Analytical Characterization of the Single Frequency Network Gain Using Effective SNR Metrics

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***Abstract*—The design of broadcasting networks operating in a single frequency way is challenging due to the difficulty of predicting the performance in a frequency selective channel, caused by natural multipath and echoes coming from different transmitters. In this paper we resort to the use of frame error rate prediction metrics (also known as *effective SNR* metrics) to characterize the performance gain (or loss) under different multipath and SNR regimes in a simplified scenario with two transmitters. The analysis shows clearly that receivers with a dominant line of sight reception and high SNR are more sensitive to the presence of echoes, while those users in low SNR or strong multipath conditions are easily enforced by the insertion of a second transmitter.**

***Index Terms*—Single frequency network, Effective SNR metrics, broadcasting**

I. Introduction

Single Frequency Networks (SFN) are broadcast networks where different transmitters radiate the same waveform simultaneously. This network structure offers clear advantages over the classical Multiple Frequency Networks (MFN), as different transmitters emitting the same information in nearby locations can use the same frequency channel and, therefore, a higher frequency reuse factor is attained. Most modern broadcasting systems like DVB-T [1], DVB-T2 [2], Multimedia Broadcast Multicast Services (MBMS) in LTE [3], and even hybrid terrestrial-satellite systems like DVB-SH [4] support an SFN configuration.

This single frequency operation is possible by the use of Orthogonal Frequency Division Multiplexing (OFDM) with a sufficiently long Cyclic Prefix (CP): if all the signals from the different transmitters arrive inside the CP interval, then the presence of multiple transmitters has the effect of creating an artificial multipath (due to the reception of different SFN *echoes*), from a receiver point of view.

The particular structure of SFN has also changed the way a broadcast network is planned: on the one hand, the length of the CP, the separation between transmitters (which determines the maximum delay between different contributions) and the radiated power have to be carefully selected so that non-negligible signal replicas always arrive inside the CP interval; on the other hand, the coverage region, which is usually defined in terms of Frame Error Rate (FER), is not easy to characterize due to the difficulty of mapping Channel State Information (CSI) to the actual FER in OFDM systems operating over multipath channels, since average Signal to Noise Ratio (SNR) is not a good metric to characterize reception quality.

Research supported by the European Regional Development Fund (ERDF) and the Spanish Government under projects DYNACS (TEC2010-21245-C02-02/TCM) and COMONSENS (CONSOLIDER-INGENIO 2010 CSD2008-00010), and the Galician Regional Government under project CN 2012/260 "Consolidation of Research Units: AtlantTIC".

In this paper we resort to the use of FER prediction metrics, or Effective SNR Metrics (ESM) [5], [6] to compare the performance of a receiver under SFN and MFN operation. This kind of metrics, together with the statistics of the received signals, allows us to characterize analytically the impact of the SFN structure in the receivers, achieving larger insights than empirical measurements. Particularly, we will focus on a simple scenario with two transmitters, and characterize the effect the network structure has depending on the operational point, defined in terms of SNR and multipath regimes. We conclude that the SFN operation is beneficial for receivers with a low SNR or strong multipath environment, while those users operating under strong Line of Sight (LOS) and high SNR suffer some performance loss due to the reception of two different echoes.

II. Prior work

The study of SFN is quite extensive in the literature, and can be roughly divided into two well differentiated groups. On the one hand, those works related to the design and analysis of SFN systems, that are basically mathematical and simulation-based: in [7] a comparison between the ATSC and MBMS systems is performed; in [8] the insertion of a local transmitter conveying its own information by means of the use of hierarchical constellations in a hybrid terrestrial satellite network is studied; in [9] a similar framework is presented, but in this case from the point of view of a cellular cognitive network. On the other hand, several measurement campaigns [10], [11] were performed in order to measure the performance of receivers in the presence of different transmitters. In any case, there seems to be a huge gap between the two groups of papers: while the former consists basically on performing average SNR studies to validate the proposed designs, the latter empirically shows that the presence of echoes in SFN can be an important degradation factor.

