# Self-interference in SFNs

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**With the introduction of newer digital broadcasting systems – such as mobile television – concern has been expressed about self-interference in single-frequency networks (SFNs). A study has been carried out on a simplified network to investigate this issue, considering the impact of factors such as the transmitter spacing, location variation standard deviation, signal correlation and receiver performance. The outcome of this analysis indicates that self-interference in dense SFNs cannot be ignored. Additionally, it was found that some of the factors considered have a significant impact on network coverage / prediction accuracy. Conversely, in other cases, it is possible to increase the model complexity significantly without a commensurate improvement in the results.**

One of the potential advantages of digital broadcasting systems is the possibility of improving spectral efficiency by operating a single-frequency network (SFN). However, with the introduction of newer systems, such as mobile television, concern has been expressed as to the limits of such networks due to self-interference.

You may ask why this should be so, considering that SFNs have been operating successfully for years. For example, the UK's National DAB service started in 1995. In order to understand this, we must first understand the basis of why a digital system allows the use of an SFN. For an analogue system we need to use different frequencies for signals transmitted from neighbouring sites. If we were to use the same frequency, a receiver tuned to that frequency would be trying to receive two signals – where one is arriving later than the other. This causes significant problems in the analogue world. However, digital systems reduce this problem significantly by the introduction of a "guard interval".

As long as the time difference between two signals arriving at the antenna is less than the guard interval, the receiver is able to deal with the different signals. Hence an SFN is possible. However, this does not remove all the problems. Signals with a sufficiently high delay will still cause interference. Fortunately for the UK DAB services, this has not been a major issue. The service operates in VHF Band III; the transmitter spacing is of the order of kilometres and the guard interval of 246 μs corresponds to a distance of over 70 km. Earth curvature also helps so that more distant transmitters are not visible to the receiver.

However, with the introduction of newer services, such as mobile television, the guard interval is reduced, primarily to overcome problems associated with the Doppler effect at higher frequencies. Thus, the transmitters need to be closer together and the SFN dimensions become both larger than the guard interval and considerably less than the radio horizon. Therefore, with these dense SFNs, the potential for self-interference is much greater.

### Abbreviations

| | | | |
|---|---|---|---|
| **CNR** | Carrier-to-Noise Ratio | **OFDM** | Orthogonal Frequency Division Multiplex |
| **DAB** | Digital Audio Broadcasting (Eureka-147)<br>**http://www.worlddab.org/** | **SFN** | Single-Frequency Network |
| **FFT** | Fast Fourier Transform | **UHF** | Ultra High Frequency |

Analysis of the problem is complicated due to a number of factors, the receiver model used, the transmit antenna heights and radiation patterns, the propagation model and how it deals with clutter and earth curvature, etc.

Prior to carrying out a detailed study based on a network planning tool that takes into account local terrain and clutter, a simplified initial analysis has been carried out in order to obtain some idea of the likely problems. This article describes that analysis.

## Methodology

It should be noted that a number of assumptions have been made to simplify the analysis. These are.

- The world is flat, i.e. earth curvature is not considered. This provides a worst case in terms of interference and is appropriate for the short guard intervals being considered.
- All antennas are assumed to be omni-directional and there is no allowance for the vertical radiation pattern. This again provides the worst case in terms of interference.
- No account is made for clutter and the different paths encountered, i.e. the same loss mechanism applies to all transmitters.
- The propagation loss model is simply a function of distance: $1/R^4$, a loss mechanism similar to that adopted for telecoms networks (i.e. dense urban cellular deployments), has been assumed. This is somewhat ideal since, for mixed path propagation, the loss factor is not constant. However, the aim was to create a method which was independent of particular systems. Here, all distances (network size, transmitter spacing) are defined in terms of the guard interval.
- The Schwartz & Yeh method for summing uncorrelated signals has been used [1].

