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Monte Carlo based time variation of signals in broadcast network simulations

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1. Introduction

It is well known that changes in the wireless channel, due, for example, to variations in climatic conditions and the movement of objects in the environment, may cause the field strength of radio frequency signals to vary over the course of time at any given receiving location. Such time variation occurs even though the signals are transmitted with nominally constant characteristics. In order to provide reliable, unimpaired services, the design of broadcasting networks normally should take time variation into account with an appropriate model.

The conventional time variation model used by broadcasters is to compute the wanted and interfering signal field strengths at their 50%-time and 1%-time levels respectively (referred to, hereafter, as the '50:1' model). This ensures that the wanted signal is protected against interfering signals for 99% of time.

However, a number of more recent technical studies on broadcasting systems have required models which provide the instantaneous values of field strengths in order to determine the wanted and interfering nature of signals as a function of time, as opposed to the 50:1 model which effectively defines them before the simulations begin. Such studies include, for example, the design aspects of 5G Broadcast[1] [1], networks with interference cancellation and a frequency re-use factor of one (e.g. WiB [2]), and traditional single frequency networks (SFN).

This article sets out and investigates a time variation model for Monte Carlo simulations that reflects the full distribution of field strengths as they vary over time, as opposed to the 50:1 model which is based on fixed time percentages. Hexagonal network simulations have then been used to compare the conventional and Monte Carlo time variation models applied to 5G Broadcast as an example. The results of these simulations are then discussed.

2. Background

Measurements show that the field strength of signals received at a given location with a static receiver, and static transmission parameters, vary over time. The magnitude of the variation depends on the path between the transmitter and receiver and is affected by factors such as the separation between the two, their effective heights, local terrain and climatic conditions. The variation can be particularly pronounced over water paths where signal levels are known to rise by 30 dB or more, as shown in Figure 1 [3].

[1] 5G Broadcast refers to the mobile technology defined in 3GPP as LTE-based 5G Terrestrial Broadcast

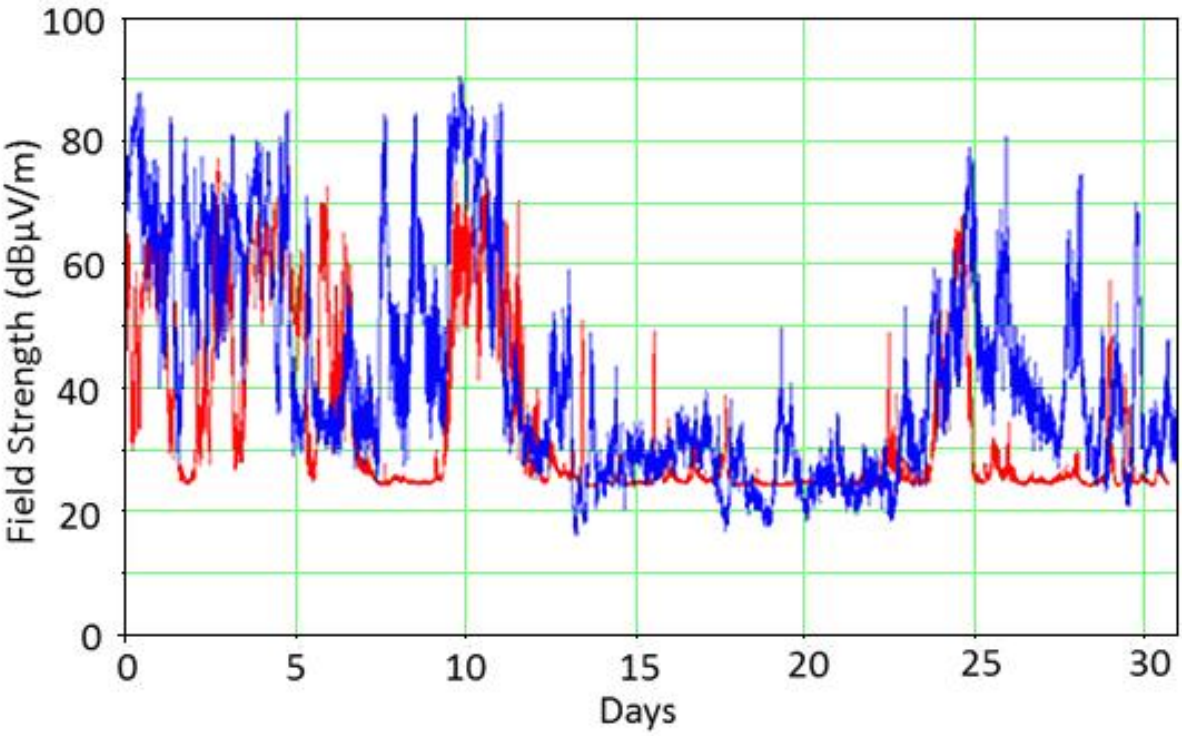


Figure 1: Measured field strengths from two stations during
a ducting event over the North Sea (red) and English Channel (blue)

The design of broadcast networks takes the time variation of signals into account in order to ensure that the transmitted programmes can be reliably received within their intended service area i.e. that they do not unduly suffer interference from distant transmitters and thus become impaired.

Conventional digital broadcasting network design is normally based on the 50:1 model. Such model is a simplification of observations made of the real world, and is based on the following three main assumptions:

- All wanted signal field strengths are computed at the value they exceed for 50% of time;
- All interfering signal field strengths are computed at the value they exceed for 1% of time;
- Once designated as wanted or interfering, all signals are kept at their corresponding field strength levels throughout the simulations – i.e. the signals do not vary over time.

