5G tool for evaluation and comparison of energy efficiency of mobile radio channel using second-order statistics

N Stefanović¹, A Kar² and V Mladenović¹,*
¹Faculty of Technical Sciences in Čačak, University of Kragujevac, Svetog Save 65, Čačak, Serbia
²Indian Institute of Information Technology, Design and Manufacturing, Kancheepuram, Chennai, India.
*e-mail: vladimir.mladenovic@ftn.kg.ac.rs

Abstract. In order to increase energy efficiency over transmissions channels, common approach for optimization tasks is by means of channel’s second-order statistics. Actual channel modeling tools for 5G networks end with channel’s first-order statistics, although these metrics are not sufficient when channel conditions are rapidly changing, either in time, frequency or space. In this paper, we establish a tool for evaluation and comparison of energy efficiency of mobile radio channel using its second-order statistics, especially level crossing rate (LCR) and average fade durations (AFD), as they can implicitly pinpoint to transmission configurations that are energy efficient or, as opposed, become a waste of energy. Using both deterministic and stochastic channel modeling, we present results after simulations of Rayleigh channel for narrowband case and further extend it to passband case, suitable for 5G scenario. We conclude about the energy efficiency of different transmission schemes used by the 5G physical layer observing LCR and AFD values.

1. Introduction
Next generation wireless systems, aiming to support communication in reliable and robust – anytime, anywhere manner, meets challenges to provide best possible performance levels [1] and concurrently satisfy defined quality of service (QoS) constraints (eg. packet error rate, packet delay budget) [2], as 5G is claimed to be first QoS driven network [3]. Beside randomly varying channel conditions, due to multiplicity of technologies applied, emerging number of device users and divergence of use cases, one of key challenges is making efficient use of energy resources. Upon this circumstance, question arise how to optimize different connection links in order to save energy as much as possible. Researches have shown that, for some wireless communication link, characterized with one of its functions - channel matrix, it is required to acquire channel's second-order statisticsto provide optimal precoding matrix and maximize energy efficiency of transmission [4]. Second, in a channel affected by varying multipath fading process, first-order statistics, such as probability density function (PDF) and cumulative distributive function (CDF) are not sufficient as they describe only its statical behaviour. To describe process dynamics, one needs higher-order statistics, such as level-crossing rate and average fade duration [5].

Previous observation leads to considering appropriate basis for development, optimization and test of transmission system through channel modelling. Latest requirements in channel modelling are to
accurately capture space-time-frequency characteristics of the mobile radio channel in a variety of scenarios and specifically first and second-order statistics, which includes the LCR and AFD [6]. This modeling is achieved by deterministic, stochastic or hybrid approach. Models can be derived mathematically or from measurements in a physical, real-world channel, as illustrated on figure 1.

**Figure 1.** Relations between different channel modeling aspects. Measurements of physical, real-world channel support validity of other models

While deterministic models usually employ ray tracing technique – computationally intensive, inherently less accurate, but reliable, stochastic or statistical models are mathematically derived or estimated upon measurements of a physical, real-world channel and – designed for fast, system level simulations.

Comprehensive (but not final) list of actual tools for 5G channel modeling is stated in [7]. All tools, as the author’s best knowledge, end with analysis of first-order statistics for 5G use cases, which is not enough knowledge to predict dynamic behaviour of channel. In our paper, we establish a tool for evaluation of mobile radio channel using its second-order statistics and make adequate conclusions of energy efficiency for each use case analyzed. Our motivation goal was the fact that optimized transmission can drastically save energy consumption. For presentation sake, urban environment was supposed where no line-of-sight between transmitter and receiver exists and multipath propagation is imminent. Hence, receiver is moving terminal, involving effects like Doppler shift and signal phase variations resulting in signal's complex envelope (CE) fluctuating and fading below some receiver's sensitivity level. Apart from other, with our tool we were able to examine important metrics, as LCR and AFD and their behaviour for different channel parameters. In addition, we extended our observation to wideband model and put it in a 5G transmission schemes framework.

