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A SURVEY ON IMPULSIVE NOISE MODELING

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ABSTRACT

Impulsive noise is an undesirable signal from the communications channel that corrupts the transmitted signal in communications systems. Example of such a systems are Digital Television, Power Line Communications and Underwater Acoustic Communications in which the transmitted signals are more affected by this type of noise than by the typical AWGN noise. The current article summarizes several studies on impulsive noise from an statistical point of view. In this concern a variety of models are presented analytically and the main characteristics are described through the use of graphical representations. Furthermore, some ideas for future research field are also discussed.

KEYWORDS: Impulsive Noise Modeling, Middleton Model, Markov Model.

RESUMEN

El ruido impulsivo es una señal no deseada del canal de comunicaciones que afecta la recepción de información en los sistemas de comunicaciones. Ejemplo de estos sistemas son los sistemas de Televisión Digital, Comunicaciones por Líneas de Potencia y Comunicaciones Acústicas Sub-Marinas, en los cuales las señales transmitidas son más afectadas por este tipo de ruido que por el típico ruido blanco. El presente artículo resume diversos estudios en la modelación del ruido impulsivo desde el punto de vista estadístico. Se presentan analíticamente diversos modelos y sus principales características se describen con el apoyo de gráficos. Adicionalmente se presentan algunas ideas de futuras investigaciones en este campo de estudio.

PALABRAS CLAVES: Modelo de Ruido Impulsivo, Modelo de Middleton, Modelo de Markov.

1. INTRODUCTION

Impulsive noise is mainly comprised by short duration noisy pulses. This noise is caused by switching devices, channel environment, clicks from computer keyboards, loads not synchronous with the power frequency, etc. Opposite to the standard AWGN model, impulsive noise is a non-stationary signal and may represent the main disturbing signal, such is the case of Power Line Communications Systems (PLC) [1]. This undesirable signal is also reported on Digital Television [2], audio broadcasting [3], xDSL technologies [4] as well as Underwater Acoustic systems [5]. In the frequency range from some hundreds of kHz up to 20MHz, the measurement of impulsive noise shows that it exhibits a duration of some microseconds up to a few milliseconds[6], and it could be as high as 40 dB above the background noise [7].

Reports in regard to impulse noise are focused on three major areas: noise modelling, noise detection and noise reduction. Noise modelling is addressed by the definition of both, the main parameters and the associated probability density functions. As explained by the pioneer work of Middleton in [8], the modelling of impulsive noise allows to provide a realistic and quantitative description of this kind of

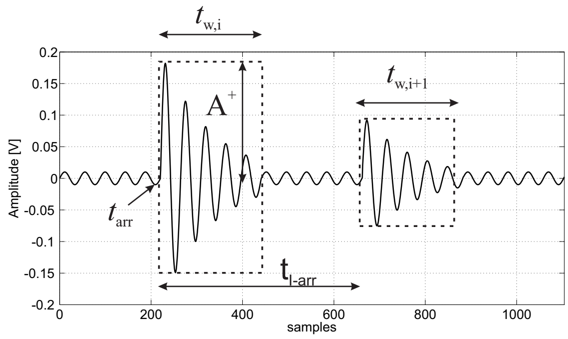

Figure 1: Impulsive noise pulses.

interference, to specify and guide experiments for measuring the effects of this interference. This is used to determine the optimum receiver in this environment.

The model to be derived must be canonical, i.e., the general expression does not depend on the source, it is invariant of the particular noise source [9]. Besides, since this type of noise is impulsive, only some portions of the signal are affected. In this regard, noise detection algorithms attempt to detect the portions of the signals contaminated with noise. Finally, noise reduction algorithms are employed to cancel the noisy portions of the signal through the modelled and corrupted samples.

In order to model this kind of noise, it is classified in three different groups [10]: periodic impulses synchronous to the main frequencies, periodic impulses asynchronous to the main frequencies, aperiodic impulsive noise, all of these caused by supplies. From this classes of noise, the lats one is the stronger and causes severe deterioration to the system's performance [11]. This is considered as the system's impulsive noise and the main cause of errors in PLC Communications [12]. Additionally, impulsive noise is described by the following parameters, as depicted in Figure 1 [13]: Peak amplitude (A^+), Damping factor , Width (t_w), Pseudo frequency f_0 associated to the damped sinusoid, Arrival time (t_{arr}), Inter-arrival time ($t_{\text{I-arr}}$): Time between consecutive pulses.