Once the wanted and interfering signals have been defined, the aggregate wanted field can be computed from the 50%-time field strengths from the wanted transmitters in the network. Similarly, the aggregate interfering field is computed from the 1%-time field strengths of the interfering transmitters.

The intention of the 50:1 model is to ensure that the wanted signal is available for 99% of the time in the presence of interference. This is achieved by using the 1%-time values for the interfering signals.

In the past, the 50:1 model has been proven to produce networks with reliable reception, particularly for multiple frequency networks (MFN) where relatively few interferers need to be considered at any given receiving location. Some recent studies, however, have needed to explore alternative methods for dealing with the time variation of signals, examples of which are described below.

2.1 Modelling Single Frequency Networks

In SFN each signal may be defined as either a wanted or interfering signal, or both, depending on a signal's time of arrival at the receiving location relative to others in the SFN. Figure 2 illustrates the situation where the SFN weighting function – in which the left hand sides of the equalisation interval and cyclic prefix (CP) are assumed to be aligned – determines the extent of the wanted and interfering portions of signals depending on their relative delays [4]. Signals with relative delay (τ_d) that fall within the duration of the cyclic prefix (T_{CP}), or guard interval, (i.e. $0<\tau_d<T_{CP}$) contribute entirely as wanted signals and are, by definition, computed at their 50%-time levels.

Signals with relative delay exceeding the equalisation interval (T_{EI}) i.e. $\tau_d>T_{EI}$ are wholly interfering and are computed at their 1%-time levels, again by definition. Signals for which $T_{EI}>\tau_d>T_{CP}$ contribute partially as wanted and partially as interfering signals. It follows from the 50:1 model that the 50%-time value should be used for the wanted portion of the signal while the 1%-time value should be used for the interfering portion. This simple methodology implies that a signal with a relative delay in this region simultaneously occurs with its 50% and 1%-time field strengths. Clearly this is not possible.

Additionally, in the 50:1 model the FFT window positioning is done with respect to the signals' 50%-time values. Once the FFT window has been positioned, the magnitudes of the signal echoes are adjusted according to their delay, with the 1%-time weighting being applied to signals arriving outside the CP. Signals in this range would then be increased, which may cause a comparatively low SINR to be computed. Should it be found to be practically beneficial, a receiver would have the ability to reposition the FFT window in order to capture these signals should they indeed arrive at their 1%-time levels. In effect, the magnitude of signals in the 50:1 model is determined after the FFT window has been positioned. In reality, the signal magnitudes are independent of the receiver's operation.

A model in which the signal level of each transmitter can be described by a continuous function of time, with a single value at each particular instance regardless of its relative delay, would be more in line with the physical world, and avoid the anomalies highlighted above.

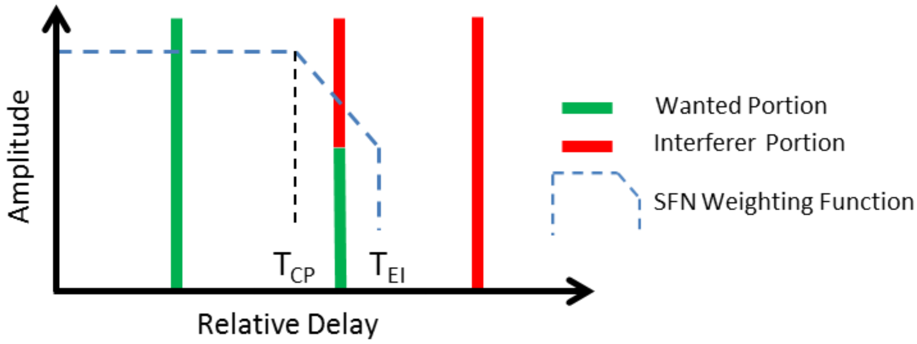


Figure 2: Stylised SFN weighting function showing wanted and interfering components

2.2 Cell Acquisition Subframe Reception in 5G Broadcast

Mobile receivers attempting to decode the Cell Acquisition Subframe (CAS) of 5G Broadcasts can decode the strongest signal at any time and location. In this situation the wanted signal is defined to be the strongest signal in both time and space. Correctly simulating the performance of the CAS therefore requires a model that includes the instantaneous values of signals in both these dimensions.

Figure 3 [5] illustrates the deficiency in the 50:1 model with respect to the CAS for signals received at a given location. The figure is based on the 50:1 model in conjunction with the ITU-R P.1546 propagation model.