Additionally, the following conditions were set:

- Regular hexagonal grid.
- Consideration of different transmitter spacings, up to 1.0 x guard interval.
- Location Standard Deviation varying between 5 and 10 dB.
- All transmitters co-timed.

It is recognized that the above assumptions limit the accuracy of the calculations. However, this analysis is not intended to be used instead of a detailed planning tool with more complex algorithms for propagation path loss and use of terrain and clutter data. Rather, it is intended as a method for a preliminary assessment of network dimensioning requirements and a way of identifying which parameters have a significant effect on predicted coverage.

The aim has been to investigate the extension of networks beyond one guard interval in the case where the guard interval is smaller than the trans-horizon distance. With such networks the number

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[1] S.C. Schwartz and Y.S. Yeh, 1982: **On the Distribution Function and Moments of Power Sums With Log-Normal Components**
BSTJ. Vol. 61, No. 7, September 1982.

of interferers increases rapidly as additional layers are added, even though the number of wanted signals arriving remains constant.

Finally, calculations were carried out where it was assumed that there was some degree of correlation between signals arriving from similar angles. Correlation is usually discounted in such calculations. However, for dense SFNs, where there may be several signals arriving from similar directions, correlation is arguably more significant. For these calculations, the summation was carried out by an extension to the Schwartz and Yeh method as detailed by Safak [2]. It was the availability of an algorithm for correlated variables that led to the use of the Schwartz and Yeh method.

In the absence of hard data for the correlation coefficients, some assumptions were made. Firstly, it was assumed that signals arriving from a similar direction would have a higher correlation than signals arriving from different directions. As a result of this, the basis of the correlation coefficients was taken to be a co-sinusoidal distribution as shown in *Fig. 1*.

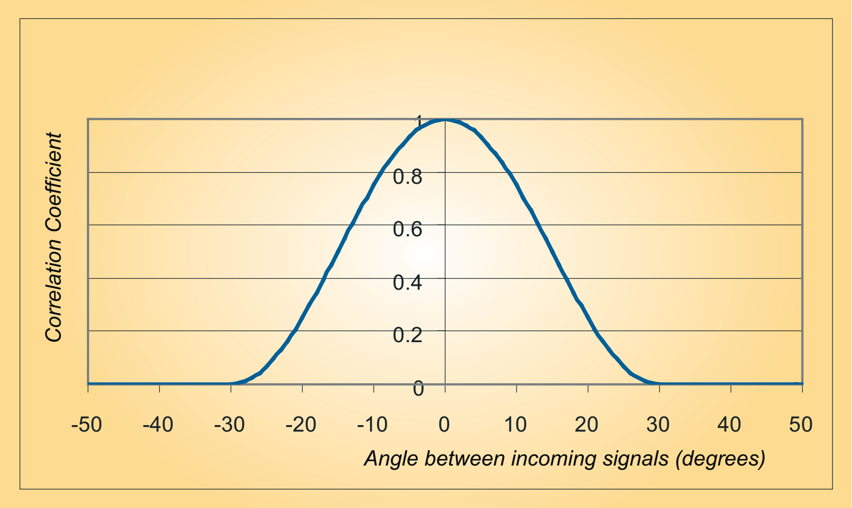

**Figure 1**
**Basis for correlation coefficients**

Taken alone, this gives a correlation coefficient of unity for signals arriving from the same direction and smaller values as the angle increases, falling to zero for angles greater than 30 degrees. The choice of a 30 degree cut-off was arbitrary; it should *not* be assumed from this that correlation does not continue up to higher angles. Secondly, it was considered reasonable to take distance into account. The distance from the reception point to each of the two sources was determined and the ratio of these distances evaluated. The basic sinusoidal distribution was then multiplied by this ratio. Thus, only signals coming from the same direction and at the same distance would have a correlation coefficient of unity.