Only recently published works showed the importance of taking into account the underlying multipath channel when designing SFN: in [12] a quality prediction metric, very similar to the Mutual Information ESM [5], was used to determine the average SNR threshold for coverage under different multipath (both *natural* and *artificial* - SFN echoes) environments. Although providing a useful tool for SFN planning, this work does not offer analytical insights on the effect of SFN operation. In [13] analytical expressions for the Exponential ESM in Rician channels with two transmitters were obtained, although the work was focused on analyzing mechanisms to overcome the degradation due to the presence of echoes. In this work, our objective is to identify those receivers that experience a performance gain due to the SFN operation depending on two main factors: SNR regime and multipath environment.

III. CHARACTERIZATION OF THE SFN GAIN

We consider an SFN scenario where a receiver is inside the area of influence of two different transmitters. Let us denote by h_n and g_n the impulse responses of the channel from the first and second transmitter, respectively, to the receiver under study, by N the number of OFDM carriers, by x_n the (common) time domain signal, with $\mathbb{E}|x_n|^2 = 1$, and by $w_n \sim \mathcal{CN}(0, \sigma^2)$ the received thermal noise. If we assume an overall channel length shorter than the CP, the received time-domain signal after CP removal is

$$y_n = (h_n + g_n) \circledast x_n + w_n \; n = 1 \dots N, \tag{1}$$

and the corresponding signal after the Fast Fourier Transform (FFT) operation is

$$Y_k = (H_k + G_k) X_k + W_k \; k = 1 \dots N \tag{2}$$

with Y_k, H_k, G_k, X_k and W_k the N-points FFT of y_n, h_n, g_n, x_n and w_n, respectively. With this, the SNR at the k-th carrier is

$$\gamma_k = \frac{|H_k + G_k|^2}{\sigma^2} \tag{3}$$

while the SNR in an MFN network with the receiver attached to the first transmitter would be

$$\gamma_{0,k} = \frac{|H_k|^2}{\sigma^2}. \tag{4}$$

Based on these quantities, we can define the Exponential ESM (EESM) of the SFN and MFN networks as

$$\hat{\gamma} \triangleq -\frac{1}{\beta} \log \left(\frac{1}{N} \sum_{k=1}^{N} e^{-\beta \gamma_k} \right), \; \hat{\gamma}_0 \triangleq -\frac{1}{\beta} \log \left(\frac{1}{N} \sum_{k=1}^{N} e^{-\beta \gamma_{0,k}} \right) \tag{5}$$

respectively, with β a parameter that has to be tuned according to simulations or measurements, and the SFN gain as

$$\Delta\hat{\gamma} \triangleq \frac{\hat{\gamma}}{\hat{\gamma}_0}. \tag{6}$$

A. Derivation of the quality metric

In this section we present a brief sketch of the derivation of an approximation to the EESM (5). The complete derivation and some examples showing the accuracy of this approximation can be found in [13].

Let us consider that both channels H_k and G_k have LOS and non-LOS (NLOS) components, so that the channel coefficients are identically distributed according to $H_k \sim \mathcal{CN}(e^{-j\theta_k}, K^{-1})$ and $G_k \sim \mathcal{CN}(\alpha, \alpha^2 K^{-1})$, where $\theta_k \sim \mathcal{U}[0, 2\pi)$ represents the (assumed to be random) phase between the LOS contributions, K is the Rician-K factor, assumed to be the same for the channels from both transmitters, and α^2 is the LOS power arriving from the second transmitter.

The EESM approximation consists on approximating the mean in (5) by an expected value:

$$\hat{\gamma} = -\frac{1}{\beta} \log \left(\frac{1}{N} \sum_{k=1}^{N} e^{-\beta \gamma_k} \right) \approx -\frac{1}{\beta} \log \left(\mathbb{E}\, e^{-\beta \gamma} \right) \tag{7}$$

where the expectation is taken over the random multipath and the angles θ_k, and has the following closed form expression:

$$\begin{aligned} \hat{\gamma} \;\; = \;\; & \frac{1}{\beta} \log \left(1 + \beta \frac{1 + \alpha^2}{K \sigma^2} \right) + \frac{1 + \alpha^2}{\beta \frac{1+\alpha^2}{K} + \sigma^2} \\ & - \frac{1}{\beta} \log \left(I_0 \left(\frac{2\beta\alpha}{\beta \frac{1+\alpha^2}{K} + \sigma^2} \right) \right) \end{aligned} \tag{8}$$

where I_0 denotes the zeroth order modified Bessel function of the first kind. The EESM for MFN can be obtained from the previous equation just by setting $\alpha = 0$. Note that this approximation is deterministic, while the original $\hat{\gamma}$ was a random variable. The approximation is going to be better for increasing values of N, but it is quite accurate for moderate number of carriers, as shown in [13].

