Coverage Performance Analysis of OFDM-based Spatial Multiplexing Systems

Li-Chun Wang, Cheng-Wei Chiu, Chu-Jung Yeh and Wern-Ho Sheen
National Chiao Tung University, Taiwan
Email : lichun@cc.nctu.edu.tw, kimula.cm93g@nctu.edu.tw, teensky.cm93g@nctu.edu.tw, whsheen@mail.nctu.edu.tw

***Abstract*— Combining multi-input multi-output (MIMO) antenna techniques with orthogonal frequency division multiplexing (OFDM) modulation (MIMO-OFDM) becomes an attractive air-interface solution for the next generation high speed wireless systems. Nevertheless, because the total available transmit power is split uniformly across transmit antennas in MIMO-OFDM systems, increasing the number of transmit antennas leads to a smaller signal-to-noise ratio (SNR) per degree of freedom. Thus the coverage performance of this kind of MIMO-OFDM system becomes an essential issue. In this paper by means of order statistics and *Glivenko-Cantelli theorem*, we develop an analytical expressions for the link outage probability and cell coverage reliability of OFDM-based spatial multiplexing systems in a frequency selective fading channel, respectively.**

***Index Terms*— MIMO, OFDM, cell coverage, link outage, multiplexing**

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has become a popular modulation technique for transmission of broadband signals. OFDM can convert a frequency selective fading channel into a parallel collection of frequency flat fading sub-channels and thus can overcome inter-symbol interference (ISI) [1] [2]. In the meanwhile, multi-input multi-output (MIMO) antenna techniques can provide spatial multiplexing gain and diversity gain to increase spectrum efficiency and link reliability, respectively [3] [4] [5] [6]. Combining MIMO with OFDM (MIMO-OFDM) becomes an attractive air-interface solution for the next generation high speed wireless systems.

Generally, there are three categories of MIMO-OFDM techniques.

- The first aims to realize spatial diversity and frequency diversity gain without the need for channel state information (CSI) at the transmitter. In the first category, the results in [7] proposed a transmit diversity scheme in a frequency selective fading channel. A space-time code across space and frequency (rather than time) was shown in [8] to yield spatial diversity. In [9], [10], a low-density parity-check (LDPC)-based space time code was proposed to exploit both spatial diversity and selective fading diversity for MIMO-OFDM system in correlated channel. [11] presented the space-frequency code that can achieve full diversity in space and frequency for non-coherent MIMO-OFDM systems, where neither transmitter and receiver has perfect CSI. [12] investigated the performance of space-frequency coded MIMO-OFDM as a function of Riciean K-factor, angle spread, antenna spacing and power delay profile. In [13], a code design framework for achieving full rate and full diversity in MIMO frequency-selected fading channels was proposed.
- The main goal of the second class of MIMO-OFDM techniques is to increase capacity by exploiting multiplexing gain in the spatial domain, i.e., transmitting independent data streams across antennas and tones. The V-BLAST system suggested in [5] is a well-known layered approach to achieve spatial multiplexing gain in multi-antenna systems. [14] showed that a MIMO delay spread channel can provide both higher diversity gain and multiplexing gain than MIMO flat-fading channels. However, increasing the number of transmit antennas results in a smaller signal-to-noise ratio (SNR) per degree of freedom because the total available transmit power is split uniformly across transmit antennas. This leads to link outage or coverage issue of the spatial multiplexing MIMO system. This issue has been investigated originally in [15] and a multiuser scheduling solution to address this issue in MIMO flat-fading channels was proposed in [16]. Nevertheless, the coverage performance for spatial-multiplexing-based MIMO-OFDM systems in frequency-selective fading channels has not been widely discussed so far.
- The third type of MIMO-OFDM technique is to decompose the channel coefficient matrix by singular value decomposition (SVD) and construct pre-filter and post-filters at the transmitter and the receiver to achieve the capacity [17]. This technique requires perfect CSI available at both the transmitter and receiver.

In this paper, we focus on the second type of MIMO-OFDM systems and aim to derive the closed form ex-

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pressions for link outage and cell coverage cell coverage of the OFDM-based spatial multiplexing systems over frequency-selective fading channels. The rest of this paper is organized as follows. In Section II, we describe the system model. In Section III, we define the link outage for MIMO-OFDM systems. In Section IV, we derive the exact analytical expression form of link outage of MIMO-OFDM systems. In Section V, we provide an approximation analytical form of link outage of MIMO-OFDM systems and discuss the coverage performance. In Section VI, we show numerical results and give concluding remarks in Section VII.