Finally, another somewhat arbitrary factor of 0.9 was included for all coefficients (except those corresponding to the same physical site). This was included to ensure the correlation matrix was mathematically valid. It must be emphasized that the above is purely supposition and further work is required in order to determine the correlation coefficients in practice.

## Calculations

*Fig. 2* illustrates the network used for the calculations. The calculations were carried out for the point at the *centre* of the network, represented by the star.

The transmitters are assumed to be positioned in the centre of each hexagon.

The different colours in the figure are used to indicate how the network builds up: the first “layer” comprises the three transmitters in the yellow hexagons; the second layer comprises the nine transmitters in the green hexagons and so forth.

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[2] A. Safak: **Statistical Analysis of the Power Sum of Multiple Correlated Log-Normal Components** IEEE Transactions on Vehicular Technology, Vol. 42, No. 1, February 1993.

Note: the number of layers used varies depending upon the specified network size and assumed transmitter spacing. When the transmitter spacing is small, the hexagons are small and a large number of layers and transmitters must be included. Conversely, as the transmitter spacing approaches a distance corresponding to the guard interval, the hexagons are much larger and then only a few layers and transmitters are needed. This means that in the results illustrated, the number of layers included varies across the charts.

For the calculations described in this article, the network radius has been set at twice the guard interval. However, the method is applicable for larger networks.

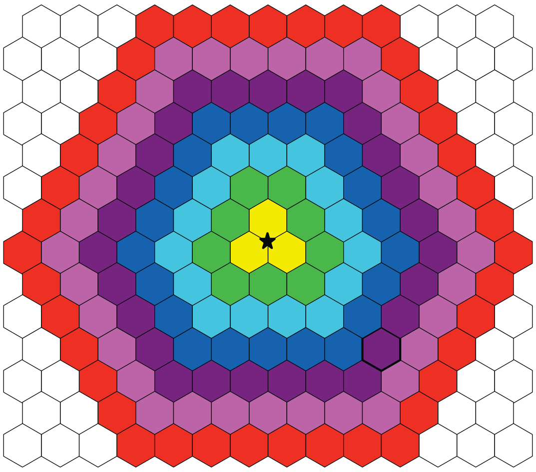

**Figure 2**
**Idealised Network**

By calculating the fields from each transmitter in each layer and comparing the difference in distances to our centre point (star) with the guard interval, we can determine the ratio of wanted to unwanted (interfering) signals. Different receiver models are available for this:

- All signals received within the guard interval are assumed to contribute zero interference. These are ”wanted” signals;
- All signals arriving outside the guard interval are assumed to contribute fully to the interference. These are “unwanted” signals.
- An “Effective” guard interval may be set whereby only signals arriving within, say, 90% of the guard interval are considered to contribute zero interference. Such a receiver will exhibit poorer performance than one satisfying the first bullet point.
- A region extends outside the guard interval where the arriving signals may be considered to contribute partly to the wanted and partly to the unwanted signals. Such a receiver will exhibit superior performance to one behaving as defined in bullet point 2.

Finally, we need to model how the receiver will operate in the presence of many signals. Consider three scenarios:

- All transmitters within the guard interval are considered to contribute constructively to the wanted signal;
- Only the nearest transmitter is considered to contribute constructively to the wanted signal;
- Only the nearest transmitter is considered to contribute constructively to the wanted signal. However, the location standard deviation is reduced to that obtained by considering all wanted signals.

Clearly, the first option will give the best reception conditions. However, modelling the network in this way is overly simplistic as the carrier-to-noise ratio required (CNR) for satisfactory operation also changes [3].

Conversely, the second option would appear to be overly pessimistic.

Therefore, the third option has been used in the following calculations; this would appear to be possibly more realistic than either of the other two options.

In order to determine sensitivity to location standard deviation, the calculations are carried out assuming that the location variation of the signals from the individual transmitters varies between 5.0 dB and 10.0 dB. This covers the range of standard deviations usually quoted for networks at UHF.