The rest of the paper is organized as follows. In the section 2, we give short review of other state-of-the-art tools for 5G channel modeling with discussion on second-order statistics usage. In section 3, starting from well known Clarke's deterministic model in Rayleigh channel, we put short description of a tool with observation considering a case with a moving receiver on small travel route section and capturing CE to evaluate its statistics. Hereafter, we put our simulation setup in the context of 5G transmission schemes, known as numerologies and finally, in section 4, present results concluding on benefits and further work possibilities of presented tool.
2. On channel model tools with second-order statistics for 5G use cases

2.1. Channel models for 5G use cases

Sublimated list of provided in 3GPP’s study gives an comprehensive overview of actual channel model tools for next generation network evaluation and design. First comes 3GPP’s NR (New Radio) channel model in the form of TDL and CDL channels and implemented in Matlab’s 5G Toolbox, bringing all relevant setup for testing, signal generation and analysis, as map-based propagation simulating scenarios [8]. In QuaDRiGa (QUAsi Deterministic RadIo channel GenerAtor) [9], geometry-based stochastic channel model is used of multipl-input-multiple-output (MIMO) radio links providing all relevant parameters as absolute path delays, Doppler spread, channel impulse response (CIR), etc. Based on this model, Quamcom proposed simulator [10] for further research and development of 5G NR physical layer [11]. Statistical, cluster based, modeling tool as COST 2100 [12], was developed and used for analysis some time before of ITU-R’s vision of 2020 and beyond, focusing on multi-user, distributed MIMO and moving Tx-Rx scenarios in the 4G communication system. Program METIS [13], belongs to deterministic types of channel modeling tools, it was intended to complement time-consuming and expensive measurement campaigns for overall 5G scenarios, offering wide range of parameters and scenario’s setup, but as previous finalizing with PDF and CDF statistics. At the end to mention, but not as final on the list, is NYUSIM [14] model, built up from extensive propagation measurements carried out during time period of four years and proposed as statistical spatial channel model using time cluster-spatial lobe approach. Designed primarily for mmWave directional channels, as presented, does not cover second-order statistics analysis, although fading behaviour in this range is literally highly dynamic [15].

2.2. Second-order statistics analysis

As for the LCR and AFD statistical metrics from 5G view, not much results are exploited in available papers. One of rare works is done by [16], where different carrier mmWave statistics was presented but no passband behaviour examined, nor energy efficiency of such transmission. Another performance analysis of 5G transmission over fading channels was conducted in [17], [18] again without passband or efficiency performance. In tool proposed through this paper, we extend current analysis with passband cases, suitable for appliance to flexible 5G transmission schemes, called numerologies [19] and related to different subcarrier spacings (SCS) in chosen orthogonal-frequency-division-multiplex (OFDM) waveform.

Before going onward, it is desirable to illustrate these metrics, figure 2, as they show how often signal crosses defined treshold and how long on average the signal remains below that level.

![Figure 2. Level-crossing rate and average fade duration definition](image-url)
Analytical expression for rate that complex envelope $r$ is crossing level $L$, is derived from its definition:

$$N_L = \int_0^\infty \dot{r} p_{r\dot{r}}(L, \dot{r}) \, d\dot{r}, \quad r \geq 0 \quad (1)$$

where $p_{r\dot{r}}(L, \dot{r})$ denotes joint probability density function of stochastic variable $r(t)$ particularized at level $L$ and its derivative $\dot{r}(t) = \frac{dr}{dt}$ at the same time instant. By definition, AFD is the expected value of the length of the time intervals in which stochastic process is below a given signal level $L$ and is calculated by

$$T_{afd} = \frac{P_{CDF}(r < L)}{N_R} \quad (2)$$

and $P_{CDF}(r < L)$ is cumulative distributive function – probability that stochastic process (complex envelope $r$) is less or equal to $L$. These metrics, although often hard to express analytically, numerically are not intensive to calculate and measure. Additionally, we refer to the definition of energy efficiency as maximum number of bits that can be delivered per joule of consumed energy in the network,

$$C_J = \frac{R}{P_{\Sigma}} \quad (3)$$

where $R$ presents data rate (b/s) and $P_{\Sigma}$ total consumed energy. For simplicity, here we override presenting expressions for single each use case, as it can occupy too much space. Other definitions are rate per energy, or rate per unit cost.