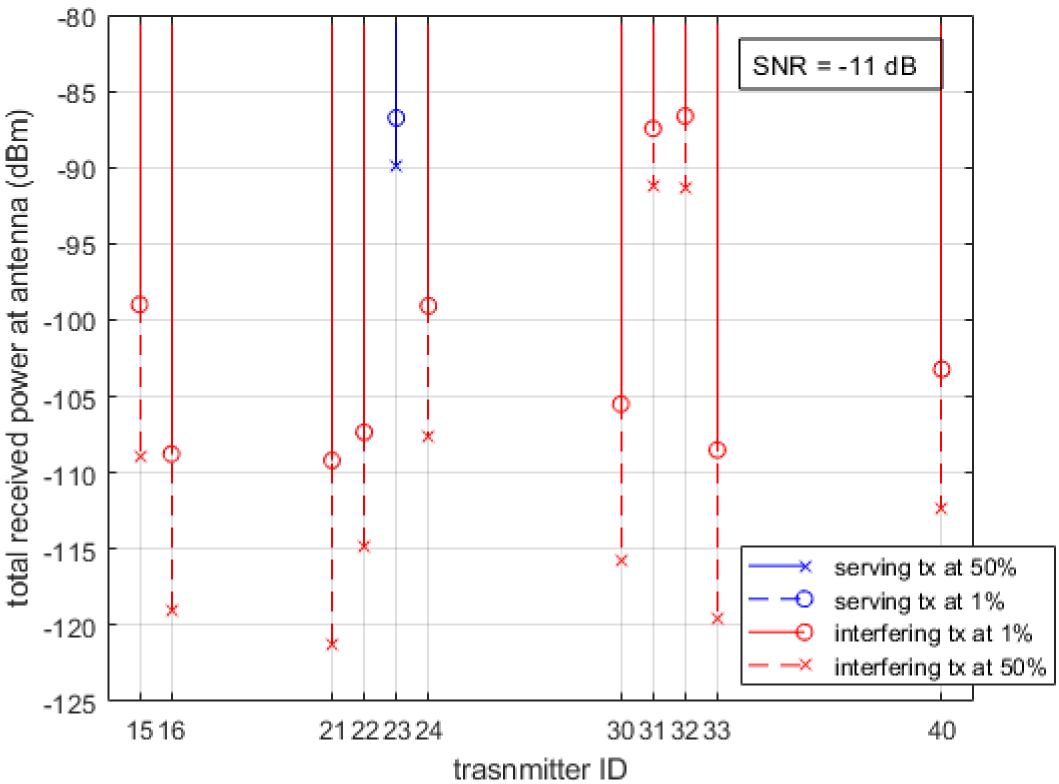


Figure 3: Example of low SINR caused by the 50:1 model

The 50:1 model would define the signal from transmitter 23 as the wanted signal, as it has the highest 50%-time field strength. However, it is 3 dB below the 1%-time values of interfering transmitter 31 and 4 dB below transmitter 32. The 50:1 model would therefore produce a comparatively low SINR. In practice, however, if for a given instance in time the 1%-time signal strengths from each transmitter were received, as they appear in Figure 3, the receiver would instead select the highest instantaneous signal as the wanted (e.g. Tx32), and the SINR would improve. Should the signal strengths change, the receiver would undergo cell reselection and again attempt to decode the strongest signal, which may instantaneously come from a different transmitter, and so on.

A time variation model that enabled the ‘real’ behaviour of such a receiver to be incorporated would be much more satisfactory in these situations.

2.3 Interference Cancellation

In networks, especially those based on a frequency re-use factor of one, ‘interference cancellation’ (IC) techniques may be used [2] in order to access and decode the desired/wanted signal in the presence of other, potentially interfering signals, even when the SINR of the wanted signal is below the SINR threshold for direct demodulation. With IC this is possible when the SINR of the interfering signal is high enough to allow demodulation. The interfering signal can then first be demodulated and then subtracted from the originally-received signal. The wanted signal may finally be decoded, now with a higher SINR since the main source of interference has been removed. This process may also be extended to more than two signals. Figure 4 illustrates the concept.

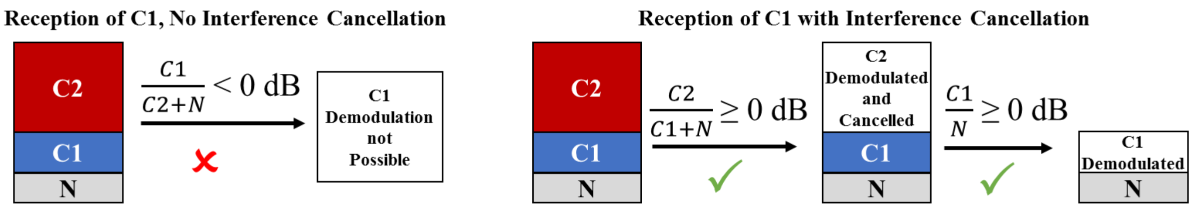


Figure 4: Interference cancellation

With interference cancellation there is no clear distinction between wanted and interfering signals, as, depending on the demodulation process and the relative levels of the signals, the signal in question might be treated as either the Wanted Signal or as interference. Therefore, whether one signal or another should be computed at its 1%-time or 50%-time level is also unclear. The requirement is instead to know the instantaneous power received from the relevant transmitters in the network. The receiver then determines which signals may be decodable, with or without the need of ‘cancellation’. In order to accurately simulate the performance of these systems, a time variation model is needed that generates instantaneous values of the field strengths of all the transmitters in the network, for any given instance in time, irrespective of whether a particular transmitter is seen as wanted or interfering.

Studies such as [2] indicate that interference cancellation-based networks would operate at low values of SINR where small changes in the achievable SINR would have a noticeable impact on the network's spectral efficiency. Accurate time variation models would therefore greatly aid system level simulations of these networks.

3. Monte Carlo based Time Variation

The examples in § 2 call for a time variation model where signals take on a singular, known value at any instance in time, regardless of whether they are defined to be wanted or interfering signals.

Instead of modelling the wanted and interfering signals at fixed time percentages, as is done in the 50:1 model, the instantaneous values of signals, as they occur in the time domain, may be modelled with Monte Carlo techniques. Such a Monte Carlo model requires two main factors to be in place:

- A pathloss model that permits signal strengths to be calculated over the interval 0% to 100% of the time.
- An appropriate approach for the Monte Carlo analysis in the time and spatial domains in which signals are treated as random variables, drawn from appropriate distributions in both dimensions.

3.1 Pathloss Models

The ITU-R P.2001 and ITU-R P. 1546 pathloss models have been considered. Both are briefly discussed below with respect to hexagonal grid simulations, the context of this work.