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[3] J.H. Stott: **The how and why of COFDM**
EBU Technical Review No. 278, Winter 1998

# Results.

The Results are plotted below.

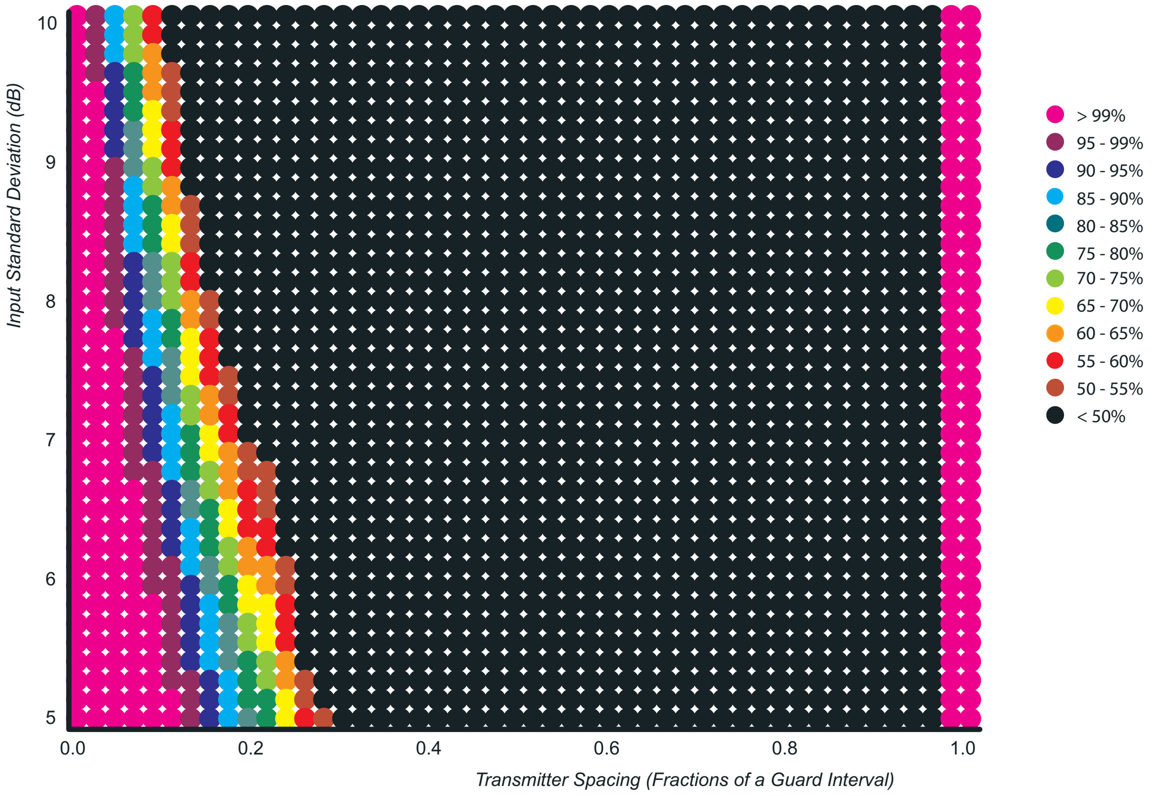

**Figure 3**
**No correlation; destructive interference only outside the guard interval; network radius = 2 x guard interval; R^4 roll-off; required C/I = 15.5 dB.**

- *Fig 3* illustrates the basic results for a network with a radius equal to twice the distance corresponding to the guard interval. The receiver is assumed to exhibit a “brick wall” type response: i.e. all signals received within the guard interval are assumed to contribute zero interference; all signals arriving outside the guard interval are assumed to contribute fully to the interference. The required carrier-to-interference threshold is taken to be 15.5 dB.
- *Fig 4* shows the results for a similar network. However, in this case, the receiver is taken to have an effective guard interval of 90% the true guard interval. Additionally, signals outside the guard interval but within 10% of the useful symbol period, are assumed to contribute only partially to the interference [4].
- *Fig 5* repeats the first case but assumes there is some degree of correlation between signals arriving from similar directions.