3. Tool description and simulation setup

3.1. Tool description

Real-world multipath/multiscatter propagation scenario is often depicted as on figure 3. Apart from usual presentations, spatial separation is highlighted, meaning presence of multiple beams from base stations (denoted as gNB) in the same environment. Mobile user (well known as User equipment - UE) is moving with some constant velocity $V$, causing an existence of Doppler frequency at each beam $i$ that arrives at the receiver with the angle $\alpha_i$. Buildings, roofs, towers, high trees, etc, make the environment multiscattering and consequently multipath propagated. Starting from well known Clarke’s deterministic model, at this instance we focus on fast variations of signal complex envelope $r$ at receiver point (fast fading) when no direct line-of-sight is available. It is main source of signal drops and degradation in this case (urban environment). For analysis of fast fading separate from slow variations (slow fading due to distance change), one must define small local area, where observing route section $\Delta l$ takes typically 10 – 40 wavelengths ($\lambda$) of transmitted signal. Samples of $r$ are taken at some fractions of wavelength $F$, at each $\Delta x = \lambda F$ point of UE movement, equivalently every $\lambda F V$ second. Regarding to multipath of rays, two effects are considered at the receiver: Doppler and phase variations. For $i$-th ray, contribution to receiving signal with Doppler shift depends on the angle of arrival $f_{Di} = f_{max} \cos \alpha_i$, where $f_{max}=V/\lambda$ presents maximum Doppler shift. Phase increment of signal in sample point $x[n]$ equals

$$\Delta \phi_n = \frac{2\pi}{\lambda} \, d[n] \quad (4)$$
Term $d[n]$ represents path distance that ray travels from base station to receive point. That way, narrowband channel model was built up, leading to deterministic expression of receiving complex envelope term

$$r(t) = a_0e^{-j2\pi\frac{V}{\lambda}t} = a_0 e^{-j\frac{2\pi}{\lambda}d[n]}$$

where $a_0$ presents its constant magnitude. Considering small area, it is assumed that rays coming from the same scatterer in each sampling point are parallel, figure 4. Urban environment, on the other hand, is often statistically described with Rice or Rayleigh distribution, where it is shown that LCR

$$N_L = \sqrt{b \frac{L}{\sigma_0^2}} e^{-\frac{L^2}{4\sigma_0^2}} = \sqrt{\frac{b}{2\pi}} p_r(L), \quad L \geq 0,$$

showing that practically LCR depends on acf $p_r(L)$, where $\sigma_0^2$ denotes mean power and $\beta$ is short notation of negative curvature for the autocorrelation function (ACF) at the origin $\tau = 0$,

$$\beta = -\frac{d^2}{d^2\tau}R(\tau)\bigg|_{\tau=0}$$

and $R(\tau)$ is ACF of CE. At the same time, ACF is found to be

$$R(\Delta x) = J_0\left(\frac{2\pi}{\lambda}\Delta x\right)$$

with $J_0$ noted well known Bessel function of first kind and zero order. Note that distance and time are connected here through $\Delta x = V\Delta t = V\tau$. Analogously, for AFD in Rayleigh channel, we can express

$$T_{afd} = \sqrt{\frac{2\pi \sigma_0^2}{\beta L}} \left(e^{-\frac{L^2}{2\sigma_0^2}} - 1\right), \quad L \geq 0,$$
From the front user interface of our tool, a set of parameters can be adjusted, according to small area description, figure 4: distance from the base station, UE velocity, number of scatterers, number of samples (sample points) and measurement sample rate (related to fraction $F$), frequency (wavelength), transmission power and simulation length. In the case shown on figure 5, scatterers are distributed randomly around UE, in some radius which can be arbitrary set. Small area is presented with a red dot or dash, proportional to calculated value of route $\Delta l$. On the right side of a view there are several different analysis results displayed within separate tabs: amplitude and phase behaviour of complex signal envelope, Doppler spectrum, first-order statistics including cumulative distributive function (CDF) and autocorrelation function (ACF), second-order statistics including LCR and AFD, as well as random FM.