In the following, we will analyze the power regime and multipath response influence on the SFN gain.

B. AWGN channel

If no multipath is present, then we have that $H_k = e^{j\theta_k}$, $G_k = \alpha$, and the SFN gain is

$$\Delta\hat{\gamma} = 1 + \alpha^2 - \frac{\sigma^2}{\beta} \log \left(I_0 \left(\frac{2\beta\alpha}{\sigma^2} \right) \right). \tag{9}$$

This equation has a very clear interpretation: $1 + \alpha^2$ is the power gain due to the reception of signal from two different transmitters, while $\frac{\sigma^2}{\beta} \log \left(I_0 \left(\frac{2\beta\alpha}{\sigma^2} \right) \right)$ takes into account the fact that we are transforming an AWGN channel into a multipath one by the insertion of the SFN operation. In any case, it is quite difficult to obtain some insight from the previous equation, as the SFN operation will be preferred to the MFN one if

$$e^{\frac{\beta\alpha^2}{\sigma^2}} > I_0 \left(\frac{2\beta\alpha}{\sigma^2} \right), \tag{10}$$

so we will analyze the performance in the high and low SNR regime.

1) Low SNR: In this case, we can approximate for $x \to 0$ [14]

$$I_0(x) = 1 + \frac{1}{4}x^2 \tag{11}$$

and

$$\log(1+x) = x, \tag{12}$$

leading to

$$\lim_{\sigma^2 \to \infty} \Delta\hat{\gamma} = \lim_{\sigma^2 \to \infty} 1 + \alpha^2 - \frac{\sigma^2}{4\beta}\left(\frac{2\beta\alpha}{\sigma^2}\right)^2 = 1 + \alpha^2. \tag{13}$$

2) High SNR: In the high SNR regime, we can approximate [14]

$$I_0(x) = \frac{1}{\sqrt{2\pi x}} e^x, \tag{14}$$

so the limit SFN gain reads as

$$\lim_{\sigma^2 \to 0} \Delta\hat{\gamma} = \lim_{\sigma^2 \to 0} 1 + \alpha^2 - 2\alpha + \frac{\sigma^2}{2\beta}\log\left(2\pi\frac{2\beta\alpha}{\sigma^2}\right) = (1-\alpha)^2. \tag{15}$$

In this case, values of $\alpha < 2$ will lead to a lower EESM value, with the SFN performing worse than the MFN. Note that this case is expected to be very common, as $\alpha < 1$ implies that a receiver is associated to the transmitter from which is receiving a higher power.

We conclude that for an AWGN channel the SFN outperforms the MFN in the low SNR regime, while the opposite effect is found in the high SNR regime.

C. Rayleigh channel

The Rayleigh channel has only NLOS component or, equivalently, $H_k \sim \mathcal{CN}\left(0, \sigma_h^2\right)$, $G_k \sim \mathcal{CN}\left(0, \alpha^2\sigma_h^2\right)$. In this case, the SFN gain is

$$\Delta\hat{\gamma} = \frac{\log\left(1 + \frac{\beta\sigma_h^2\left(1+\alpha^2\right)}{\sigma^2}\right)}{\log\left(1 + \frac{\beta\sigma_h^2}{\sigma^2}\right)} \geq 1. \tag{16}$$

It is clear that in this case the SFN is going to provide a better result, since $G_k + H_k \sim \mathcal{CN}\left(0, \left(1+\alpha^2\right)\sigma_h^2\right)$, thus resulting in a power gain of α^2. This power gain has different effects on the SFN gain, which is measured in terms of ESM, depending on the SNR regime.