The behavior of these random parameters are described by statistical models in order to obtain the probability density functions. The focus of this report is the description of asynchronous impulsive noise based on Markov Chain and Middleton Models. This is given by the fact that the structure of bursty pulses, commonly observed when impulsive noise is present, are modeled by the Markov Chain in a more realistic way [14]. The rest of the paper is organized as follows: Section 2 summarizes the reported models of impulsive noise. Section 3 outlines some future directions of research. Finally, conclusions are presented in Section 4.

2. STATISTICAL DESCRIPTION OF IMPULSIVE NOISE

Impulsive noise is described through an stochastic process with properties Non-stationary, Binary-state sequence, Random amplitude and Random position of occurrence [15]. The impulsive noise parameters to be modelled are Peak Amplitude, Damping factor, Phase, Width, Pseudo frequency f_0, Inter-arrival time. These parameters are modeled by probability distributions. The amplitude is usually modeled by Gaussian or α-stable (SαS) distributions. The amplitude and time of arrival are jointly modeled by means of the processes: Middleton Model [9], Two term mixture model [16], Bernoulli-Gaussian Model [15], Poisson-Gaussian Model [11], Poisson-α-stable Model [7] and Markov Chain Model [6].

Except for the Markov Chain Model, the amplitude is modeled as an identical independent distributed (i.i.d.) process. This assumption limits the applicability when bursty pulses are considered. In this case Markov Chain offers a more realistic model [14].

Analytically, one single pulse of impulsive noise can be described by [13]:

$$n_I(t) = A\,sin(w \cdot t + \varphi)e^{-\frac{t}{\tau}}, \tag{1}$$

where A represents the amplitude, ω the frequency, φ the phase and τ the damping factor equivalent to the width of the pulse.

The single pulse can also be represented in a complex representation as the superposition of damped sinusoids [17]:

$$n(t) = \sum_{i=0}^{M-1} A_i\, e^{-\alpha_i\, t} e^{-j2\pi f_i t} \tag{2}$$

where A_i, α_i and f_i represent amplitude, damping factor and frequency respectively. The value of M represents the total number of damped sinusoids.

In a similar fashion, burst pulses of impulsive noise are described by three different terms as follows [15] (discrete domain):

1. $h[n]$: Describes the duration and shape of the noisy pulse. Typically determined by the impulse response of the channel.
2. $n[m]$: Describes the amplitude of the noisy pulse. This is a continuous-value random process.
3. $b[m]$: Describes the time of occurrence of impulse noise. This is a binary-valued random sequence.

These three terms determine the impulsive noise by the following relation:

$$n_I[m] = \sum_{k=0}^{P-1} h[k]\, n[m-k]\;b[m-k], \tag{3}$$

Fig. 2 depicts the model as well as the impulsive noise sequence at the output. This statistical models establish the probability density function of the sequence:

$$n_i[m] = n[m]\, b[m], \tag{4}$$

In this case $n_i[m]$ modulates the amplitude and inter-arrival time of waveform $h[m]$ given by $n[m]$ and $b[m]$, respectively.

A third and more complex analytical expression is considered when the effect of the channel as well as the filter at the receiver are taken into account. These considerations yields the following expression for the received interference $\mathbf{I}_m(T)$ as [12]:

$$\mathbf{I}_m(T) = \gamma(d_m) \sum_{i=1}^{\mathbf{k_m}} \mathbf{h}_{m,i} e^{j\theta_{m,i}} \mathbf{X}_{m,i}, \tag{5}$$

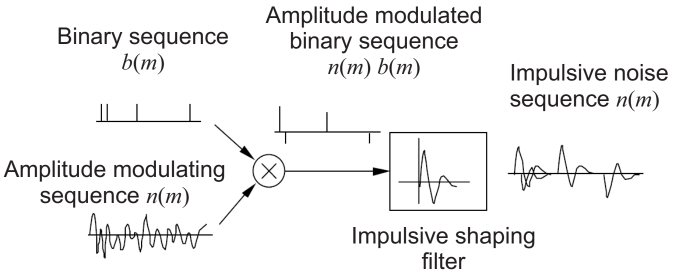

Figure 2: Impulse noise model [15].