The charts should be interpreted as follows: Suppose a network is to be built in an environment where it is assumed that the appropriate signal location variation standard deviation is 5.5 dB. Now suppose that the transmitter spacing is set to 10% of the distance corresponding to the guard interval. Look at the point representing this standard deviation and spacing. If we consider *Fig. 3*, then the relevant coloured circle is magenta. Reference to the key indicates that we can expect >99% of locations to be served for such conditions. However, if we increase the transmitter spacing

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[4] For further information on receiver performance and signals outside the guard interval, see:
R. Brugger and D. Hemingway: **OFDM receivers — impact on coverage of inter-symbol interference and FFT window positioning**
EBU Technical Review No. 295, July 2003

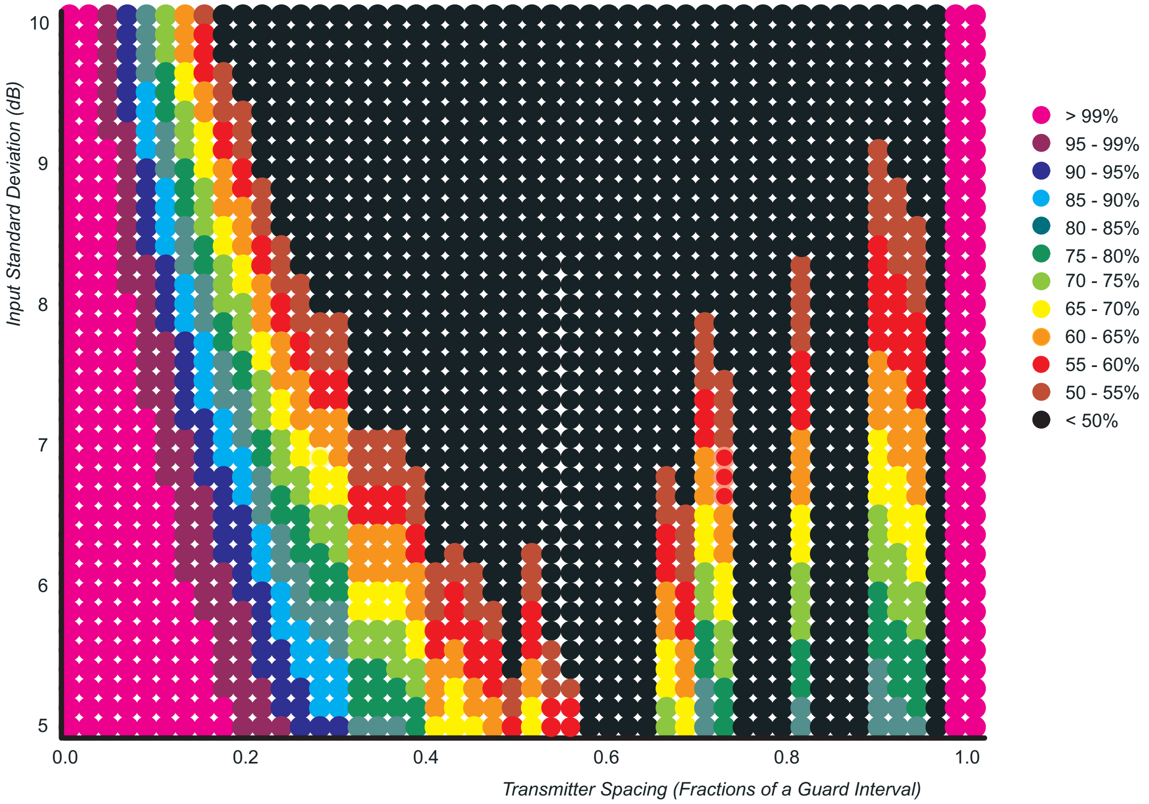

**Figure 4**
**No correlation; partial destructive interference only for delays up to 10% Tu; effective guard interval is 90% of true guard interval; network radius = 2 x guard interval; R^4 roll-off; required C/I = 15.5 dB**

