmitter SFN. First, the terrain-sensitive coverage predictions were performed in a RF design tool using the Longley-Rice propagation model with 3-arc second resolution USGS terrain data. A receive height of 2 meters was chosen to represent ground-based (especially vehicular) coverage. Land-use land-cover adjustments were used to improve accuracy of predicted fields. Next, numeric arrays containing the propagation study for each transmitter were imported into MapInfo®, a GIS tool, where custom software was developed to:

- Calculate signal propagation time from the primary and booster transmitters to a grid of finely-spaced points across the study area;

- Compare the field strength ratio of primary and booster signals at the same points as above;

- Determine field ratios *and* time-of-arrival differences that may result in intersymbol interference of the HD Radio signals from primary and booster transmitters); and

- Generate a map showing the locations that exceed the parameter guidelines.

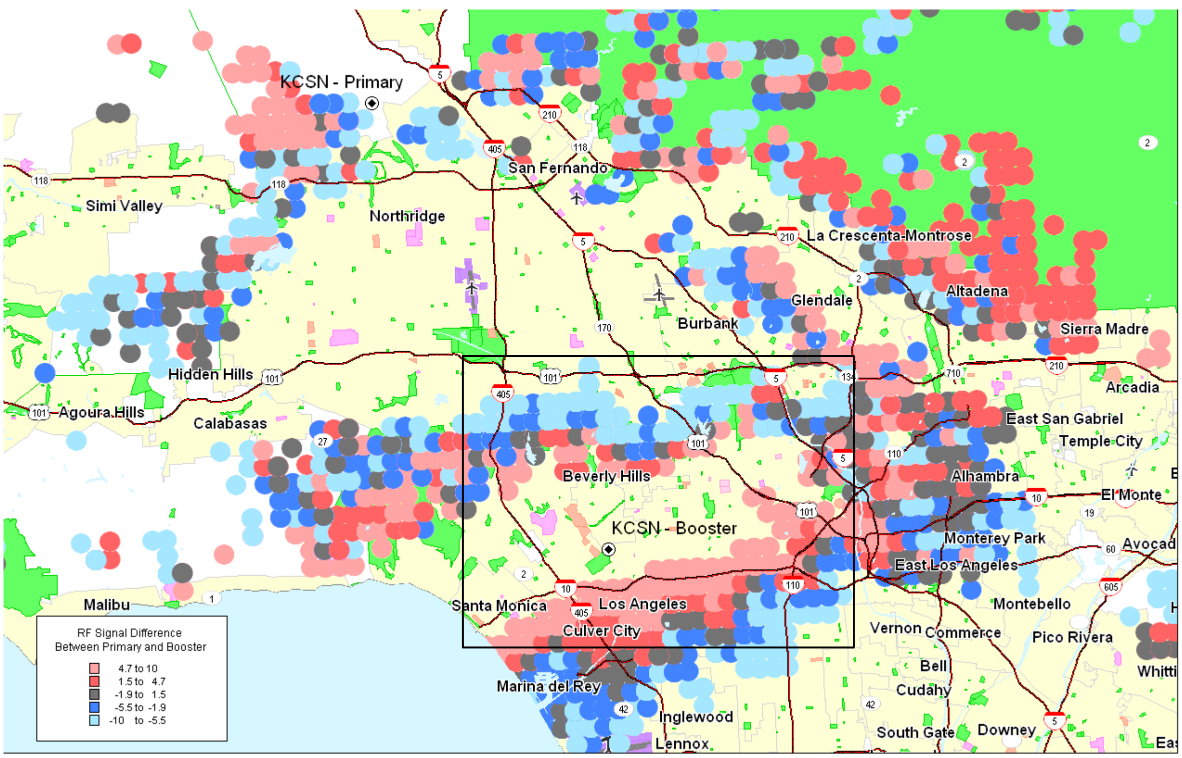


**Figure 11** Map showing locations of potentially high primary and booster multipath as colored dots. Reddish dots indicate where the signal from the primary transmitter is stronger and bluish dots indicate where the signal from the booster is stronger; the signal ratios of the gray dots are within 1.5 dB. The rectangular box shows the study area of the measurement test map shown below.

Figure 11 shows the result of the multipath model as a geographic map, where locations of potentially high multipath are predicted. This depiction is based on field ratios within 10 dB and signal propagation difference of greater than 75 µS, as discussed earlier for HD Radio. To eliminate locations that are below practical reception, only field strengths greater than 50 dBu for the stronger signal are shown.

The locations are color-coded to indicate whether the primary or booster signal is stronger, although this is unimportant from a multipath standpoint. It is apparent that the area near each transmitter, where its signal dominates, is free of multipath. A zone of potential multipath rings each transmitter at greater distances, depending on the radiated power, distance and terrain attenuation effects. In the booster's case, the signals mix along the south ridge of the mountains (north of Santa Monica and Beverly Hills) and south of the booster (near Marina Del Rey, Culver City and Los Angeles, which are mostly in the signal fringe).

To evaluate the multipath prediction model NPR Labs used its HD Radio Logger to collect digital receive status, analog field strength, GPS location and time. Figure 12 shows an enlarged portion of the KCSN coverage surrounding the transmitter. The measurement van's drive-test route is shown as a series of small boxes, in which the percentage of local digital reception (as a function of measurement time) is black for 97-100% availability, gray for 90-97% availability and white for less than 90% availability. Most areas experience high availability of digital reception (black squares).