where:
m: interference source,
i: impulse noise indicator,
T: window duration,
$\gamma(d_m) = e^{-\alpha_0 d_m}$ is the channel attenuation if m is a wired source,
d_m: distance between the source and the receiver,
$\mathbf{k_m}$: total number of impulses in T,
$\mathbf{h}_{m,i} e^{j\theta_{m,i}}$: flat channel gain between the source m and the receiver,
$\mathbf{X}_m, i$ is the random emission given by the duration of the impulse i and is represented by:

$$\mathbf{X}_{m,i} = \mathbf{B}_{m,i} e^{j\phi_{m,i}} \mathbf{1}(\tau_{m,i} < \mathbf{T}^E_{m,i}) \tag{6}$$

$\mathbf{B}_{m,i} e^{j\phi_{m,i}}$: represents the result of narrowband filtering of interference emissions performed at the receiver,
$\mathbf{B}_{m,i}$: is an *i.i.d.* envelope, $\phi_{m,i}$: random phase uniformly distributed on $[0, 2\pi]$,
$\mathbf{T}^E_{m,i} >> \frac{1}{\Delta f_r}$: duration of a noisy pulse,
Δf_r: receiver bandwidth ($\Delta f_r \approx 1$ MHz for broadband PLC),
$\mathbf{1}$: indicator function.

2.1. Middleton Model

Middleton Model describes the probability density function (pdf) of impulsive noise as the linear superposition of Gaussian functions with different variances as [9]:

$$p_X(x) = \sum_{m=0}^{\infty} \frac{A^m \, e^{-A}}{m!} \, \frac{1}{\sqrt{2\pi\sigma_m^2}} e^{-\frac{x^2}{2\sigma_m^2}}, \tag{7}$$

where:

$$\sigma_m^2 = \left(1 + \frac{1}{\Gamma}\right) \left(\frac{\frac{k}{A} + \Gamma}{1 + \Gamma}\right) \sigma_N^2, \tag{8}$$

where the parameter A is called impulsive index. The parameter Γ is the background-to-impulsive noise ratio, the value of Γ gives how strong the impulsive noise is in comparison with the AWGN component [18]. The value of $\sigma_N^2 = \sigma_n^2 + \sigma_I^2$ is the total power given by the contribution of the impulsive noise power σ_I^2 and AWGN process σ_n^2.

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On the other hand, the term $\frac{A^m e^{-A}}{m!}$ in (7), represents the Poisson-distributed probability describing the event that m noise sources contribute to the impulsive event [19]. This term describes independent impulse emissions Poisson distributed in space and time [18].

The term A is directly related to the pulse rate λ and the impulse mean duration $\overline{T}$ at the receiver, this is given by $A = \lambda \overline{T}$. Lower values of A describe lower number of impulses and/or duration. In this case, noise is globally dominated by a typical event, as the impulsive scenario dictates. Higher values of A describe AWGN processes. The PDF described in (7) exhibits a mean value equals to zero. Besides, the non-impulse AWGN process is also included in the first term considering $m = 0$ [18].

This model describes the Class-A Middleton Model from a total of three classes, including B and C. Class A describes impulsive pulses having narrower spectral band than the receiver. Class A is used to model a wide variety of electromagnetic emissions, requires the lowest number of parameters and has the most tractable probability density function [18]. Class B describes impulsive pulses involving higher spectral band than the receiver. Class C includes the additive mixture of A and B classes.

The Middleton Class-A model is used to determine the probability density function of noise amplitude. Using the distribution in (7), impulsive noise is described by the canonical parameters A, $\mathit{\Gamma}$ and σ_N^2. The use of this model is an attractive approach, since it results to be canonical (i.e., invariant to a particular noisy source mechanism) and the model is totally described by just three parameters [18].

Although, several classes of impulsive noise can be expressed by this approach, the model does not define time-domain features [20] and does not describe the PLC channel noise in an accurate way [7]. Additionally, this model fails when bursty impulsive noise is considered. Usually, pulses in bursts are time correlated and the Middleton model assumes i.i.d. behaviour. The Middleton model only describes the first-order statistic [18] without assumptions to the correlation between consecutive pulses.