1) Low SNR: For low SNR values, we can approximate

$$\log\left(1 + \frac{\beta\sigma_h^2\left(1+\alpha^2\right)}{\sigma^2}\right) \approx \frac{\beta\sigma_h^2\left(1+\alpha^2\right)}{\sigma^2} \tag{17}$$

so we arrive to the same result as in the AWGN channel:

$$\lim_{\sigma^2 \to 0} \Delta\hat{\gamma} = 1 + \alpha^2. \tag{18}$$

2) High SNR: If the SNR is sufficiently high, then we have that

$$\lim_{\sigma^2 \to 0} \Delta\hat{\gamma} = \lim_{\sigma^2 \to 0} \frac{\log\left(1 + \frac{\beta\sigma_h^2\left(1+\alpha^2\right)}{\sigma^2}\right)}{\log\left(1 + \frac{\beta\sigma_h^2}{\sigma^2}\right)} = 1. \tag{19}$$

This asymptotic behavior of the SFN gain is related to the fact that for a Rayleigh channel the EESM increases logarithmically with SNR, so in the high SNR regime an SNR increase (which is the effect of the SFN under Rayleigh channels) has a very small effect in the EESM.

We conclude that for a Rayleigh channel the SFN is always preferred to the MFN, specially for low SNR, although in the high SNR regime both network structures have approximately the same effect.

D. AWGN + Rayleigh channel

In an SFN structure it is common to have high LOS reception with a nearby transmitter while receiving some diffuse multipath components from a far-off transmitter. In this case, one of the channels is AWGN ($H_k = 1$) and the other is Rayleigh distributed ($G_k = \mathcal{CN}\left(0, \sigma_g^2\right)$), thus leading to an overall Rician channel. Now, if we define $\bar{\gamma}_N \triangleq \frac{\sigma_g^2}{\sigma^2}$ the average SNR due to the multipath component, and $\bar{\gamma}_L \triangleq \frac{1}{\sigma^2}$ the average SNR caused by the direct component, we have that the MFN EESM is $\hat{\gamma}_0 = \frac{1}{\sigma^2}$, while the SFN EESM is

$$\hat{\gamma} = \frac{\bar{\gamma}_L}{\beta\bar{\gamma}_N + 1} + \frac{1}{\beta}\log\left(1 + \beta\bar{\gamma}_N\right), \tag{20}$$

so we can find two different contributions to the ESM:

- The LOS component $\frac{\bar{\gamma}_L}{\beta\bar{\gamma}_N+1}$ is similar to the one in AWGN, but in this case the NLOS contribution acts as an additional noise source (it could be thought as a *self-interference* term).
- The NLOS component $\frac{1}{\beta}\log\left(1 + \beta\bar{\gamma}_N\right)$ is the same as in the Rayleigh case.

Like in the previous channels, we will analyze the overall SFN gain in high and low SNR.

1) NLOS effect in low SNR: We will write $\bar{\gamma}_N = s\tilde{\gamma}_N$, $\bar{\gamma}_L = s\tilde{\gamma}_L$, and calculate the ESM gain with respect to an AWGN channel with only the LOS component. In this case

$$\begin{aligned} \Delta\hat{\gamma} &= \lim_{s \to 0} \frac{\frac{s\tilde{\gamma}_L}{\beta s\tilde{\gamma}_N + 1} + \frac{1}{\beta}\log\left(1 + \beta s\tilde{\gamma}_N\right)}{s\tilde{\gamma}_L} \\ &= \lim_{s \to 0} \frac{1}{\beta s\tilde{\gamma}_N + 1} + \frac{1}{\beta s\tilde{\gamma}_L}\log\left(1 + \beta\bar{s}\tilde{\gamma}_N\right) \\ &= 1 + \frac{\tilde{\gamma}_N}{\tilde{\gamma}_L} = 1 + \sigma_g^2, \end{aligned} \tag{21}$$

so in the low SNR regime, once again, we have a positive SFN gain.

2) NLOS effect in high SNR: Following the same approach as in the low SNR case,

$$\Delta\hat{\gamma} = \lim_{s\to\infty} \frac{\frac{s\tilde{\gamma}_L}{\beta s\tilde{\gamma}_N+1} + \frac{1}{\beta}\log\left(1+\beta s\tilde{\gamma}_N\right)}{s\tilde{\gamma}_L} = 0. \tag{22}$$

As in the high SNR regime the SFN EESM $\hat{\gamma}$ (20) increases logarithmically while the MFN EESM $\hat{\gamma}_0 = \frac{1}{\sigma^2}$ increases linearly.