The areas of adequate field strength (blue, green or yellow shading) with low availability (white squares) suggest conditions where intersymbol interference may degrade digital reception. In Figure 12, the areas of low availability appear in East Los Angeles on US Hwy. 101, along Mulholland Drive, north of Beverly Hills and through the canyons of the Santa Monica Mountains on I-405. Comparison with the Figure 11 shows good agreement with these predicted multipath areas. This supports the need to use a multipath model in the design of single frequency networks, to determine the extent and location of intersymbol interference.

Multipath models work well for FM reception using suitable parameters. However, analog stereo has far less tolerance to differential delay than digital systems such as as HD Radio. Multipath delays of greater than 1-2 µS will cause audible distortion and crosstalk. The intolerance to multipath begins at field ratios of approximately 20 dB. Consequently, single frequency

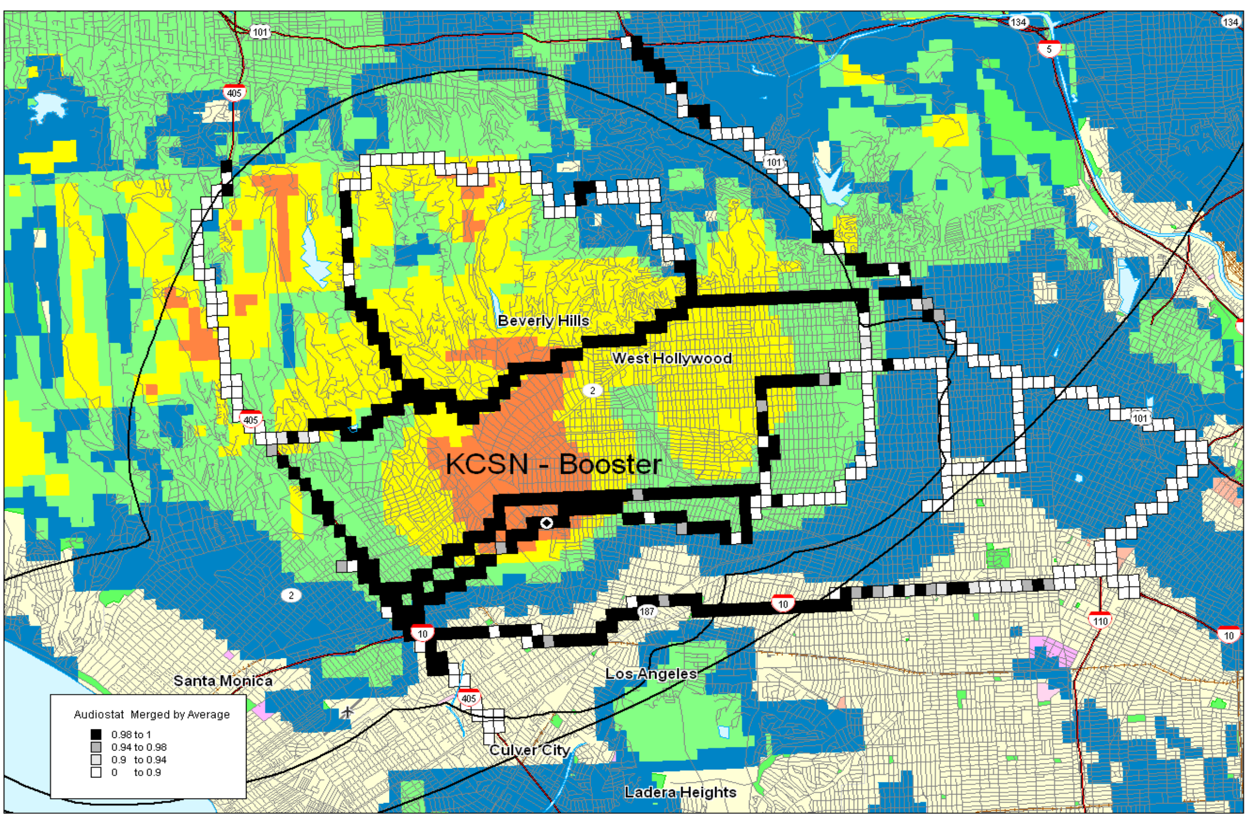


**Figure 12** Measurement of HD Radio reception around the KCSN booster. A Longley-Rice field strength prediction underlay shows locations where the booster's field strength is 50-60 dBu (blue) or greater.

networks are likely to create large areas of multipath effect with analog FM stereo. Most successful analog SFNs have substantial terrain shielding between the primary and booster transmitters, or the zones of multipath can be shifted to sparsely populated areas.

## HYBRID SYSTEMS

In a system such as hybrid HD Radio using both digital and analogue carriers, the whole question about SFNs becomes complicated. As discussed above, the digital part of the signal is not a problem, but the analogue part will suffer from the known problems of analogue SFNs. (Note that the problem is not a fundamental imitation with analogue signal; the problem is that the analogue signal, just as many digital signals, requires an equalizer to work in a multipath environment.)

A receiver that can handle digital signals does have the processing power to implement an equalizer for the analogue signal. But since existing analogue receivers lack one, it is presently a moot point.

## CONCLUSIONS

Digital radio lends itself naturally to SFN implementations. The main advantage is the potential of very flexible coverage and easy expansion - simply add more transmitters. Depending on the length of the guard interval is, some care will be needed to avoid excessive multipath. The hybrid IBOC system warrants some further studies with respect to the analog part of the signal, before it is clear how well SFN will work in this case. For all other systems, SFN should not pose any fundamental RF related problem.

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