II. System model

We consider a point-to-point MIMO system with M transmit antennas and M receive antennas. In the meanwhile, we adopt OFDM modulation with total N_T subcarriers and let a group of adjacent N_T/N subcarriers form a subchannel. The total bandwidth of each subchannel is assumed to be smaller than the channel coherent bandwidth. Figure 1 shows the considered structure of the OFDM-based spatial multiplexing systems, where MN independent data streams are multiplexed in M transmit antennas and N subchannels. The transmit power is uniformly split to M transmit antennas. It is assumed that the length of the cyclic prefix (CP) in the OFDM system is greater than the length of the discrete-time baseband channel impulse response so that the frequency-selective fading channel indeed decouples into a set of parallel frequency-flat fading channels [19]. With $\mathbf{x}_n$ and $\mathbf{y}_n$ denoting the $M\times 1$ transmit and receive signal vectors, respectively, we can write

$$\mathbf{y}_n = \sqrt{g_n}\mathbf{H}_n\mathbf{x}_n + \mathbf{n}_n \ , \tag{1}$$

where n is the subchannel index and $\mathbf{H}_n$ represents the $M \times M$ MIMO channel matrix of the n_{th} subchannel and each entry of $\mathbf{H}_n$ is an i.i.d. circular-symmetric complex Gaussian variable [12]. Represent $\mathbf{n}_n$ the $M \times 1$ spatially white noise vector with $E[\mathbf{n}_n\mathbf{n}_n^*] = \sigma_n^2\mathbf{I}$ where $(\cdot)^*$ is the transpose conjugate operation. At last g_n depicts the large-scale behavior of the channel gain. For a user at a distance of r from the base station, g_n can be written as [18]

$$10\log_{10}(g_n) = -10\mu\log_{10}(r) + g_0 \quad [dB] \ , \tag{2}$$

where μ is the path loss exponent and g_0 is a constant subject to certain path loss models.

III. Definitions

A. Link Outage Probability

To begin with, we first define the link outage probability which reflects how reliable a system can support the corresponding link quality. For a single-input single-output (SISO) system in flat fading channel, link outage is usually defined as the probability that the received SNR is less than a predetermined value γ_{th}, i.e. $P_{out} = P_r\{\gamma < \gamma_{th}\}$ [20]. The link outage for the spatial multiplexing MIMO system in a flat fading channel is defined as the event when the receive SNR of any substream is less than γ_{th} [15] [16]. When all the degrees of freedom in the spatial domain of a MIMO system are used for the transmission of parallel and independent data streams to exploit the spatial multiplexing gain, the data stream with the lowest SNR in the MIMO system will dominate the link reliability performance especially when the link reliability likely of high percentile, such as 90% or even higher, is concerned.

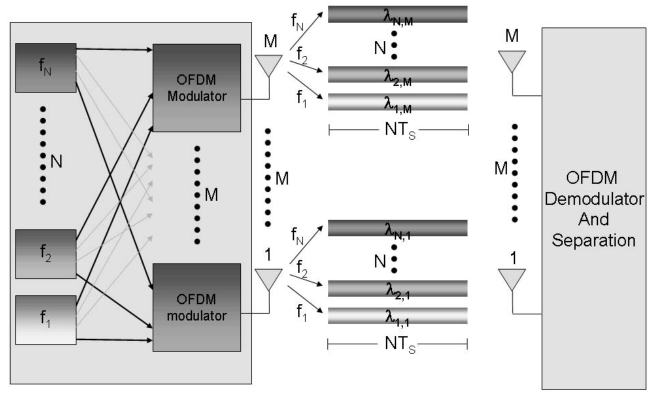

Fig. 1. OFDM-based spatial multiplexing systems.