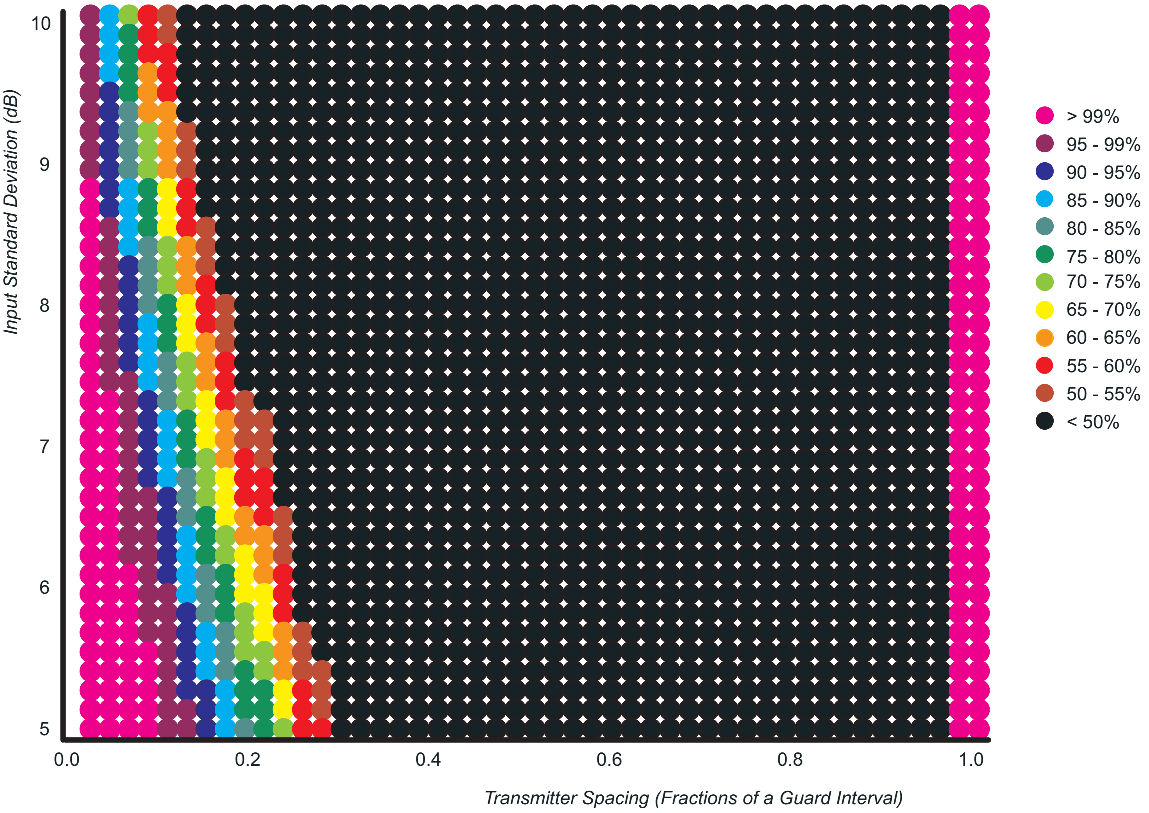

**Figure 5**
**Correlation up to 30 degrees; destructive interference only outside the guard interval; network radius = 2 x guard interval; R^4 roll-off; required C/I = 15.5 dB**

to 30% of the guard interval, fewer than 50% of locations would be served. Similarly, if we keep the transmitter spacing at 10% but build the network in an environment where the appropriate location variation standard deviation is closer to, say 8 dB, then we would expect only 80 - 85% of locations to be served.

