

Novel Narrowband Interference Model to Analyze the Electromagnetic Resilience of OFDM Systems

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Abstract—Orthogonal Frequency Division Multiplexing based protocols are increasing in popularity for use in applications where dependability under harsh Electromagnetic conditions are of major importance, for example Vehicle-to-Everything communication. Orthogonal Frequency Division Multiplexing is especially vulnerable to narrowband interferences and thus, evaluating the electromagnetic resilience of Orthogonal Frequency Division Multiplexing systems to narrowband interferences is particularly interesting and important. Current narrowband interference models either don't take into account the bandwidth of the narrowband interference or are constructed in such a way that in depth analysis on short time scales is impossible. Therefore, this paper presents a novel narrowband interference model for electromagnetic resilience analysis without the aforementioned limitations. The model is mathematically defined, a mathematical derivation for the interference spectrum is given and simulations for the model are performed when it behaves as a QAM16 interferer.

Index Terms—Orthogonal Frequency Division Multiplexing (OFDM), Electromagnetic Interference (EMI), Narrowband Interference (NBI)

I. INTRODUCTION

There has been a growing interest in recent years from both academia and industry to use Orthogonal Frequency Division Multiplexing (OFDM) based wireless communication protocols in applications for which dependability, i.e. reliability, availability, functional safety, etc., is of major importance. A good example is Vehicle-to-Everything (V2X) communication, where 5G and Wi-Fi are viewed as the key enabling technologies for autonomous vehicles and for which a dedicated Wi-Fi version (IEEE802.11bd) is under development [1][2]. Another example is Industrial Internet-of-Things (IIoT), one of the cornerstones of Industry 4.0, for which 5G is heavily being investigated [3][4].

The Electromagnetic (EM) environment of these applications is usually harsher, i.e. there is an increased presence of Electromagnetic Interference (EMI), then what Wi-Fi and 5G were originally designed for. Challenges caused by EMIs

are expected to increase as our society's electrification and connectivity increases in nearly all domains. Therefore, it is important to carefully assess the EM resilience of wireless communication techniques used in these applications, to be able to guarantee their dependability under harsh EM conditions. For OFDM based wireless communication systems, Narrowband Interferences (NBIs) are of particular interest because of OFDM's vulnerability to this type of interference [5]. These NBIs could originate from power inverters used for electrical motors, other wireless communication systems with a significantly smaller channel bandwidth, jammers, etc.

The vulnerability of OFDM systems to NBI has been a topic of research of many previous papers. This vulnerability reveals itself in two distinct ways. The first way is the distortion of the data symbols by the NBI due to spectral leakage as discussed in [5][6]. Non coherent sampling of the NBI, followed by the Fast Fourier Transform (FFT) operation used in the receiver of the OFDM system, causes the frequency contents of the NBI to be spread out over multiple subcarriers, possibly leading to data symbol errors on multiple subcarriers.

The second way is through to the distortion of synchronization preambles as discussed in [7][8]. These preambles are known OFDM symbols that are used for the receiver to be able to synchronize to the transmitted signal in both time and frequency domain. The conventional methods of performing synchronization, through the use of time domain correlators, are very sensitive to distortions of the preamble patterns due to NBIs [7].

To study the effect of NBIs on OFDM systems, a mathematical interference model is required. A widely used model is the single frequency model, also referred to as the Continuous Wave (CW) model. In [5], Fors et al. analysed this CW model for its effect on an OFDM system. They showed that a CW interference could deteriorate OFDM performance significantly already at low Signal to Interference Ratio (SIR) levels. The CW model makes practical sense when the bandwidth of the

NBI is orders of magnitude smaller than the bandwidth of the OFDM system. This is the case, for example, when the NBI originates from harmonics of power converters. However, there are several sources of NBIs where the bandwidth is only around 5 or more times smaller than that of the OFDM system. Think about single carrier QAM wireless communication system, like the 802.15.4 protocol used in Zigbee which has 5 MHz channels and compare that to Wi-Fi's channel bandwidth ranging from 20 MHz to 320 MHz. For these cases, the CW model doesn't represent reality because of the lack of bandwidth.