The OFDM-based spatial multiplexing system in a frequency selective fading channel can be viewed as the sum of flat fading MIMO channels. As discussed before, the high-percentile link reliability performance of each MIMO flat-fading channel is dominated by the weakest substream. Considering the average weakest eigen-mode over a series of N's MIMO flat-fading subchannels, we define the link outage probability of the spatial-multiplexing-based MIMO OFDM system as follows:

$$P_{out} = P_r\left(\frac{1}{N}\sum_{n=1}^{N}\gamma_{n,M} \le \gamma_{th}\right) \ , \tag{3}$$

where $\gamma_{n,M}$ represents the receive SNR of the weakest substream in subchannel n for $n = 1, \ldots, N$.

B. Cell Coverage Reliability

With P_{out} being the link outage probability, we define $(1 - P_{out})$ to be the cell coverage reliability for its corresponding cell radius associated with the required SNR. That is, for a user at the cell radius with cell coverage reliability $(1 - P_{out})$, the probability of the received SNR being higher than the required threshold γ_{th} is no less than $(1 - P_{out})$.

IV. Link Outage Analysis

To begin with, we first analyze the received SNR of the weakest substream (denoted by $\gamma_{n,M}$) at the n_{th} MIMO flat-fading subchannel. With $\{\lambda_{n,i}\}_{i=1}^{M}$ representing the eigenvalues of the Wishart matrix $\mathbf{H}_n\mathbf{H}_n^*$, we can express $\gamma_{n,M}$ as

$$\gamma_{n,i} = \rho_n\lambda_{n,i}/M \ , \tag{4}$$

where ρ_n is the average receive SNR at the n_{th} subchannel and is equal to

$$\rho_n = \frac{P_t g_n}{N\sigma_n^2} = \frac{P_t\ 10^{(g_0/10)}}{N\ \sigma_n^2\ r^{\mu}} \quad . \tag{5}$$

Arrange $\{\lambda_{n,i}\}_{i=1}^{M}$ in the decreasing order so that $\lambda_{n,1} \geq \lambda_{n,2} \geq ... \geq \lambda_{n,M} \geq 0$. According to [16] [21], the probability density function (PDF) of the minimum eigenvalue $\lambda_{n,M}$ is exponentially distributed with parameter M as follows

$$f_{\lambda_{n,M}}(\lambda) = Me^{-M\lambda}\ ,\ \lambda \geq 0; \tag{6}$$

and its cumulative distribution function (CDF) can be written as

$$\begin{aligned} F_{\lambda_{n,M}}(\lambda) &= \int_0^{\lambda} f_{\lambda_{n,M}}(x)dx \\ &= 1 - e^{-M\lambda},\ \lambda \geq 0. \end{aligned} \tag{7}$$

By applying the singular value decomposition (SVD) method, it can be shown that the MIMO-OFDM channel ($\mathbf{H}_n$) is equivalent to MN parallel substreams, each of which has effective output SNR $\gamma_{n,i} = \rho_n\lambda_{n,i}/M$ at the receive antenna. Notice that $\gamma_{n,M}$ is also an exponentially distributed random variable of which CDF is written

$$F_{\gamma_{n,M}}(\gamma) = 1 - e^{-\frac{M^2\gamma}{\rho_n}}\ ,\ \gamma \geq 0. \tag{8}$$

For the i.i.d. exponentially distributed random variables $\{\gamma_{n,M}\}_{n=1}^{N}$, the sum of exponentially distributed random variable $\Omega = \frac{1}{N}\sum_{n=1}^{N}\gamma_{n,M}$ becomes the Erlang distributed random variable. Thus, the PDF of Ω is

$$f_{\Omega}(x) = \frac{N(\frac{M^2}{\rho_n})^N(Nx)^{N-1}e^{-\frac{M^2N}{\rho_n}x}}{\Gamma(N)}, \quad x > 0 \tag{9}$$

and its CDF is

$$\begin{aligned} F_{\Omega}(x) &= \int_0^{x} f_{\Omega}(x)dx \\ &= 1 - e^{-\frac{M^2N}{\rho_n}x}\sum_{j=0}^{N-1}\frac{(\frac{M^2N}{\rho_n}x)^j}{j!}, \quad x > 0 \end{aligned} \tag{10}$$

Thus, for a given threshold $\gamma_{th} > 0$, the link outage probability of the OFDM-based spatial multiplexing systems can be expressed as

$$\begin{aligned} P_{out} &= P_r\left(\frac{1}{N}\sum_{n=1}^{N}\gamma_{n,M} \leq \gamma_{th}\right) \\ &= P_r\left(\Omega \leq \gamma_{th}\right) \\ &= F_{\Omega}(\gamma_{th}) \\ &= 1 - e^{-\frac{M^2N}{\rho_n}\gamma_{th}}\sum_{j=0}^{N-1}\frac{\left(\frac{M^2N}{\rho_n}\gamma_{th}\right)^j}{j!}. \end{aligned} \tag{11}$$