**NB:** These calculations indicate *interference-limited* coverage only. No account is taken of noise. One result of this is that poor coverage indicated here cannot be overcome simply by increasing the transmitter power.

In short, the results can be summarized as follows:

- For a receiver with a “brick wall” response and a required carrier-to-interference ratio of 15.5 dB, then it appears that in general the transmitter spacings should be less than 20% (possibly closer to 10%) of the distance corresponding to the guard interval for coverage at 99% of locations. It is believed that 99% of locations served is necessary for satisfactory mobile TV coverage.
- For receivers where signals arriving outside but close to the guard interval contribute a reduced level of interference, then transmitter spacings can be increased whilst maintaining satisfactory coverage.

A more detailed discussion follows in the next section.

## Discussion

### General comments

First, it must be emphasized again that these results are for indicative purposes only; for the illustration of trends. As a result of the simplifying assumptions made, such as a constant loss factor and neglect of noise limitations to coverage, the results cannot be used to determine the precise transmitter spacings required.

### Effect of increasing transmitter spacing

It is interesting to note that, on first sight, it appears that there are some circumstances where increasing the transmitter spacing does not necessarily worsen the coverage. However, care must be taken when coming to this conclusion.

This study was based on a rigorously defined network area. In practice, this would not occur. As the transmitter spacing is increased, there will be sudden, apparently step changes in the network performance. This is because we are considering coverage at the centre of the network and, as we increase the spacing, we reach the situation where we lose another layer of transmitters. Thus we get a sudden decrease in interfering signals with only a small corresponding decrease in the wanted signal. However, it must be noted that this occurs only in configurations already resulting in relatively poor coverage. Where we are interested in at least 90% of locations served, then an increase in transmitter spacing does indeed cause worse coverage. The only exception to this is when we approach a transmitter spacing equal to the guard interval. This is because, in our example, the network radius is twice the guard interval; therefore, in this case, we have no interferers. For larger networks, this would not be the case.

### Effect of receiver performance

In terms of receiver performance, in the presence of more than one signal, we can define two limits on the behaviour of the receivers. The first limit is that all transmitters within the guard interval do not interfere but only the best serving (strongest signal) transmitter contributes. The second limit is that all transmitters contribute and the wanted signal is the power sum of all contributions. Both of these cases have been considered in the preceding analysis; but which should we use? Bearing in mind the associated change in required CNR, together with the likelihood that the answer will also be dependent on the receiver implementation, we assume it will lie somewhere between the two limits, probably closer to the first. Therefore, a third intermediate case has also been considered; this is similar to the first case but the resultant standard deviation for the wanted signal is derived from the Schwartz and Yeh summation of all the signals within the guard interval. In this third case however, the mean of the wanted signal used the nearest transmitter only.

*Figs 3* and *4* illustrate the significance of the receiver performance on network coverage. Clearly, coverage is significantly better if the receiver does not exhibit a brick wall response to signals arriving outside the guard interval. In the example shown, signals arriving up to 10% of the Useful Symbol period outside the guard interval are considered to contribute only partially to the interference; they are also considered to contribute partially to the wanted signals. It can be seen that generally, if the requirement is for >99% of locations to be served then the improvement in coverage for the conditions in *Fig. 4* over those in *Fig. 3* is represented in simplest terms by consideration of the possible increase in transmitter spacing of at least 50%. This corresponds to a reduction in site numbers of a factor of over two [5]. Note that this improvement has occurred even though the receiver model used in the development of *Fig. 4* is considered to have an effective guard interval of only 90% of the actual guard interval. Thus it is in the interests of broadcasters to encourage the development of higher performance receivers.

## *Improvements in prediction accuracy*

As network density increases, it becomes more important to use accurate prediction methods. Installation of more sites than necessary results in a network cost which is higher than it needs to be. Similarly, if the initial plan does not include sufficient sites, the addition of sites later in the build-out will be more difficult and costly. Thus it is important to look at aspects of coverage prediction which may have been neglected in the past.