Further studies in regard to this model establishes the characteristic function for the noise amplitudes as:

$$\mathit{\Phi}_{\mathbf{I}_m}(w) = e^{-\lambda_m \mu_m} \sum_{k=0}^{\infty} \frac{(\lambda_m \mu_m)^k}{k!} e^{\frac{-k|w|^2 \mathbb{E}\{\mathbf{h}_m^2 \mathbf{B}_m^2\}}{4}}, \tag{9}$$

taking into account the channel parameters. Where:

$\mathbf{I}_m$: noise amplitude,
m: interference source,
λ_m: average total of pulses per second
μ_m: expected value of $\mathbf{T}^E_{m,i} >> \frac{1}{\Delta f_r}$
$\mathbf{T}^E_{m,i} >> \frac{1}{\Delta f_r}$: noisy pulse duration
$\mathbf{h}_{m,i} e^{j\theta_{m,i}}$: amplitude flat channel gain between the source m and the receiver,
$\mathbf{B}_m$: represents the result of narrowband filtering of interference emissions performed at the receiver, is an *i.i.d.* envelope,

2.2. Markov Chain Models

Markov chains can be used to describe non-stationary process whereas the random events can be described by states. Indeed, this is the case of impulsive noise, whether the noise is present or not can be described by two states (Binary Model), for instance.

Through the use of Markov chains three approaches has been derived:

1. Binary state model [15, 14],
2. Markov-Middleton model [18],
3. Partitioned Markov chain [21, 6],
4. Second level Markov chain [22]

The use of Markov chains allows to describe the memory of the channel when pulses occur in bursts. However, in case of multicarrier modulation like OFDM, the nature of pulses becomes irrelevant (in bursts or randomly), since all the subcarriers are affected in the time domain because of the DFT operation at the receiver. One or several impulses, causes the same symbol error as long as the noise impulse variance remains constant. On the contrary, in case of single pulse modulation it is important to distinguish impulse noise with or without memory. If one impulse happens then just a few symbols are affected [23].

2.2.1. Binary State Model

The binary state model is described as depicted in Figure 3. The state S_1 describes the transmission of noisy samples from impulsive noise. The state S_0 describes the absence of noise, in this case samples of zero value are transmitted. The probabilities of transitions from S_i to S_j are given by the values p_{ij}, $i, j \in \{0, 1\}$.

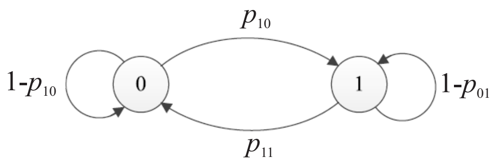

Figure 3: Binary State Model of the impulsive noise [14].

For this model the following figures related to bursty pulses are defined [14]:

- Average percentage of pulses: $S_{nz} = p = \frac{p_{01}}{p_{01}+p_{10}}$,
- Average percentage of non-pulses: $S_{nz} = 1 - p = \frac{p_{10}}{p_{01}+p_{10}}$,
- Average block size of pulses: $B_{nz} = \frac{1}{p_{01}}$
- Average block size of non-pulses: $B_{nz} = \frac{1}{p_{10}}$
- Noise Memory: $\eta = \frac{1}{p_{01}+p_{10}}$

In can be shown that when the $\eta = 1$ the noise is memoryless. For instance, this happens when $p_{10} = 0.1$ and $p_{01} = 0.9$. In this case, the Markov chain is equivalent to a Bernoulli-Gaussian model with i.i.d. samples [14]. When $\eta > 1$ the noise has a persistent memory, and the average permanence in a given state is longer compared to the memoryless case.

The i.i.d. process takes places when the columns of the transition matrix is given by:

$$P = \begin{bmatrix} 1 - p_{10} & p_{10} \\ p_{01} & 1 - p_{01} \end{bmatrix} \tag{10}$$

are equals. That is, when $p_{10} + p_{01} = 1$ which in turn gives $\eta = 1$. In this case the arrival to the state i is independent from the previous state, $p_{ij} = p_j$. Thus, the process is said to be memoryless.