E. Effect of SNR regime for general fading channels

From the previous section we can extract that in the low SNR regime the SFN gain is always greater than zero, while in the high SNR regime the results depend on the underlying channel structure. In this section, we present a general result that explains the behavior of a family of ESMs (including the EESM) for general fading channels in high and low SNR: for low SNR values, the EESM tends to the average SNR, while for high SNR values it tends to the minimum SNR.

Proposition 3.1: Let

$$\hat{\gamma} = \Phi^{-1}\left(\frac{1}{N}\sum_{k=1}^{N}\Phi\left(\gamma_k\right)\right) \tag{23}$$

be an ESM with the following properties:

$$\left.\frac{\partial\Phi\left(\gamma\right)}{\partial\gamma}\right|_{\gamma=0} \neq 0 \tag{24}$$

$$\lim_{t\to\infty}\frac{\Phi\left(t\left(x+\epsilon\right)\right)}{\Phi\left(tx\right)} = 0 \ \ \forall\epsilon>0. \tag{25}$$

$$\lim_{t\to 0}\frac{\Phi^{-1}\left(at\right)}{\Phi^{-1}\left(t\right)} = 1 \ \ \forall a>0. \tag{26}$$

Then,

- if $\gamma_k \to 0 \ \forall\gamma_k$ then $\frac{\hat{\gamma}}{\bar{\gamma}} = 1$, with $\bar{\gamma} \triangleq \frac{1}{N}\sum_{k=1}^{N}\gamma_k$
- if $\gamma_k \to +\infty \ \forall\gamma_k$ then $\frac{\hat{\gamma}}{\gamma_{\min}} = 1$, with $\gamma_{\min} \triangleq \min_k\{\gamma_k\}$.

Proof: The proof for the low SNR case is straightforward, and follows after applying a Taylor expansion of the ESM (23) around 0 and using property (24). We can study the high SNR case by writing $\gamma_k \triangleq t\tilde{\gamma}_k$, $\gamma_{\min} \triangleq t\tilde{\gamma}_{\min}$ and making t tend to infinity, so

$$\begin{aligned}
\lim_{t\to\infty}\frac{\hat{\gamma}}{\gamma_{\min}} &= \lim_{t\to\infty}\frac{\Phi^{-1}\left(\frac{1}{N}\sum_{k=1}^{N}\Phi\left(t\tilde{\gamma}_k\right)\right)}{t\tilde{\gamma}_{\min}} \\
&= \lim_{t\to\infty}\frac{\Phi^{-1}\left(\Phi\left(t\tilde{\gamma}_{\min}\right)\frac{1}{N}\sum_{k=1}^{N}\frac{\Phi\left(t\tilde{\gamma}_k\right)}{\Phi\left(t\tilde{\gamma}_{\min}\right)}\right)}{t\tilde{\gamma}_{\min}} \\
&\overset{(i)}{=} \lim_{t\to\infty}\frac{\Phi^{-1}\left(\frac{1}{N}\Phi\left(t\tilde{\gamma}_{\min}\right)\right)}{\Phi^{-1}\left(\Phi\left(t\tilde{\gamma}_{\min}\right)\right)} \\
&\overset{(ii)}{=} 1
\end{aligned} \tag{27}$$

where (i) is due to (25) and (ii) is due to (26). ■

This proposition generalizes and explains some of the results in the previous sections: on the one hand, in the low SNR regime the SFN outperforms the MFN, as the fact of receiving useful signal from different transmitters increments the average SNR and, therefore, an increment on the ESM is produced. On the other hand, for high SNR values the effect of creating an artificial multipath channel due to the SFN operation is more important, as the ESM follows the minimum SNR value. Therefore, if the fact of incrementing the average received power implies an increment in the variations of the channel (like in the AWGN+AWGN or AWGN+Rayleigh cases) the MFN is expected to be preferred to the SFN.