Another NBI model was presented in [9] in the context of OFDM systems for powerline communications. This model addresses the previous bandwidth concern of the CW model. However, this model starts from a Power Spectral Density (PSD) that is assumed to be known. Therefore, the performance analysis with PDF only considers the impact of average interference. This is certainly useful, but to get a full look at the mechanics with which the NBI affects an OFDM system, it would be useful to be able to analyze the behaviour on shorter time scales, to see how any realization of the NBI can affect the OFDM system. To achieve this, the model presented in this paper starts from a time domain representation over a finite time interval from which the interference spectrum can be calculated for any realization of the NBI. By subsequently randomly generating a large number of these interference spectra, behaviour on both large and smaller time scales can be identified.

The remainder of the paper is organized as follows. Section II presents the mathematical derivation of the novel generalized NBI model. In Section III a digitally modulated NBI is fitted onto this new model and its interference spectrum is mathematically derived. Section IV analyses the general behaviour of the digitally modulated NBI model through simulations when it affects OFDM systems. Concluding remarks are drawn in Section V.

II. NARROWBAND INTERFERENCE MODEL

The CW model for a NBI is simply modelled using a sinusoidal wave as shown in Eq. (1):

$$i_{cw}(t) = A \cos(\omega t + \varphi), \quad (1)$$

where $i_{cw}(t)$ is the CW interference and A , ω and φ are the amplitude, frequency and phase of the CW, respectively. Such an CW interference can be seen as a NBI with an infinitely small bandwidth. While easy to work with mathematically, a NBI with an infinitely small bandwidth is not always realistic. Therefore, it would be useful to construct a model that does not have an infinitely small bandwidth. This can be done by taking the CW model and making its parameters (amplitude, phase and frequency) time varying, as shown in Eq. (2). This essentially models the NBI as a carrier wave with some arbitrary signal modulated onto each of its fundamental parameters:

$$i_{nbi}(t) = A(t) \cos(\omega(t)t + \varphi(t)). \quad (2)$$

One can now imagine this interference arriving at the receiver of a wireless system. There, it would get mixed down to baseband by mixing it with the carrier frequency f_c of the wireless system, see Eq. (3), according to the Zero-IF receiver architecture.

$$r(t) = i_{nbi}(t) \cos(\omega_c t) + j i_{nbi}(t) \sin(\omega_c t). \quad (3)$$

Here, $r(t)$ represents the complex received interference after downmixing to baseband and $\omega_c = 2\pi f_c$. After applying a lowpass filter (denoted by the LPF{ } operation) to this signal Eq. (3) becomes:

$$\text{LPF}\{r(t)\} = \frac{A(t)}{2} e^{-j((\omega(t) - \omega_c)t + \varphi(t))}. \quad (4)$$

If this signal gets sampled with the sampling frequency f_s of the wireless system, then the following expression is obtained:

$$i[n] = A_b[n] e^{j(\omega_b[n] \frac{n}{f_s} + \varphi_b[n])}, \quad (5)$$

with n the discrete time variable ($t = n/f_s$), $\omega_b = -(\omega[n] - \omega_c)$, $\varphi_b = -\varphi[n]$ and $A_b[n] = A[n]/2$.

Equations (2) and (5) are the mathematical expressions for the NBI model in continuous and discrete time, respectively. In essence, this model allows us to represent any modulated signal with any bandwidth. Whether or not the model is narrowband strictly depends on the bandwidth of the generated signal by the model, relative to the bandwidth of the signal it interferes with. The bandwidth of this model is determined by the (maximum) rate of change of the time varying parameters. If this bandwidth exceeds a certain (not precisely definable) boundary, the interference can be seen as a non-narrowband interference, or potentially even a wideband interference. However, for the remainder of this paper, it will be assumed that the bandwidth of the interference signal is significantly smaller than the bandwidth of the OFDM signal, thus making it narrowband.