3.1.1 ITU-R P. 2001

ITU-R P. 2001 [6] has been designed for use in simulations where time variation must be taken account of. The recommendation states that the model "*predicts path loss due to both signal enhancements and fading over effectively the range from 0% to 100% of an average year. This makes the model particularly suitable for Monte Carlo methods...*"

With respect to time variation, the ITU-R P. 2001 model has the precise qualities required for the approach outlined in this article. However, the recommendation is path-specific, and is therefore suitable for applications where detailed data (e.g. terrain and ground clutter databases, accurate antenna patterns etc) is available for each path. As the context of this document is of regular hexagonal networks where detailed path data is not known, we turn our attention to the ITU-R P. 1546 recommendation, which is non-path specific.

3.1.2 ITU Recommendation ITU-R P.1546

In principle ITU-R P.1546 [7] should be well suited to hexagonal grid simulations as it is a general path model where no specific path information is necessary. However, the recommendation states that it *"is not valid for field strengths exceeded for percentage times outside the range from 1% to 50%".* The Monte Carlo time model for this work requires field strengths over the full range of time i.e. 0% to 100% of the time. The next section sets out a methodology for extrapolating ITU-R P.1546.

3.1.3 Extrapolating ITU-R P.1546

For all time values greater than 50% of the time it is assumed that the 50%-time value is appropriate and may be used. The same approach is suggested in [3].

For time values lower than 1% it is necessary to extrapolate ITU-R P.1546. This is made possible by permitting Qi(x), the inverse complementary cumulative normal distribution function, described in § 7 of the recommendation's annex, to operate on inputs lower than 1% of the time. This extrapolation is also in line with the methodology set out in [3].

These two modifications allow field strengths to be generated over the range from 0 to 100% of the time. The field strength distribution, with the application of these two modifications, is shown for an illustrative path in Figure 5, where we see the <1%-time extrapolation and 'clipping' of the field strength for time values greater than 50%. The signal strength rises rapidly for increasingly low time percentages. The dotted red line shows the 1%-time level.

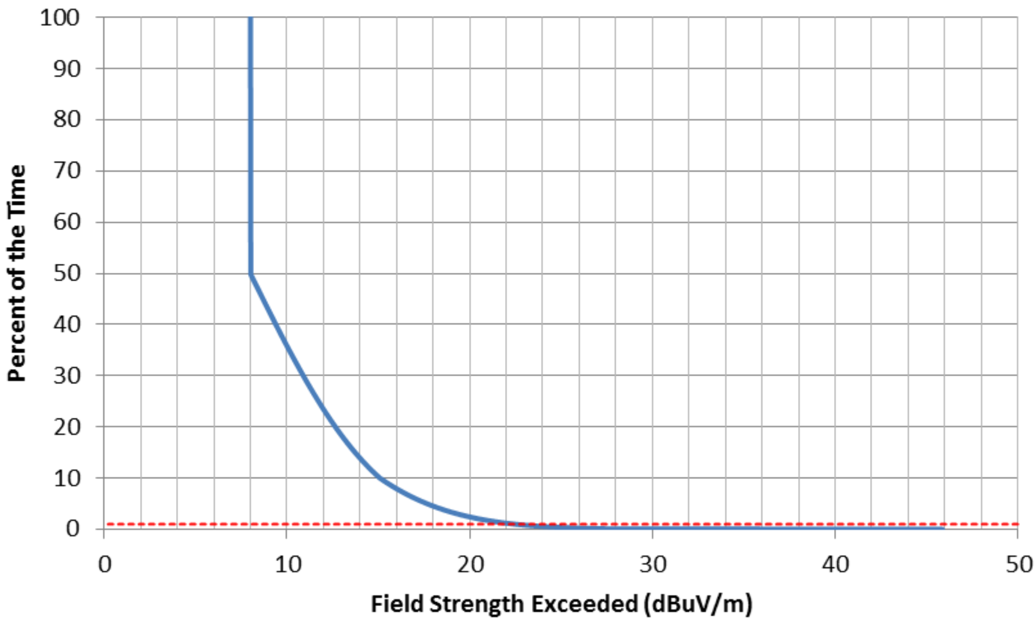


Figure 5: ITU-R P.1546-5 Field Strength distribution extrapolated over the range [0,50]% of time.

It is emphasised in [3] that "*the values returned by the model at >50% and <1% are not valid in themselves; these modifications are simply required to allow the use of*

Recommendation ITU-R P.1546 in a Monte Carlo framework and any errors introduced in the estimation of aggregate power between 1% and 50%-time are expected to be insignificant".

It has been assumed that due to the relatively large number of transmitters considered, any errors introduced by the extrapolation of ITU-R P.1546 are also insignificant in the context of this work.

3.2 Time Domain Monte Carlo Analysis

Now that a methodology for generating field strengths over the range of 0 to 100% of the time has been established, the methodology needs to be incorporated into the Monte Carlo simulations. The first step for doing so is to generate vectors of field strengths for each transmitter, as they vary over time, sampled in the time domain. The general method in [3] describes a way of doing this based on the Clayton copula function. It sets out a procedure for generating field strengths for multiple transmitters with user-defined cross-correlation that may be adjusted to reflect conditions found in the real world.