For simplicity purposes, the model can be assumed to be memory-less, hence the probabilities of transition are independent of time. This binary model can be used to simulate the transmission of a variety of impulsive noises, each with a different shape. An additional state can be included to describe additional

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oscillations between noisy pulses. This assumption is equivalent to Bernoulli-Gaussian model with i.i.d. samples.

This binary model uses an exponential distribution to describe the width of the pulse and time of arrival [21]. This is known as the Gilbert-Elliot model described in [24]. Besides, one of this state may model the presence of impulsive noise just assigning a Gaussian distribution of higher variance to describe the amplitude of the signal [18].

2.2.2. Markov-Middleton model

The Markov-Middleton model employs the Middleton PDF equation in (7) reduced to the first 4 terms in order to describe the amplitude of noise [18]. Using a Markov chain description, the history of past events is considered on the current event and bursty pulses are modelled more accurate.

The proposed Markov chain model is depicted in Figure 4 a). This model represents by 4 states the first four terms of the Middleton Class-A model in (7). Additionally, there is a transition state of duration null to connect the states. The probabilities p'_i describe the probability of arrival to the state i from the transition state. The value of x considers the correlation between the noisy samples and is independent from the canonical parameters of the Middleton model A, $\mathit{\Gamma}$, and φ_N^2.

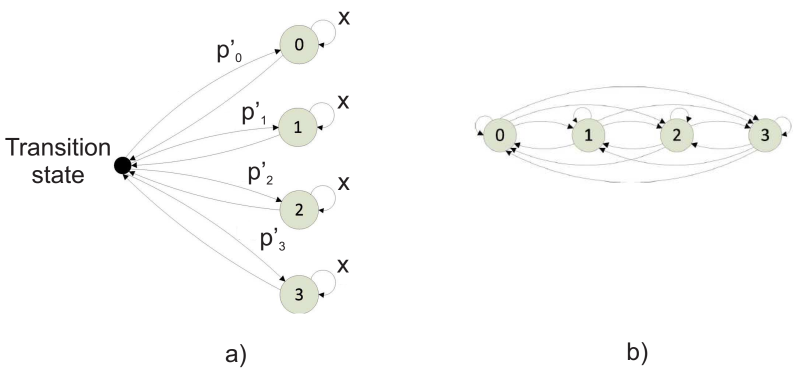


Figure 4: a) Markov-Middleton model. b) Equivalent representation of the Markov-Middleton model.

The equivalent representation of the model in Figure 4 a) is shown in 4 b). The associated matrix $P = [p_{ij}]_{4\text{x}4}$ of transition probabilities is given by:

$$P = \begin{bmatrix} x+(1-x)p'_0 & (1-x)p'_1 & \dots & (1-x)p'_2 & (1-x)p'_3 \\ (1-x)p'_0 & x+(1-x)p'_1 & \dots & (1-x)p'_2 & (1-x)p'_3 \\ (1-x)p'_0 & (1-x)p'_1 & \dots & x+(1-x)p'_2 & (1-x)p'_3 \\ (1-x)p'_0 & (1-x)p'_1 & \dots & (1-x)p'_2 & x+(1-x)p'_3 \end{bmatrix} \quad (11)$$

The Markov chain presented in Figure 4b) is irreducible, every state communicates with each other. This condition is sufficient to establish a stationary state vector given by $\pi = [p'_0\ p'_1\ p'_2\ p'_3]$ independent of the initial state. This result establishes that the amplitude distribution of the considered Markov chain model represents a Middleton Class-A model as long as each state generate a Gaussian noisy sample of variance σ_m. Thus, the parameters of this model are the same of the Middleton Class-A parameters $A, \mathit{\Gamma}, \varphi_N^2$ plus the correlation parameter x.

Besides, the case $x = 0$ reduces the current model to the Middleton Class-A model. In this case, the transition probabilities $p_{ij} = p_j$ does not depend on the previous state, hence the states are i.i.d.