The discrete time model in Eq. (5) will be used further in the paper to analyse its effect on OFDM systems. Although this paper focusses on OFDM systems, this model can be used to analyse the effect of an NBI on any other electrical or communication system.

III. OFDM ANALYSIS OF THE NBI MODEL

A. Finalizing the NBI model for OFDM analysis

The NBI model in Eq. (5), is a very general model. This model can be slightly changed to make it easier to work with for OFDM analysis. Let $w_b[n] = ((d[n] + \alpha[n]) \frac{2\pi f_s}{K})$ in Eq. (5), with K the number of subcarriers in the OFDM system, then one gets:

$$i[n] = A_b[n] e^{j(2\pi(d[n] + \alpha[n]) \frac{n}{K} + \varphi_b[n])}. \quad (6)$$

In the above equation, $d[n] + \alpha[n]$ represents the frequency of the NBI expressed as the sum of the closest subcarrier index with a lower frequency than that of the NBI ($d[n] \in \{-\frac{K}{2}, -\frac{K}{2} + 1, \dots, \frac{K}{2} - 1\}$) and a fractional offset to this

subcarrier index ($\alpha[n] \in [0, 1]$). Or in other words, $d[n] + \alpha[n]$ represents the frequency of the NBI expressed in units of subcarriers.

B. Interference spectrum of NBI as digitally modulated wireless signal for OFDM symbol

Let us introduce some constraints to make the signal act like something that might occur in a real wireless system, more specifically a digitally modulated wireless interference. This could, for example, be a Bluetooth or QAM modulated signal that interferes with our OFDM system.

Additionally, since an analysis of the effect of this NBI model on a OFDM system is desired, it would be beneficial to restrict the interference to have a length equal to the length of an OFDM symbol. This way, the effect of the NBI can be analysed on a per OFDM symbol basis by looking at the spectrum of the interference, as will be explained later.

If the interference is a digitally modulated signal, then one can assume that this signal stays constant throughout its symbol period. During an OFDM symbol multiple interference symbols will occur and thus the interference will make L changes of amplitude, phase and frequency. This creates $L + 1$ interference sections (l) where the start time of these sections are indicated with τ_l . Therefore, the NBI model can be rewritten as:

$$i[n] = \sum_{l=0}^L A_l e^{j(2\pi(d_l + \alpha_l) \frac{n}{K} + \varphi_l)} P_l[n], \quad (7)$$

$$\text{with } P_l[n] = \begin{cases} 1 & \text{if } \tau_l \leq n < \tau_{l+1} \\ 0 & \text{if } n < \tau_l \text{ and } n \geq \tau_{l+1} \end{cases}.$$

This expression now represents a NBI with a discrete number of sections ($L + 1$), during an OFDM symbol, with each section l being a complex sinusoidal wave with a certain amplitude (A_l), frequency ($d_l + \alpha_l$), phase (φ_l) and start time τ_l . All the parameters of interest of this model are shown in Table I. Each section is multiplied with an activation function $P_l[n]$, which is equal to 1 when the n is within the section (l) of interest, and 0 elsewhere. Such an NBI is shown in Fig. 1, where the blue samples show the NBI and the orange sample represent the activation function for section 1.

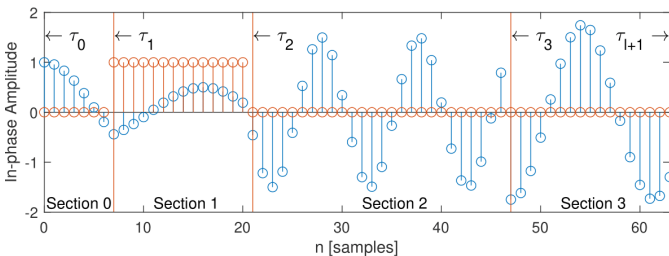


Fig. 1. Example of NBI generated by the novel digitally modulated NBI model with 4 sections. Note that only the real part of the NBI is shown.