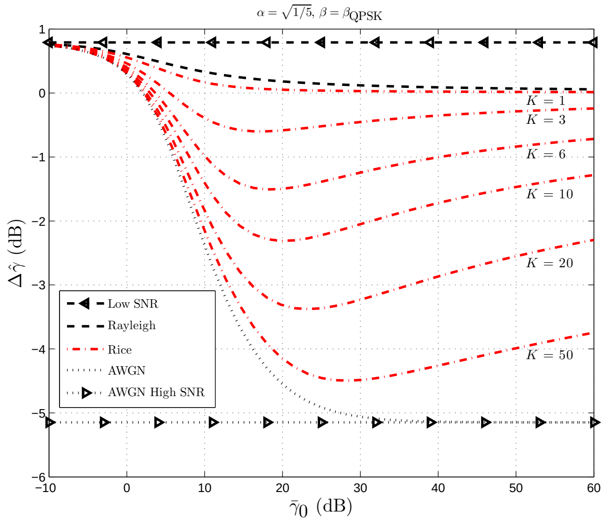

Fig. 1. Evolution of the SFN gain $\Delta\hat{\gamma}$ with the average SNR, for different K factors.

IV. Numerical Results

We have numerically evaluated the derived expressions to observe the evolution of the SFN gain with the average SNR and the Rician K factor, as well as to verify the predicted asymptotic behavior. We assume for simplicity that both channels H_k and G_k have the same Rician K factor, although the SFN gain can be also computed for different K factors just by using (8). In all cases, the EESM parameter β was set to $\beta_{\text{QPSK}} \approx 0.66$, which is the result of fitting the EESM function (5) to the Mutual Information Effective SNR Metric curve [5] for a QPSK constellation, and the parameter $\alpha = \sqrt{1/5}$, i.e., the power received from the first transmitter is five times the one received from the second transmitter. Moreover, we define $\bar{\gamma}_0 \triangleq \frac{1}{N}\sum_{k=1}^{N}\gamma_{0,k}$ as the average SNR in the MFN scenario.

In Figure 1 we can see the evolution of the SFN gain with the average SNR for different K values. As predicted, in the low SNR regime the gain is positive and equal for all channels, while for higher SNR values the behavior is highly dependent on the Rician factor: while for low K values the gain is always positive and rapidly tends to zero, for stronger LOS environments there is an increasing loss at moderate SNR values. Note that the gain in all Rician channels tends to zero as the SNR increases due to the fact that, as shown in Section III-D, in the high SNR regime the ESM increases

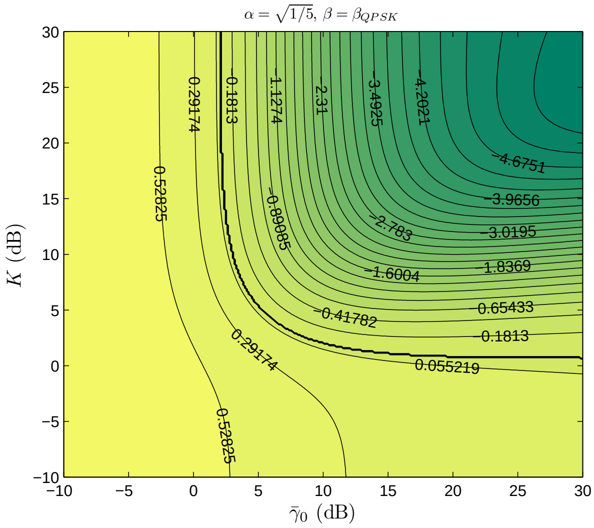

Fig. 2. Contour plot of the SFN gain $\Delta\hat{\gamma}$ (in dB) for different values of average SNR and K factor. The thick line delimites the region with a negative SFN gain.

logarithmically and, therefore, the behavior is similar to that of a Rayleigh channel.

In Figure 2 there is a contour plot of the SFN gain as a function of the average SNR and Rician factor. We can see that, as predicted, the receivers operating in the high SNR and large K region suffer some degradation due to the SFN operation, while those receivers working in a strong multipath environment or in the low SNR regime benefit from the power gain provided by the second transmitter.

These results provide an analytical justification of the measurements in [15], and predict that the degradation in strong line of sight environments does not happen in the low SNR regime as shown in [16] for the cognitive radio channel, for example, where it was shown that channel state information is not important in the low SNR regime, or in [17, Fig. 2] for the AWGN channel.