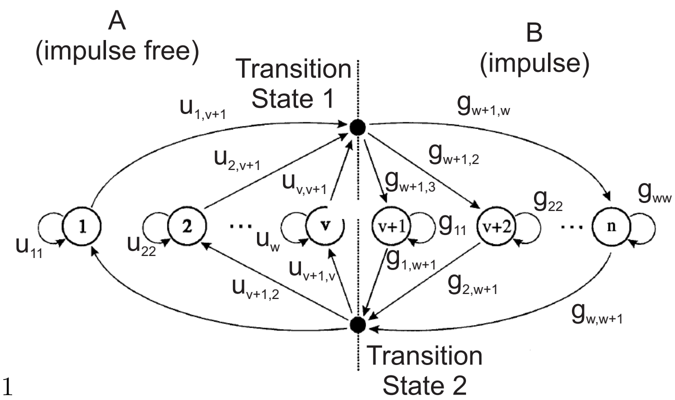
distributed and the model is identical to the Middleton Class-A model. By means of this model, the total of samples $\overline{n}_i$ on each state (duration) is given by:

$$\overline{n}_i = \frac{1}{1 - P_{ii}} = \frac{1}{(1-x)(1-p'_i)} \quad i = 0, 1, 2, 3. \tag{12}$$

2.2.3. Partitioned Markov Chain Model

The Partitioned Markov Chain Model is described as depicted in Figure 5 [21, 6]. This represents a special form of a Markov chain, as proposed in [25], to represent asynchronous impulse events.

The binary case, as depicted in Fig. 3, exhibits exponential distributed duration. However, current measurements revealed that duration as well as time of arrival are corresponded to the superposition of exponential functions.



g1,1

Figure 5: Partitioned Markov chain model [21, 6].

The model in Fig. 5 is represented by n states plus two transition states. The duration within the transition state is null. The n states are partitioned in two groups; Group A comprised by v states represents the impulse free states, whereas Group B represents the impulse state. Figure 5 can be interpreted as two Markov chains (Group A and Group B) joined by the two transition states. Depending on the Group, the transition states represent a source or a sink node. The transition state 1 summarizes the jump from Group A to Group B. The transition states 2 summarizes the jump from Group B to Group A. These transition states allows to represent the partitioned Markov chain by two independent transition probability matrices.

By means of this model, the probability to have m time span without impulsive noise is given by:

$$\begin{aligned} p_A(m) &= 1 \quad \text{for } m = 0 \\ p_A(m) &= \sum_{j=1}^{v} u_{v+1} \cdot u_{j,j}^{m} \quad \text{for } k = 0, 2, \ldots, M, \end{aligned} \tag{13}$$

and the probability to have k time span of impulsive noise is given by:

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$$p_B(k) = 1 \quad \text{for } k = 0$$
$$p_B(k) = \sum_{j=1}^{w} g_{w+1} \cdot g_{j,j}^{k} \quad \text{for } k = 0, 2, \ldots, L. \tag{14}$$

The values of $p_A(m)$ and $p_B(m)$ are derived instead of the state's transition probabilities, since u_{ij} and g_{ij} are not directly observable. In this case, the use of exponential curve-fittings represents an affordable solution to the problem. In this regard it is defined a cost function by the sum of the squared errors between the measured statistic and its modelled fit as:

$$C_A = \sum_{m=1}^{M} \left(y_A(m) - p_A(m)\right)^2 \tag{15}$$

where $y_A(m)$ represents the measured data, and $p_A(m)$ is modelled by the parameters u_{ij}'s given in (16). The general approach is to find the values of u_{ij} that result in a minimum of the cost function C_A and the similar C_B. This is performed using the solutions:

- Simplex Method [21],
- Genetic Algorithms [6].

The report in [6] exhibits a better performance for Genetic Algorithms than the Simplex Method.

2.2.4. Second Level Markov Chain

This model is described by means of the diagram depicted in Figure 6, in which each state is sequentially interconnected. That is, the state II_i is interconnected with II_{i-1} and II_{i+1} but not with II_{i+2} or II_{i-2}. Jumps are only possible between the states i and $i+1$, similar to the random walking process.