The pseudo-code in [3] outlines how to generate random variables of (μ_1 and μ_2) with arbitrary correlation between them set by α, the Clayton copula parameter. μ_1 is used as a 'seed' variable while μ_2 is the correlated variable. μ_1 and μ_2 are variables of time probability that may be passed to ITU-R P.1546 in order to generate correlated field strengths for appropriate path geometries[2]. N values of μ_2 are then computed for N transmitters based on a single value of μ_1 for a given instance in time. A new value of μ_1 is generated for each successive instance in time and the process of generating the μ_2 vector is repeated for a statistically sufficient number of trials.

Figure 6 illustrates these steps for an arbitrary reception location 60 km away from each of three 'medium-power medium-tower' transmitters (MPMT).

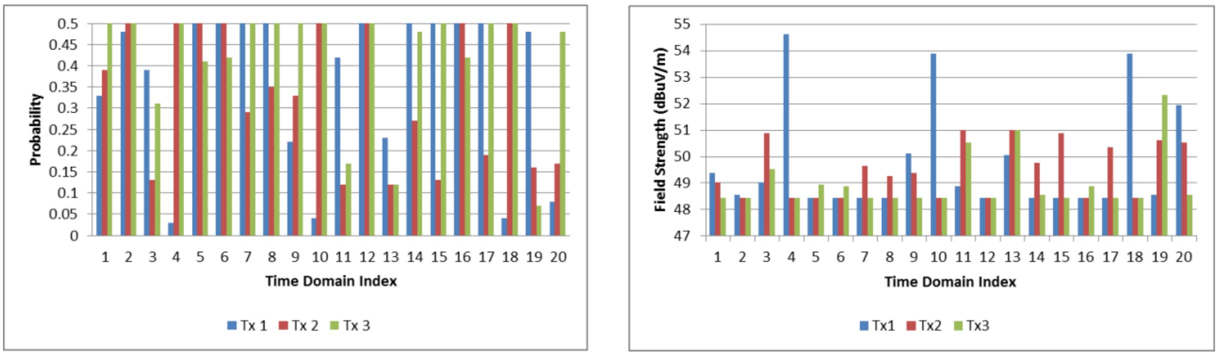


Figure 6: Time domain probabilities and corresponding field strengths.

Although the general appearance of the field strengths in Figure 6 may differ from Figure 1 (i.e. the 'lifts' are dispersed over time in Figure 6 while they appear clustered

[2] Note that the correlation is applied in the time probability domain, and therefore indirectly to the field strength domain.

together in Figure 1), over a sufficiently long time period the statistics of the field strength distributions would be similar.

Once the time-domain field-strength vectors have been generated for each transmitter, the achievable SINR may then be computed for each instance in time and then stored in a time-domain SINR vector. From this vector the SINR, achievable for a given percentage of time (e.g. the 99%), may then be found. This value may then be stored in a location availability vector and the process repeated for all other locations. The desired percentile of the location availability may then be obtained (e.g. 95%). Thus, the achievable SINR in the network may be determined for the desired percentiles of time and location.

Figure 7 sets out pseudo-code for the main steps in the Monte Carlo time and location variation analysis used in this document. It is based on aligning the receiving antenna to the strongest signal after shadow fading at each location (the receiving antenna is aligned to the strongest 50%-time signal after shadow-fading, but remains fixed in a single direction for all time at each location).

```
1    Generate µ2 for 61 transmitters and 10000 time domain
     samples; see Figure 8
2    For location = 1 to 10000
3      Generate random shadow fading (SF) for 61 transmitters
4      Compute 50%-time Field Strength, FS_50, for 61 transmitters
       using P1546 with probability = 50%
5      FS_50_SF = FS_50 + SF
6      Align Rx antenna to max(FS_50_SF)
7      For time = 1 to 10000
8        Compute 61 instantaneous field strengths (FS_Instantaneous)
         using P1546 with probability = µ2*100%
9        Add SF to FS_Instantaneous
10       Adjust FS_Instantaneous vector according to Rx antenna
         alignment
11       Randomly select the wanted from signals where
         FS_Instantaneous≥ (max(FS_Instantaneous) - handover margin)
12       Apply SFN weighting function to FS_Instantaneous vector
13       Compute SINR from FS_Instantaneous vector, store in SINR_time
         vector
14       Next time
15       Store 99th percentile of SINR_time in vector
         SINR_time_then_location
16   Next location
17   Output the 99th percentile of SINR_time_then_location
```

Figure 7: Pseudo-Code for Monte Caro analysis in time and location.

Line 1 of Figure 7 assumes that the time probability statistics are constant across the entire coverage area i.e. they are 100% correlated in space for a given instance in time.

Line 1 of Figure 7 uses the pseudo-code in Figure 8, which has a small modification compared with the procedure in [3]. The modifications reflect the need to generate vectors of the instantaneous field strengths for all the transmitters in the network. In all cases the value of α (the factor setting the correlation between signal levels over time) has been set to 1, as suggested in [3].

```
FOR index_timedomain = 1 to 10000 {
  get initial Random Variable, μ1, from uniform distribution in
  range [0, 1]
  FOR index_tx = 1 to 61 {
    get Random Variable, ν, from uniform distribution in range
    [0, 1]
    get μ2,   μ2(index_tx, index_timedomain) = μ1(ν^(−α/(α+1)) − 1 + μ1^α)^(−1/α)
  }
}
```

Figure 8: Pseudo code for generation of correlated time-probabilities

4. Study Case: 5G Broadcast

The CAS (Cell Acquisition Subframe) is the synchronisation subframe of 5G Broadcast. It contains several control channels and signalling information that are essential for decoding the desired MBSFN (Multicast Broadcast SFN) payload data carried in the PMCH (Physical Multicast Channel). As the CAS must be decoded successfully before the payload may be accessed, understanding whether the CAS is robust enough to provide reliable reception of broadcasters' content in physical networks is of great interest.