As mentioned before, the paper will now focus on the spectrum of this interference, which will from now on be

TABLE I
DIGITALLY MODULATED NBI MODEL PARAMETERS

K	number of subcarriers = FFT Length
n	discrete time $\in \{0, 1, 2, \dots, K - 1\}$
L	number of changes $\Rightarrow L + 1$ sections and $L < K$
l	section index $\in \{0, 1, 2, \dots, L\}$
τ_l	section start times $\in \{1, 2, \dots, K - 1\}$ and $\tau_0 < \tau_1 < \dots < \tau_L < \tau_{L+1}$ with $\tau_0 = 0$ and $\tau_{L+1} = K$
A_l	Section Amplitude
$d_l + \alpha_l$	Section frequency
φ_l	Section phase

referred to as the interference spectrum $I[k]$, with k the discrete frequency parameter. The interference spectrum is of interest because this shows the amount of interference that each subcarrier of a OFDM symbol experiences for a given realization of this interference model. Furthermore, one can then look at multiple realizations, by for example randomly generating parameters, and analyse the general/shared behaviour of these realizations.

The following derivation gives a generalized solution to the interference spectrum that an OFDM symbol experiences when an NBI, that behaves as a sinusoidal wave with L changes of amplitude, frequency and phase, interferes with the OFDM symbol.

$$\begin{aligned} I[k] &= DFT\{i[n]\} \\ &= \sum_{n=0}^{K-1} i[n] e^{-j2\pi \frac{k}{K} n} \\ &= \sum_{n=0}^{K-1} \sum_{l=0}^L A_l e^{j2\pi(d_l + \alpha_l) \frac{n}{K} + \varphi_l} P_l[n] e^{-j2\pi \frac{k}{K} n} \\ &= \sum_{l=0}^L A_l e^{j\varphi_l} \sum_{n=\tau_l}^{\tau_{l+1}-1} e^{j2\pi(d_l + \alpha_l - k) \frac{n}{K}}. \end{aligned} \quad (8)$$

To simplify this, the following expressions is used:

$$\sum_{i=P_1}^{P_2} a^i = a^{P_1} \frac{1 - a^{P_2 - P_1 + 1}}{1 - a}, \quad (9)$$

$$1 - e^{j2x} = -2j \sin(x) e^{jx}. \quad (10)$$

Applying (9) and (10) to the second summation in (8) gives:

$$\begin{aligned} &\sum_{n=\tau_l}^{\tau_{l+1}-1} e^{j2\pi(d_l + \alpha_l - k) \frac{n}{K}} \\ &= e^{j\pi(d_l + \alpha_l - k) \frac{\tau_{l+1} + \tau_l - 1}{K}} \frac{\sin(\pi(d_l + \alpha_l - k) \frac{\tau_{l+1} - \tau_l}{K})}{\sin(\pi(d_l + \alpha_l - k) \frac{1}{K})}. \end{aligned} \quad (11)$$

Substituting (11) in (8) results in the following:

$$I[k] = \sum_{l=0}^L A_l e^{j\varphi_l} e^{j\pi(d_l + \alpha_l - k) \frac{\tau_{l+1} + \tau_l - 1}{K}} \frac{\sin(\pi(d_l + \alpha_l - k) \frac{\tau_{l+1} - \tau_l}{K})}{\sin(\pi(d_l + \alpha_l - k) \frac{1}{K})}. \quad (12)$$

Equation (12) gives the solution for the interference spectrum that an OFDM symbol experiences due to a digitally modulated NBI as described earlier. Or in other words, for each subcarrier (k) the amount of interference added onto that subcarrier can be calculated using this equation. Intuitively this equation can be interpreted as the sum of the interferences that each individual section (l) of the NBI generates. With the interference of each section being determined by the equation after the summation in (12).