V. Conclusions

In this paper we have characterized the performance gain (or loss) due to SFN operation depending on the SNR regime and multipath environment. We conclude that the power gain provided by the SFN structure is beneficial for receivers operating under diffuse multipath or low SNR conditions, while in those scenarios with high SNR and strong LOS the presence of SFN echoes degrades the reception quality.

References

[1] Digital Video Broadcasting (DVB), "Framing structure, channel coding and modulation for digital terrestrial television ETSI EN 300 744 V1.6.1 (2009-01)," 2009.

[2] Digital Video Broadcasting (DVB), "Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system (DVB-T2) ETSI EN 302 755 V1.2.1 (2011-02)," 2011.

[3] 3rd Generation Partnership Project. Technical Specification Group Services and System Aspects., "Multimedia broadcast/multicast service; stage 1 (release 9) 3GPP TS 22.146 V9.0.0 (2008-06)," 2009.

[4] DVB.org, "Framing structure, channel coding and modulation for satellite services to handheld devices (SH) below 3 GHz (dEN 302 583 V1.2.1)," 2010.

[5] K. Brueninghaus, D. Astely, T. Salzer, S. Visuri, A. Alexiou, S. Karger, and G.-A. Seraji, "Link performance models for system level simulations of broadband radio access systems," in *Proc. IEEE PIMRC*, vol. 4, (Berlin, Germany), pp. 2306–2311, Sept. 2005.

[6] Y. Blankenship, P. Sartori, B. Classon, V. Desai, and K. Baum, "Link error prediction methods for multicarrier systems," in *Proc. IEEE VTC-Fall*, vol. 6, (Los Angeles, CA), pp. 4175–4179, Sept. 2004.

[7] J. Huschke, J. Sachs, K. Balachandran, and J. Karlsson, "Spectrum requirements for TV broadcast services using cellular transmitters," in *Proc. IEEE DySPAN*, (Aachen, Germany), pp. 22 –31, may 2011.

[8] H. Jiang, P. Wilford, and S. Wilkus, "Providing local content in a hybrid single frequency network using hierarchical modulation," *IEEE Trans. Broadcast.*, vol. 56, no. 4, pp. 532–540, 2010.

[9] J. Sachs, I. Maric, and A. Goldsmith, "Cognitive cellular systems within the TV spectrum," in *Proc. IEEE DySPAN*, (Singapore), pp. 1 –12, april 2010.

[10] J. Boveda, G. Marcos, J. Perez, S. Ponce, and A. Aranaz, "MER degradation in a broadcast mobile network," in *Proc. IEEE BMSB*, (Bilbao, Spain), pp. 1 –5, May 2009.

[11] D. Plets, W. Joseph, P. Angueira, J. Arenas, L. Verloock, and L. Martens, "On the methodology for calculating SFN gain in digital broadcast systems," *IEEE Trans. Broadcast.*, vol. 56, pp. 331–339, Sept. 2010.

[12] K. Yan, F. Yang, C. Pan, and J. Song, "Reception quality prediction in a single frequency network for the DTMB standard," *IEEE Trans. Broadcast.*, vol. 58, pp. 629 –636, Dec. 2012.

[13] A. Rico-Alvarino and C. Mosquera, "On the effect of echoes in hybrid terrestrial-satellite single frequency networks: Analysis and countermeasures," in *Proc. ASMS and SPSC*, (Baiona, Spain), pp. 168 –175, Sept. 2012.

[14] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions*. Dover Publications Inc., New York, 1964.

[15] A. Dammann, R. Raulefs, and S. Plass, "Soft cyclic delay diversity and its performance for DVB-T in ricean channels," in *Proc. IEEE GLOBECOM*, pp. 4210–4214, 2007.

[16] A. Jovicic and P. Viswanath, "Cognitive radio: An information-theoretic perspective," *IEEE Trans. Inf. Theory*, vol. 55, no. 9, pp. 3945–3958, 2009.

[17] A. Rico-Alvariño, C. Mosquera, and F. Pérez-González, "On the coexistence of primary and secondary transmitters in a broadcast network," in *Proc. COGART*, (Barcelona, Spain), Oct. 2011.