The statistics associated with calculating the coverage control the allowance made for uncertainty in the prediction method. For the statistics associated with location variation there is a considerable range in values quoted which can result in a significant allowance. The range of values for the standard deviation used in this analysis extends from 5 – 10 dB and is used to illustrate how this can impact the required network density. For example, consider the results shown in *Fig. 3*. Suppose satisfactory coverage is defined by having at least 99% of locations served. Then a network where the standard deviation is 7 dB will require the transmitters to have a spacing of about half that of a network where the standard deviation is 5 dB. This demonstrates the need to gain an accurate determination of the location variation standard deviation when planning a network. Of course, it is important here to recognize the difference between improvements in predicted coverage and improvements in network coverage. Network coverage does not improve in practice, simply because a lower standard deviation is assumed; rather, it is that coverage is overestimated if the standard deviation is higher than assumed.

Another aspect of modelling complexity is illustrated by reference to *Figs 3* and *4*.

One of the assumptions made as part of the analysis for *Fig. 3* is that there is no correlation between the signals arriving at a given location. If a given area is populated with a sparse network, such an assumption holds. However, as the number of transmitters is increased there is arguably a degree of correlation between signals arriving from similar angles; moreover, it could be expected that this increases with an increase in network density. The introduction of correlation between transmitters will reduce the uncertainty in the calculations and thus the allowance required to ensure coverage. In the example here, it is assumed that the correlation is related to the cosine of the angle and falls

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[5] If the transmitter spacing in *Fig. 4* is 1.5 x spacing in *Fig. 3*, then the number of sites in *Fig. 4* will be reduced by a factor of ~$(1.5)^2$ = 2.25.

to zero if the angle is greater than 30 degrees. It should be noted that this is not based on any measurements; rather, it has been introduced simply to investigate the impact on coverage which can be expected by inclusion of correlation. Further work is required in this area to ascertain practical values of correlation coefficients.

An additional point to note is as follows: comparison between *Fig. 3* and *Fig. 4* indicates that coverage at the network centre is underestimated if correlation is neglected. However, this is not necessarily true over the whole network. At the edge of the network, where there are many interfering signals arriving from similar directions, it is possible for the omission of correlation to result in an overestimate of coverage.

### *Mitigation measures*

It would appear that inclusion of correlation has a somewhat smaller impact on the prediction accuracy than accurate determination of the location standard deviation. However, for a dense SFN, even a small change may result in a significant cost saving.

As mentioned previously, this analysis is based on a simple network architecture with no account being taken of antenna patterns, local terrain etc. In practice, self interference within the network can be controlled by

- Control of site position and height – limit site height and use terrain and clutter features to limit out-going interference.
- Control of the antenna vertical and horizontal radiation pattern – use the patterns to control outgoing interference.
- Adjusting timing as appropriate to control interference where other measures fail.

## Conclusions

This paper has carried out a simplified analysis of self-interference on dense SFNs. Regular networks have been considered with different receiver models. Also, the difference in coverage is investigated for the case where correlation exists between signals arriving from similar directions. The calculations have been carried out for a range of transmitter spacings and a range of signal location variation standard deviations.

The results indicate that self-interference in dense SFNs cannot be ignored. However determination of the relevant location standard deviation and, to a lesser extent, inclusion of correlation, will have an impact on the predicted coverage accuracy. Finally, improvements in network coverage can be obtained by ensuring that receivers allow some reduction in interference to signals arriving just outside the guard interval.

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Ms Beeke read Engineering Science at the University of Oxford, graduating in 1983. Following this, she worked for the BBC in its Engineering Research and latterly its Transmission departments.

Karina Beeke has participated in the work of the EBU for 15 years, including attendance at CENELEC meetings as an EBU representative. Currently she is the Project Manager of the EBU project groups B/EIC and B/EES.