By substituting (5) into (11), the link outage can be represented as

$$P_{out} = 1 - e^{-X}\sum_{j=0}^{N-1}\frac{X^j}{j!}, \tag{12}$$

where

$$X = \frac{M^2\ N^2\ \sigma_n^2\ \gamma_{th}\ r^{\mu}}{P_t\ 10^{(g_0/10)}} \quad . \tag{13}$$

In (12), P_{out} is a function of given parameters $\{M, N, P_t, \sigma_n^2, \mu, r, \gamma_{th}\}$. The cell radius r is defined as the farthest distance at which the link quality suffices for maintaining a required receive SNR γ_{th} with the probability no less than $(1 - P_{out})$. The objective is to derive an analytical closed-form expression for the cell radius r to be a function composed of given parameters $\{M, N, P_t, \sigma_n^2, \mu, \gamma_{th}\}$ and the required P_{out} (usually 0.1). Because of complexity, it is not easy to derive an analytical closed-form expression for the cell radius r directly from (12).

V. Cell Coverage Performance

In this section we first provide another simple approximation to closed-form expression of the link outage (12) to facilitate the derivation of the closed-form expression of the cell coverage r associated with link outage probability of spatial-multiplexing-based MIMO-OFDM systems. Then we present an method to calculate the cell coverage reliability of MIMO-OFDM systems.

A. Approximation of link outage probability

For brevity, we omit the index of M and use γ_n to replace $\gamma_{n,M}$. We also use the index $F(\cdot)$ instead of $F_{\gamma_n}(\cdot)$ for the CDF of $\gamma_{n,M}$. Considering the order statistics of a N random variables $\{\gamma_n\}_{n=1}^{N}$, we reorder them and obtain $\{\gamma_{(1)} < \gamma_{(2)} < ... < \gamma_{(N)}\}$. Then $\gamma_{(i)}$ is called the i_{th} order statistic. It is assumed that $\gamma_{(\omega)}$ is the value most close to $\frac{1}{N}\sum_{n=1}^{N}\gamma_n$. Then the link outage can be rewritten as

$$\begin{aligned} P_{out} &= P_r\left(\frac{1}{N}\sum_{n=1}^{N}\gamma_n \leq \gamma_{th}\right) \\ &\simeq P_r(\gamma_{(\omega)} \leq \gamma_{th})\ , \end{aligned} \tag{14}$$

where $w \simeq 0.63N \simeq N_{\omega}$ (see the details in Appendix), and N_{ω} is an approximation integer value of ω. By doing so, link outage probability can be transformed to another form – the probability that at least N_{ω} of the γ_n are less than or equal to γ_{th}. By applying the theories of order statistics, we obtain

$$\begin{aligned} P_{out} &\simeq P_r(\gamma_{(N_{\omega})} \leq \gamma_{th}) \\ &= F_{(N_{\omega})}(\gamma_{th}) \\ &= \sum_{i=N_{\omega}}^{N}\binom{N}{i}F^i(\gamma_{th})\left[1 - F(\gamma_{th})\right]^{N-i} \\ &= I_{F(\gamma_{th})}\left(N_{\omega}\ ,\ N - N_{\omega} + 1\right) \\ &= I_{[1-e^{-X}]}\left(N_{\omega}\ ,\ N - N_{\omega} + 1\right) \end{aligned} \tag{15}$$

where X is a function of (M, N, μ, r) defined in (13) and

$$I_p(a, b) = \frac{\int_0^p t^{a-1}(1-t)^{b-1}dt}{\int_0^1 t^{a-1}(1-t)^{b-1}dt} \quad \text{For } a > 0,\ b > 0 \text{ and } 0 \leq p \leq 1 \tag{16}$$