However, this solution is not fully complete, since under certain conditions there is a divide by zero error. More specifically, when $\alpha_l = 0$ and $k = d_l$ then the sine functions become $\frac{0}{0}$. This can be solved with L'Hôpital's rule.

$$\begin{aligned} \lim_{x \rightarrow 0} \frac{\sin(\pi x \frac{\tau_{l+1} - \tau_l}{K})}{\sin(\pi x \frac{1}{K})} &= \lim_{x \rightarrow 0} \frac{\sin(\pi x \frac{\tau_{l+1} - \tau_l}{K})'}{\sin(\pi x \frac{1}{K})'} \\ &= \frac{\pi \frac{\tau_{l+1} - \tau_l}{K} \cos(0)}{\pi \frac{1}{K} \cos(0)} \\ &= \tau_{l+1} - \tau_l. \end{aligned} \quad (13)$$

From Eq. (13) it can be concluded that when $\alpha_l = 0$, the interference spectrum at index d_l due to section l is the following:

$$I[d_l] = A_l e^{j\varphi_l} (\tau_{l+1} - \tau_l). \quad (14)$$

C. Interference power of digitally modulated NBI model

Another important property of the NBI model, as defined in Eq. (7), is the amount of power the interference carries.

$$\begin{aligned} P_i &= \frac{1}{N} \sum_{n=0}^{N-1} |i[n]|^2 \\ &= \frac{1}{N} \sum_{n=0}^{N-1} \left| \sum_{l=0}^L A_l e^{j(2\pi(d_l + \alpha_l) \frac{n}{K} + \varphi_l)} P_l[n] \right|^2 \\ &= \frac{1}{N} \sum_{l=0}^L \sum_{n=\tau_l}^{\tau_{l+1}} |A_l e^{j(2\pi(d_l + \alpha_l) \frac{n}{K} + \varphi_l)}|^2 \\ &= \frac{1}{N} \sum_{l=0}^L A_l^2 (\tau_{l+1} - \tau_l). \end{aligned} \quad (15)$$

Equation (15) is the power of the digitally modulated NBI. This power is essentially the weighted average of the power of each section of the NBI with the weights corresponding to the length of the sections.

IV. SIMULATING AND ANALYSING THE NBI MODEL

With the expression for the interference spectrum due to a digitally modulated NBI, it is now possible to generate these spectra efficiently, using only the defining parameters of this interference. What follows are simulations and an analysis of this model by randomly generating these interference spectra as if a digitally modulated QAM16 signal interferences with and OFDM system. However, note that this analysis can be generalized for any QAM, PSK or FSK modulated signal. For example, a Bluetooth (GFSK) signal could be mapped onto this model and simulated. By averaging over a large number of randomly generated QAM16 NBIs, a common behaviour of this type of interference on OFDM systems can be identified.

A. Symbolrate and power constraints of the NBI

To generate the parameters that result the model to behave as a QAM modulated signal, certain new constraints have to be added. First of all, to generate the τ_l values, the symbolrate (B_i) of the NBI, relative to the OFDM system, needs to be defined. This symbolrate is related to the length of the QAM symbols of the interference as sampled in the OFDM system and the samplerate of the OFDM system. The following shows this relation:

$$B_i = \frac{1}{\Delta T \frac{1}{f_s}} = \frac{f_s}{\Delta T}, \quad (16)$$

where B_i is the symbolrate of the NBI, ΔT is the length of the QAM symbols expressed as a number of samples at the sample rate of the OFDM system f_s . Note that $\Delta T \in \mathbb{Q}$ because the QAM symbol time doesn't have to be perfectly aligned to the sample rate of the OFDM system.