The 100% broadcast mode required changes in the conventional frame structure of LTE. The new 100% broadcast radio frame is 40 ms in duration. It is made up of the new CAS comprising 12 symbols of the standard LTE subcarrier spacing (15 kHz) with 16.67 µs CP, spanning 1 ms in total (cf. Figure 9). In Rel-14, these are followed by 39 OFDM symbols of, in the example shown in the diagram, the 1.25 kHz numerology with a 200 µs CP (i.e. each symbol is of 1 ms duration).

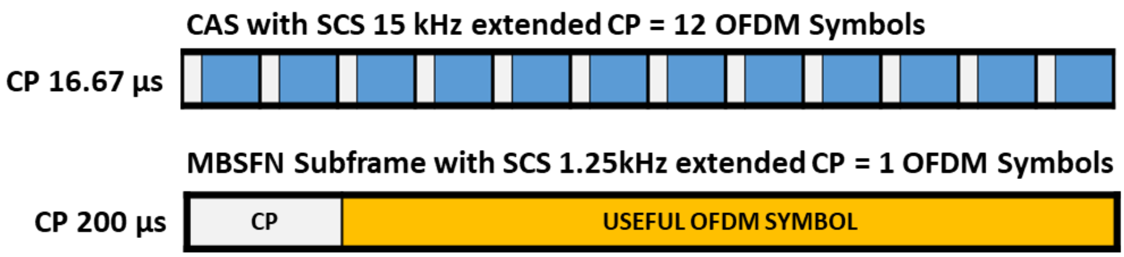


Figure 9: Numerology mismatch between CAS and MBSFN subframes

The CAS uses CS-RS (Cell Specific Reference Signals) that are inherited from the unicast design. Assuming that the content per site is the same, the longest CP for the CAS is 16.7 µs (see Table 2). A clear numerology mismatch between the CAS and the MBSFN subframes therefore arises as the MBSFN subframes and CAS are configured with CPs of 200 and 16.7 µs, respectively. In some locations the longer CP of the MBSFN subframes may protect the wanted user data while the shorter CP of the CAS may not sufficiently protect the synchronisation signal, causing it to be non-decodable. If the CAS cannot be decoded, neither can the MBSFN subframes.

4.1 Simulation Background

Network simulations incorporating the Monte Carlo based time variation model have been carried out to investigate the performance of the CAS for car mounted reception and the PMCH for fixed rooftop reception. Here we highlight the main parameters used in the network simulations.