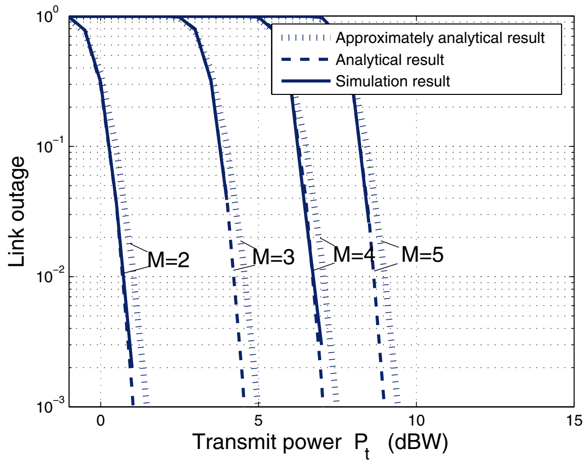

Fig. 2. Link outage probability v.s. transmit power P_t for different values of M when $N = 128$, noise power$= -103$dBm, $\mu = 3$, $r = 1$km and $\gamma_{th} = 2$dB.

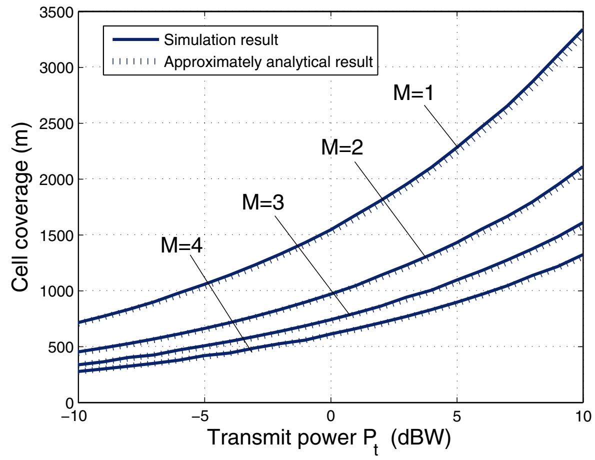

Fig. 3. Cell coverage radius v.s. transmit power P_t for different values of M when $N = 128$, noise power$= -103$dBm, $\mu = 3$, $P_{out} = 0.1$ and $\gamma_{th} = 2$dB.

is the incomplete beta function. Now we have another closed-form approximation for the approximate link outage probability. From (15), we will derive the closed-form expression for the cell radius associated with link outage probability of MIMO-OFDM system, which will be discussed in the next section.

B. Cell Coverage Reliability

To derive cell coverage r from (15), we first introduce the *inverse incomplete Beta function* which is shown as follows

$$z = I_w(a,b) \;\Rightarrow\; w = I_w^{-1}(a,b) \;. \tag{17}$$

By substituting (13) and (17) into (15), the cell coverage is given by

$$r \simeq \left[\left(\frac{P_t}{N\sigma_n^2}\right)\left(\frac{10^{\frac{g_0}{10}}}{M^2\gamma_{th}}\right)\cdot \log\left(\frac{1}{1 - I_{P_{out}}^{-1}\left(N_\omega \;,\; N - N_\omega + 1\right)}\right)\right]^{\frac{1}{\mu}} \tag{18}$$

Note that (18) can be viewed as an analytical closed form approximation for the cell radius for OFDM-based spatial multiplexing systems over frequency selective fading channels. It is a function composed of given parameters $\{M, N, P_t, \sigma_n^2, \mu, \gamma_{th}\}$ and the required P_{out}.

VI. Numerical Results

In this section, we present numerical examples to illustrate how the number of antennas could affect the link outage and cell coverage in OFDM-based spatial multiplexing systems. We first assume a predetermined value $\gamma_{th} = 2$dB, *noise power* $= -103$dBm, $g_0 = -32$, and $r = 1$km. Figure 2 shows the simulative, analytical, and the approximate link outage performances with various numbers of transmit and receive antennas for $N = 128$. One can see that when for the case $M = 2$, P_t increases, the link outage would first reduce. It indicates that the link outage probability become higher as the number of antennas increases. Thus it is hard to maintain M times of capacity for a large number of M.

Figure 3 shows the cell coverage with different numbers of antennas in the case of $N = 128$ and $\mu = 2$. We can see that the cell coverage increases as P_t increases, and it will increase more quickly with fewer antennas. That is, it indicates that the coverage area is easier to maintain M times of capacity when M is small.