The symbolrate of the NBI can now also be expressed as a number of subcarriers of the OFDM system as follows:

$$W = \frac{K}{\Delta T}, \quad (17)$$

where W is the NBI symbolrate, from now on referred to as the width of the NBI, and K is the number of subcarriers in the OFDM system. Note that ΔT needs to be at least 1 (but is typically $\gg 1$) to be able to consider the interference as narrowband. From ΔT its possible to determine the τ_l values by simply multiplying ΔT with l and rounding up, as shown in Eq. (18). Rounding up is required because τ_l indicates the first sample time when a new NBI section is sampled.

$$\tau_l = \lceil l \Delta T \rceil \text{ with } \tau_l \in \{1, 2, \dots, K-1\} \text{ and } \Delta T \geq 1. \quad (18)$$

If the τ_l values would be generated solely based on Eq. (18) then the start and ending of an OFDM symbol would always be optimally lined up with the edges of the QAM symbols of the NBI. This is of course not the case in practice. That is why one additional parameter needs to be introduced, a begin time offset $t_d \in \{0, 1, \dots, \lfloor \Delta T \rfloor\}$, which gets added to all the τ_l values.

Next to symbolrate definitions, there is a need for power constraints to be able to interpret the results that will follow.

Therefore the QAM NBI is generated using a constellation that has unit power, meaning that on average the QAM NBI will have a power of 1. If it is assumed this power is relative to the power of an OFDM system/signal, then one can analyse the effect of the NBI on an OFDM system with unit power. To be able to analyse different SIR levels, the power of the NBI constellation needs to be scaled. To do this, the amplitude of the QAM NBI constellation can be scaled as follows:

$$P_{scaled} = P c = A^2 c = (A\sqrt{c})^2 = A_{scaled}^2, \quad (19)$$

with c the power scale factor.

B. Simulations

TABLE II
SIMULATION PARAMETERS

Simulation Parameter	value
Number of subcarriers: K	64
Power scale: c	1 (i.e. unit power)(SIR = 0 dB)
NBI QAM modulation	QAM16
NBI frequency: $d + \alpha$ simulation A: simulation B:	4.5 (4, 4.1, 4.2, ..., 5.9, 6)
NBI Width: W simulation A: simulation B:	3.5 (3, 3.1, 3.2, ..., 3.9, 4)
Begin time offset: t_d	Uniform over $\{0, 1, \dots, \lfloor \Delta T \rfloor\}$
A_l	Uniform over all unit power QAM16 constellation symbol amplitudes
φ_l	Uniform over all unit power QAM16 constellation symbol phases
Sample size	100000

In the first simulation, 100.000 random NBIs were generated where the (relative) NBI frequency ($d + \alpha = 4.5$) and NBI width (3.5) were kept the same for all generated NBIs. The A_l and φ_l values for each NBI were randomly chosen from a QAM16 constellation diagram with unit power.

The results of this simulation are shown in Fig. 2, where the vertical axis is the normalized interference amplitude of the NBI, as the magnitude of the complex valued interference, on each subcarrier (k) shown on the horizontal axis. The orange, blue and yellow lines show the maximum interference, the average interference ($\pm\sigma$) and the minimum interference that occurred on each subcarrier respectively. It is clearly visible that the interference strength is higher on the subcarriers closer to a frequency value of 4.5 and is spread around that frequency. One could also identify a sinc like function pattern in the max interference graph, where every couple of subcarriers the interference strength dips significantly. This is due to the combination of the rectangular windowing performed by the DFT operation and the activation functions $P_l[n]$.

The dotted lines in Fig. 2 represent the half distance $C_{d/2}$ between two adjacent symbols in the respective unit power constellation diagrams of the OFDM system. These half distance lines show the minimum interference strength needed on a symbol/subcarrier to cause a symbol flip for that specific QAM constellation used in the OFDM system. If the max interference strength graph exceeds such a half distance

line, this means that on those subcarriers, there is a chance of NBI causing a symbol flip. On the subcarriers where the mean interference strength graph exceeds such a half distance line, it is more likely that a symbol flip will occur than that no symbol flip occurs.