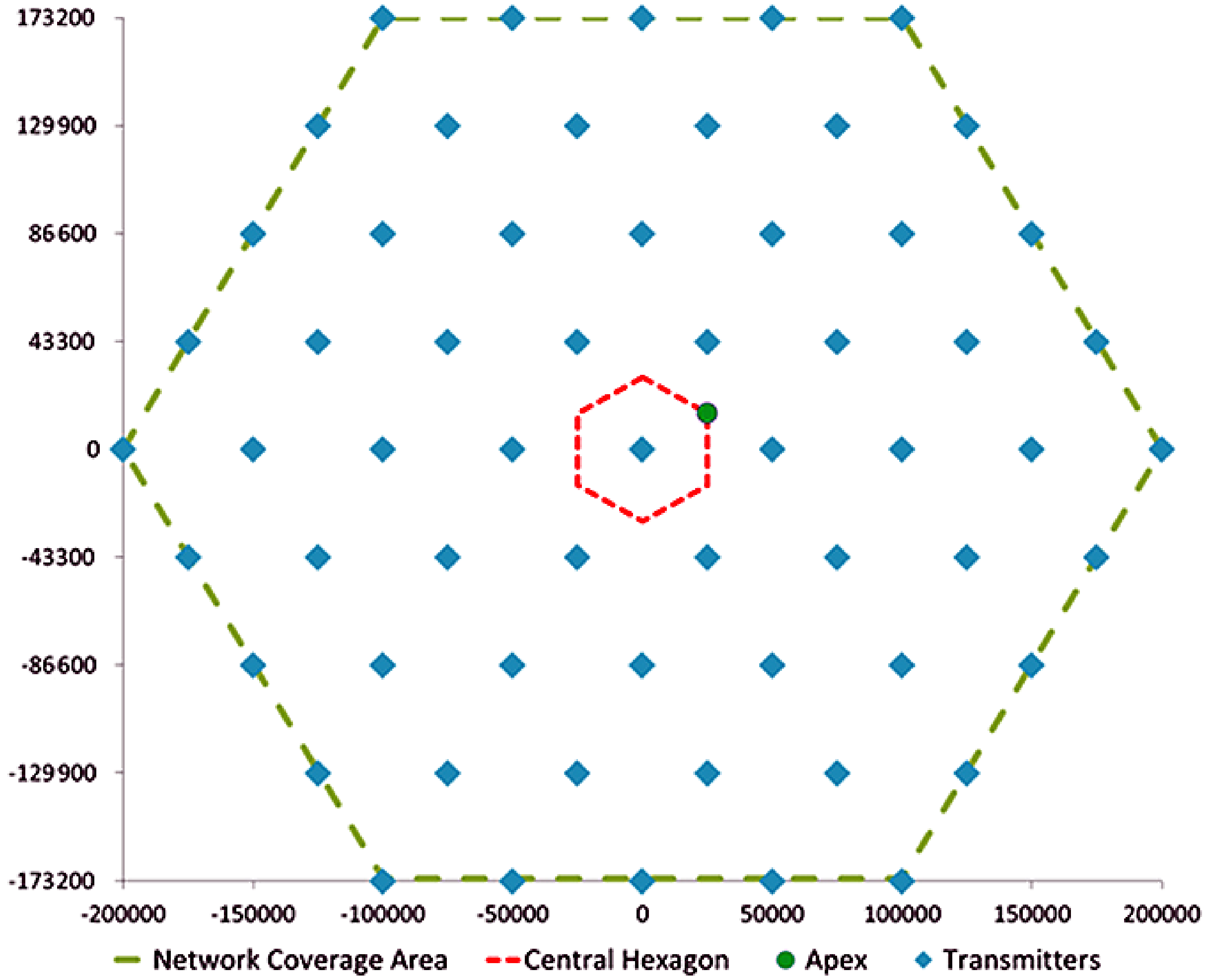


Figure 10: 61 site transmitter network layout showing the coverage area.

The simulations have all been based on the framework set out in [1] and subsequent agreements, for example [8]. The simulations were performed over a regular hexagonal network of 61 transmitters, as illustrated by Figure 10, for which the achievable SINR (in the time and space domains) is computed for randomly 'dropped' locations uniformly distributed throughout the entire coverage area i.e. the area bounded by the dotted green line in Figure 10. Only land paths were considered – no sea paths have been investigated.

Table 1 sets out the main parameters of the transmitter networks, including the inter-site distance (ISD) for the low-power low-tower (LPLT), medium-power medium-tower (MPMT) and high-power high-tower (HPHT) networks.

Table 1: Network Parameters

Network	ISD (km)	Tx Height (m)	EiRP (dBW)	Tx Antenna
LPLT	15	30	30	Sectorised
MPMT	50	100	40	Omnidirectional
HPHT	125	300	53	Omnidirectional

The simulations use the maximum energy FFT window positioning strategy illustrated in Figure 11.

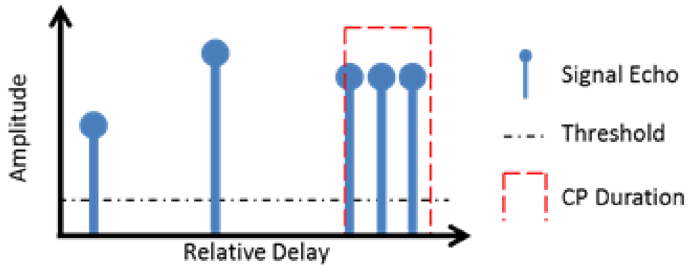


Figure 11: Maximum energy window FFT positioning strategy.

The numerologies below were used, all of which will form part of 3GPP Release 16 5G Broadcast.

Table 2: Numerologies

	Δ_f (kHz)	T_{CP} (µs)	T_U (µs)	T_{EI} (µs)	Comment
CAS	15	16.7	66.7	22.2	CAS with extended CP
PMCH	2.5	100	400	200	High mobility (Rel 16)
	1.25	200	800	267	Release 14 CP extension
	0.370	300	2700	900	HPHT fixed rooftop (Rel 16)

Where Δ_f = carrier spacing and T_U is the useful symbol period.

For comparison, simulations have been carried out for the 50:1 methodology, Monte Carlo time variation and for the 50:50 model in which all signals (wanted and interfering) are computed at their 50%-time levels.

In the 50:1 model the 1%-time value of the signal has been used for signals with relative delays in the period T_{EI}>T_d>T_{CP}. The SFN weighting function then determines the wanted and interfering signal portions from the 1%-time signal.

In the case of the 50:50 model, the 50%-time levels are used for all signals. The Monte Carlo method uses the instantaneous value of each signal, regardless of the relative delay.

4.2 Simulation Results for the CAS

System level performance analyses of the CAS have recently been carried out in the 3GPP RAN1 working group [9] [10] with the Monte Carlo time variation model. The main results from [9] are reproduced in Figure 12 for car-mounted reception in an AWGN channel (path loss, shadow fading and AWGN noise, no multipath fading) with a single receiving antenna. The single cell network configuration was used for which there is only an MBSFN between sectors at the same site – there is no MBSFN between sites. As the receiving antenna is omni-directional, there is no need to align it to any specific transmitter site [11].

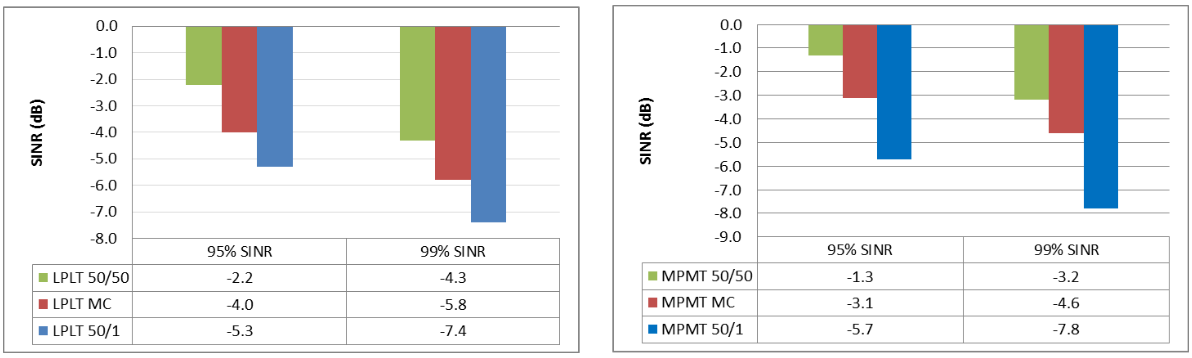
For comparison, the Monte Carlo results are shown alongside those from the conventional 50:1, and the 50:50 models.