VII. Conclusions

In the paper, we have analyzed the link outage and cell coverage performance of the spatial multiplexing MIMO-OFDM systems over frequency-selective fading channels. We present an analytical formula that can evaluate the link outage probability for spatial multiplexing MIMO-OFDM system. We also provide another simplified approximation of the exact link outage probability that can applied to calculated the cell coverage associated a certain link outage probability. From our numerical results, we validate the accuracy of the analytical model and approximation method by simulation. We also present examples to illustrate how and to what extend the number of antennas affect the link outage and the cell coverage for the spatial multiplexing MIMO-OFDM system. In the future, we will develop an optimal scheduling algorithm for multiuser OFDM-based spatial multiplexing systems, and see how to exploit the multiuser and frequency diversity to improve link quality of the diversity-deficient spatial multiplexing systems.

Appendix

In this appendix we discuss how to obtain the approximate value ω. To this end, we introduce a function called *empirical distribution*. The empirical distribution for an i.i.d. sequence $\{\gamma_1, ...\gamma_N\}$ is a random variable defined as

$$F_N(\gamma) = \frac{1}{N} \sum_{n=1}^{N} I_{(-\infty,\gamma]}(\gamma_n) \ , \tag{19}$$

where $I_{(\cdot]}$ represents indicator function.

Fig. 4 shows the diagram of $F_N(\gamma)$. Because $\{\gamma_{(1)} < \gamma_{(2)} < ... < \gamma_{(N)}\}$ and $\gamma_{(\omega)}$ is the ω_{th} order statistic for the sequence $\{\gamma_1, ...\gamma_N\}$, we can know that

$$F_N(\gamma_{(\omega)}) = \frac{1}{N} \sum_{n=1}^{N} I_{(-\infty,\gamma_{(\omega)})}(\gamma_n) = \frac{\omega}{N} \ . \tag{20}$$

Furthermore, based on *Glivenko-Cantelli Theorem*, we know that the random variable

$$D_N = \sup_{\gamma \in R} |F_N(\gamma) - F(\gamma)| \tag{21}$$

converges to 0 with probability 1 when the value of N is large. Since IEEE 802.11a employs fast Fourier transform (FFT) with 64 carriers and IEEE 802.16 uses 256 carriers furthermore [22], we can assume that the value of N is very large. (20) can be written as

$$\omega = N \cdot F_N(\gamma_{(\omega)}) \simeq N \cdot F(\gamma_{(\omega)}) \simeq N \cdot F(\epsilon(\gamma)) \tag{22}$$

where $\epsilon(\gamma)$ is the expectation value of a function $f(\gamma)$ in a variable γ, and

$$\begin{aligned} \epsilon(\gamma) &= \int_{-\infty}^{\infty} \gamma f(\gamma) d\gamma \\ &= \int_{-\infty}^{\infty} \gamma \frac{M^2}{\rho_n} e^{\frac{M^2}{\rho_n}\gamma} d\gamma \\ &= \frac{\rho_n}{M^2} \ . \end{aligned} \tag{23}$$

By substituting (23) into (22), we obtain

$$\begin{aligned} \omega &\simeq N \cdot F\left(\frac{\rho_n}{M^2}\right) \\ &= N \cdot \left(1 - e^{(-\frac{M^2}{\rho_n}\frac{\rho_n}{M^2})}\right) \\ &= N \cdot (1 - e^{-1}) \\ &\simeq 0.63N \simeq N_\omega \end{aligned} \tag{24}$$

where N_ω is an approximation integer value of ω.

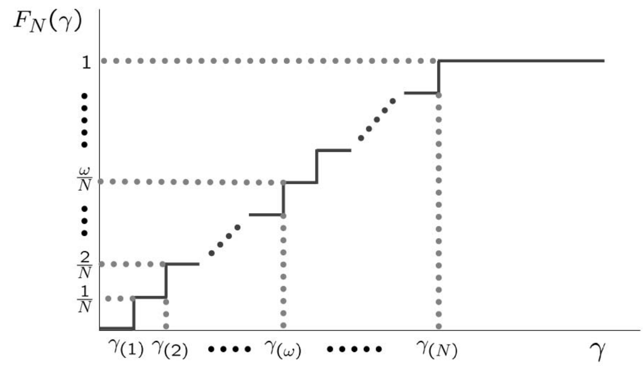

Fig. 4. Illustration of the empirical distribution for an i.i.d. sequence.

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