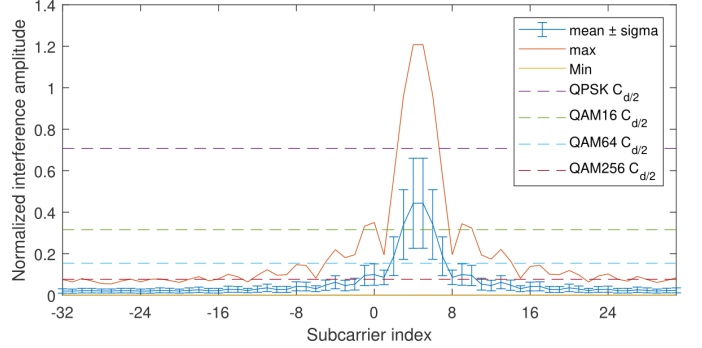


Fig. 2. NBI magnitude interference spectrum: average $\pm$ sigma (blue), maximum (red) and minimum (yellow) over 100.000 randomly generated QAM NBIs according to the parameters of simulation A from Table II. The dotted lines show the half distance between two adjacent points in the respective constellation diagrams of unit power.

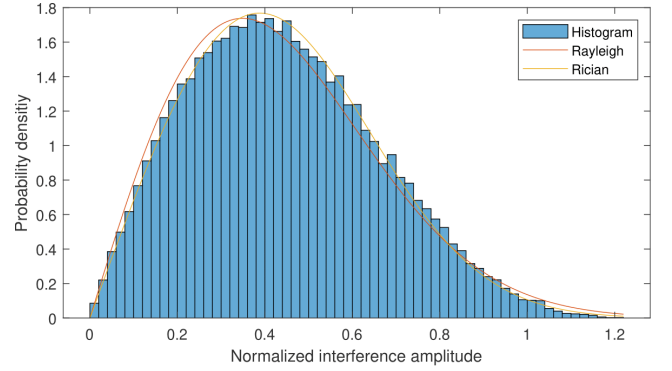


Fig. 3. Histogram and fitted probability distribution of the interference strength on the 4th subcarrier of 100.000 randomly generated QAM NBIs according to the parameters of simulation A from Table II.

Figure 3 shows a histogram of the interference strength on subcarrier 4 (subcarrier with the largest interference), measured over the 100.000 generated NBIs. An interesting question is what probability distributions the histograms of the subcarriers follow, since this could be used for estimating the interference and/or for continued modelling. This question turns out to not be trivial. Although the fitted Rayleigh and Rician distribution in Fig. 3 might suggest to conclude that the interference amplitude on individual subcarriers follows a Rician distribution, this turns out not to be true when looking at the histograms and fitted Rayleigh and Rician distributions of some other subcarriers. For example, the fitted distributions of subcarriers -6 and -24 on Figs. 4 and 5, respectively, don't fit the histogram. More interestingly even, the histogram of subcarrier -24 presents three distinct peaks in its probability density. This phenomenon was also observed for several other subcarriers. This problem should be further investigated in

the future, potentially using multimodal distributions to come to a complete statistical model of the interference on each subcarrier.

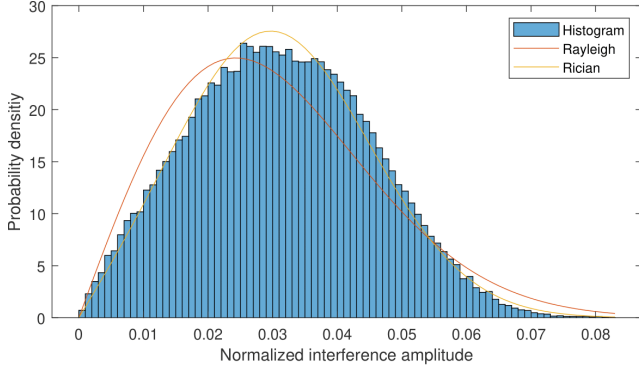


Fig. 4. Histogram and fitted probability distribution of the interference strength on the -6th subcarrier of 100,000 randomly generated QAM NBIs according to the parameters of simulation A from Table II.