The figure reveals that, as expected, the Monte Carlo (MC) time variation model is less demanding than the conventional 50:1 model, reflecting the ability of the receiver to decode the strongest signal at each instance in time, at any given location. However, the MC time variation model remains more challenging than omitting time variation entirely i.e. the 50:50 model.

Figure 12 also shows that the difference between the 50:1 and MC methodology is greater for the MPMT network compared with the LPLT network as the time variation of signals is greater over the longer paths that occur in the MPMT network.

The Monte Carlo analysis indicates that the achievable SINR in the LPLT network would be around 1.3 dB higher than would be expected from the conventional 50:1 model, and around 3 dB higher in the MPMT network.

Although the 1.3 to 3 dB differences in achievable SINR between the MC and 50:1 models may appear to be modest, designing a system to be 3 dB more robust than it may need to be in practice could involve significant additional complexity in the hardware, and also cost.



	95% SINR	99% SINR
LPLT 50/50	-2.2	-4.3
LPLT MC	-4.0	-5.8
LPLT 50/1	-5.3	-7.4

	95% SINR	99% SINR
MPMT 50/50	-1.3	-3.2
MPMT MC	-3.1	-4.6
MPMT 50/1	-5.7	-7.8

Figure 12: Achievable SINR in an AWGN channel, car mounted, single Rx antenna

4.3 Simulation Results for MBSFN

Figure 13 summarises the results for the achievable SINR of the PMCH for fixed rooftop reception at 10m above ground level in an MBSFN. The results are for the 300 µs CP numerology in the MPMT and HPHT networks in an AWGN channel. At each location the directional receiving antenna is aligned to the station providing the highest 50%-time signal strength after location variation has been applied.

Again, we see that the Monte Carlo time variation model yields a higher achievable SINR than the 50:1 model. The difference between the two models is more pronounced in the HPHT network where the path lengths are greater.

The difference between Monte Carlo and 50:1 in the MPMT network is relatively modest at around 1 dB while in the HPHT network the Monte Carlo results can be around 3.5 dB higher.

Overestimating the interference in a network by 3 dB or more may represent a significant overdesign and unnecessary cost implication. Further investigation of these aspects would be most welcome.

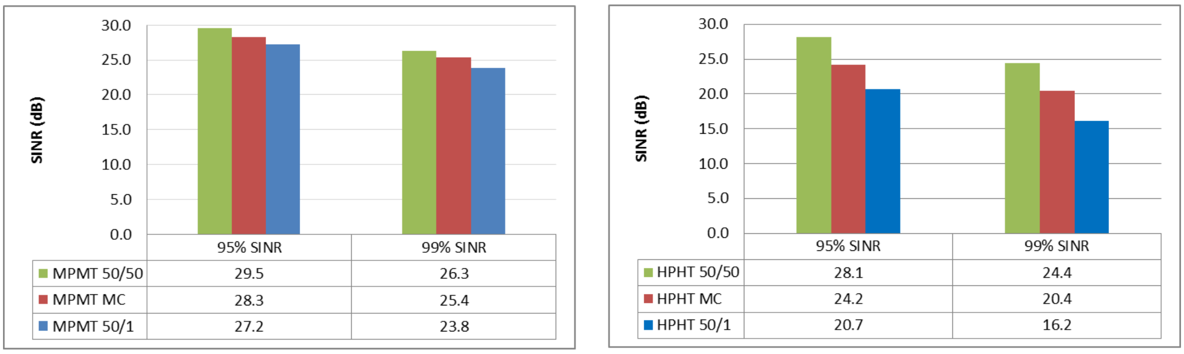


Figure 13: Achievable SINR for fixed rooftop antenna in MBSFN

5. Summary

A Monte Carlo based model has been presented to take account of the variation of field strengths received from multiple transmitters as they vary over time. In particular, the model permits the generation of instantaneous field strengths for each transmitter in a network at any given receiving location. The model is general in nature and can therefore be used in several situations where conventional time variation models are deficient. For example, the Monte Carlo model may be used for system level simulation of best server selection operation (in time and location) such as the cell acquisition subframe of eMBMS, frequency reuse one systems with interference cancellation and single frequency networks. Conventional models of time variation (e.g. the 50:1 method) have recently shown several deficiencies in studies of these systems.

In the examples investigated in this article, system level simulations with the Monte Carlo method produce higher achievable SINR levels compared with the conventional 50:1 method. The difference is dependent on the network configuration and has been found to be larger in networks with greater inter-site distance and transmission height. This is due to the greater signal variation over longer paths. The differences found in this study are in the range of 1 to 3.5 dB. Although relatively modest, an SINR increase in this range could significantly improve the apparent spectral efficiency of some systems (particularly for interference cancellation where a 1 to 3 dB increase in operating SINR would lead to an appreciable capacity increase), and reduce the design complexity of others, as well as cost.

This article has focussed entirely on regular hexagonal networks. Further investigation of these techniques in more detailed 'real world' simulations would be most welcome, potentially with the ITU-R P.2001 propagation model which would be well suited to such analysis. Network simulations incorporating Monte Carlo based time variation over sea paths would be of great interest.

The formal extension of the ITU-R P.1546 model over the full range of time probabilities would also be a welcome addition, as the propagation model is explicitly limited to the range of 1 to 50% of the time.

References

[1] 3GPP TR 36.776; "*Study on LTE-based 5G terrestrial broadcast (Release 16)*"; 3GPP; March 2019

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