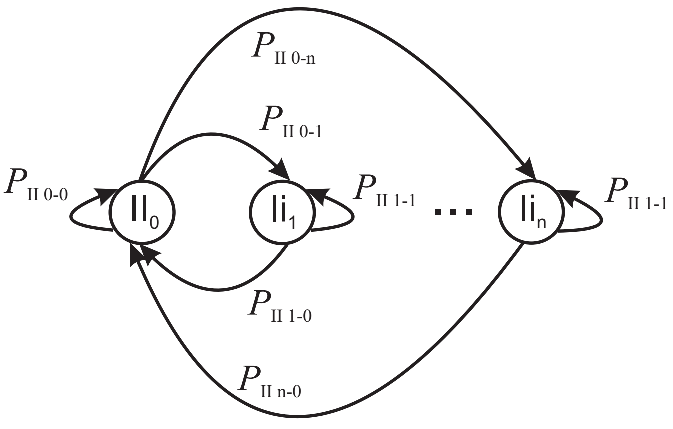

Figure 6: Second level Markov chain [22].

In this case, the first state II_0 denotes a non-impulse state, whereas the states II_1 to II_n represent the occurrence of impulses of different variances.

By means of this model, impulsive noise bursts are described by consecutive transitions between the states II_1 and II_l, $l = 1, \ldots n$. Additionally, for this model three different metrics are analytically determined:

1. Probability to have an impulsive noise burst of l states.
2. Probability that the impulsive state II_l lasts for k samples in a burst state.
3. Average impulse duration or width.
4. Inter-arrival time.

The probability to have an impulsive noise burst of l states, happens when the process enter into the state II_l and it is coming from II_1. This event is given by:

$$P_{\mathrm{II}_{1-l}} = e^{-A}\frac{A^{l-1}}{(l-1)!} \tag{16}$$

where $A = l\frac{\sigma_b^2}{\sigma_l^2}$ denotes the impulse index or the disturbance ratio, σ_B is the variance of AWGN noise in the channel, and σ_l denotes the impulsive noise variance on state l. This is in accordance with the Middleton model in (7).

On the other hand, the probability that the impulse state II_l lasts for k samples is given by:

$$P_{k-sample\, impulse} = P_{II_{1-l}} \cdot P_{II_{l-l}}^{k} \cdot (1 - P_{II_{l-l}}), \tag{17}$$

and using (16) this can be expressed as:

$$P_{k-sample\, impulse} = e^{-A}\frac{A^{l-1}}{(l-1)!} \cdot P_{II_{l-l}}^{k} \cdot (1 - P_{II_{l-l}}). \tag{18}$$

The average impulse duration or width is given by:

$$\overline{t_{\mathrm{width}}} = T_{S,II} \cdot \sum_{l=1}^{n}\sum_{k=1}^{\infty} k \cdot P(k - sample\, impulse) \tag{19}$$

where $T_{S,II}$ determines the sample interval.

Finally, the inter-arrival time is established by the transition II_{0-0}, and the probability of k transitions in this state is given by:

$$P(k - sample\, interval) = P_{II_{0-0}}^{k-1} \cdot (1 - P). \tag{20}$$

Using this relation, the average impulse interval can be established as:

$$\begin{aligned}\overline{t_{Interval}} &= T_{S,II}\sum_{k=1}^{\infty} k \cdot P(k - sample\, interval) \\ &= T_{S,II} \cdot (1 - P_{II_{0-0}}) \cdot \sum_{k=1}^{\infty} k \cdot P_{II_{0-0}}^{k-1}\end{aligned} \tag{21}$$

3. FUTURE WORK

From the reports analyzed in this paper, a variety of open problems may be considered:

1. The report in [12] describes the effect of impulsive noise taking into account the distances of the noisy sources in (5). How to model this approach when the mentioned distances are unknown?
2. In order to estimate noise the report in [19] assumes that the signal of interest is Gaussian distributed. Is it the case when the signal of interest is an OFDM waveform? How to model this?
3. Markov chain are used to describe exponential distribution of width and arrival time. However the exponent are always integers. What if we want to describe arbitrary exponents?

4. CONCLUSIONS

This report summarizes the main statistical description of impulsive noise in general. However, a better description can be obtained when , in particular, channel parameter are also included. In general, the models reported lacks of this concern. Further analyses can be conducted in this direction. Taking into account models for noise description Markov chain represents the preferred tool since this is an attempt to describe real scenarios where bursty pulses takes places. Prior information as width, time of arrival and correlation (second-order statistic) between noisy pulses can be incorporated into this formulation.

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