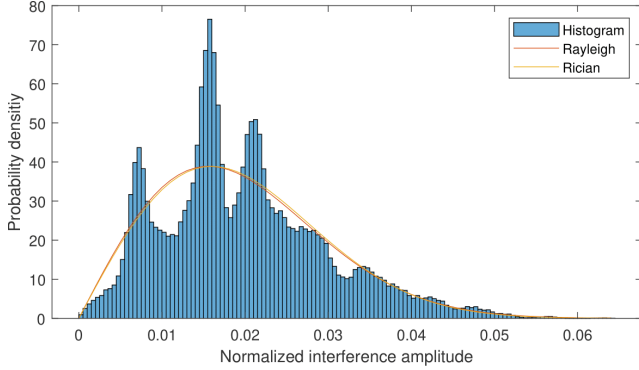


Fig. 5. Histogram and fitted probability distribution of the interference strength on the -24th subcarrier of 100,000 randomly generated QAM NBIs according to the parameters of simulation A from Table II.

In the second simulation, the same process was followed as in the first simulation, with the addition that these simulations were performed for multiple combinations of $d + \alpha$ and W . The precise $d + \alpha$ and W values are shown in Table II under simulation B. The SIR was 0 dB for all simulations. The goal is to gauge how the $d + \alpha$ and W parameters influence the experienced interference by the OFDM system. For every combination of $d + \alpha$ and W a graph like the one from Fig. 2 can be obtained. One way to gauge the possible effect of the interference is by counting the amount of subcarriers where the mean graph exceeds the $C_{d/2}$ lines for the different OFDM system constellation diagrams. This is what is shown in Fig. 6 for a QAM16 OFDM constellation.

Figure 6 shows that when the interference is in the middle of two subcarriers (i.e. $\alpha = 0.5$), the interference is slightly worse. This indicates that the NBI, on average, maximally influences the OFDM system when the NBI is right in the middle of two subcarriers. This is also the case for the CW model. [5]

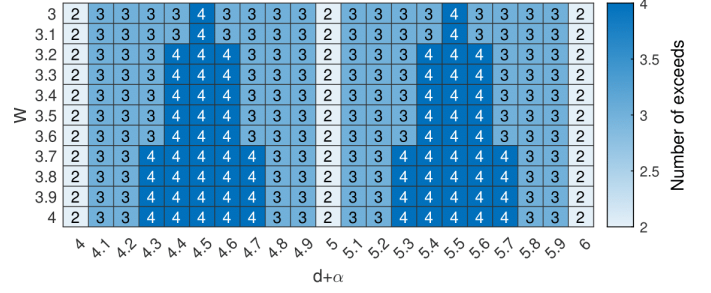


Fig. 6. Number of subcarriers where the mean line exceeds the QAM16 $C_{d/2}$ line for multiple configurations of W and $d + \alpha$ according to the parameters of simulation B from Table II.

V. CONCLUSIONS

In this paper, a novel narrowband interference model was mathematically derived. This model was then adapted to represent a digitally modulated signal as if it was sampled by an OFDM system. From this representation the interference spectrum of such a digitally modulated NBI as well as its power were mathematically derived. Simulations of this digitally modulated model, when it takes the form of a QAM16 modulated signal, showed that the model does indeed behave as a NBI for a OFDM system. It was also shown that this interference maximally influenced the OFDM system when $\alpha = 0.5$ or in other words when the center frequency of the interference is positioned right in between two subcarriers of the OFDM system.

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