![Graphical user interface of 5G tool used for LCR and AFD analysis](image)

**Figure 5.** Graphical user interface of 5G tool used for LCR and AFD analysis

3.2. **Simulation setup**

After description of applied deterministic and stochastic mechanisms, we are ready to set our simulation according to predefined transmission schemes used in 5G communication. These flexible schemes, called numerologies, table 1, are related to slicing available bandwidth to bandwidth parts which can use different predefined SCS combination, according to channel conditions. To make parallel with real state condition, we consider that measurements in 5G are done on base station’s specific secondary synchronization signal blocks (SSB) transmitted periodically and separately on single spatial beam. These blocks are 4 OFDM symbol long in time and 240 subcarriers wide in frequency scale. One more consideration is carrier frequency around which passband signal is existing, called reference point $A$. Two frequency ranges (FR) are adopted in 5G, as shown in table 1 and reference point frequency, say $f_A$, is not fixed and can be different for each block. We started our arbitrary scattering scenario with wideband signal, in FR1, more precisely with a starting frequency at NR operating in band $n77$, which is 3300-3800 MHz. After receiver detects $f_A$, orientation is done and receiver knows exact location of a reference point. Therefore, our scanning parameter should be set at the beginning and band will add SCS on it.
Table 1. Flexible 5G transmission schemes, called numerologies.

| Subcarrier spacing – SCS (kHz) | 15  | 30  | 60  | 120 | 240 |
|-------------------------------|-----|-----|-----|-----|-----|
| Frequency range -FR           | 1:410-7125 MHz | 2:24,25-52,6GHz |
| Symbol duration (μs)          | 66,7| 33,3| 16,7| 8,33| 4,17|
| CP duration (μs)              | 4,7 | 2,3 | 1,2 – normal | 4,3 – extended | 0,59 | 0,29 |
| Max. nominal bandwidth (MHz)  | 50  | 100 | 100 – FR 1 | 200 – FR 2 | 400 | 400 |
| Maximal FFT size              | 4096| 4096| 4096 | 4096 | 4096 |
| Symbols/slot                  | 14  | 14  | 14  | 14  | 14  |
| Symbols/subframe              | 1   | 2   | 4   | 8   | 16  |
| Slots/frame                   | 10  | 20  | 40  | 80  | 160 |

We choose 3500 MHz, or \( \lambda = 0,086 \) m and route we observe is 0,86 – 3,44 m (small area). Depending of numerology applied, bandwidth (240 subcarriers) and signal duration (3 symbols) take values according to table 2.

Table 2. Simulation setup parameters.

| SCS (kHz) | 15  | 30  | 60  |
|-----------|-----|-----|-----|
| Numerology| Case A | Case B | Case C |
| Symbol duration (μs) | 200 | 100 | 50 |
| Bandwidth (MHz)      | 3,6 | 7,2 | 14,4 |

Relating this to energy efficiency, we recall (3) intending to increase throughput, while maintaining constant energy engaged, figure 6. Increasing throughput, means that we are looking for shorter AFD and lower LCR regions.

![Figure 6. Energy efficiency in OFDM system at constant energy consumed](image-url)
4. Simulation results
In this session we show and describe Case A. We show LCR and AFD for narrowband signal case (single frequency at 3500 MHz), figure 7. To define small area (40λ) we take 1000 samples with sample rate 25 points per wavelength. Velocity of UE is set to 36 km/h. Most of signal is fluctuating around -3dB with reference to rms value of CE, where it reaches 1 crossing/wavelength (~ 86 mm of route). AFD is normalized to Doppler shift, for reference level set to 0 dB, most of signal fades out, transmission becomes waste of energy.

![Figure 7. a) Normalized LCR in term of level L](image1)
![Figure 7. b) Normalized AFD in term of level L](image2)

Results show good congruence between theoretical (full line) and simulated series (connected dots), validating our channel model for narrowband case.

5. Conclusion
Second-order statistics on channel state variations can help to save energy from trying lossy transmissions. Channel modeling is prerequisite for such optimization and level crossing rate and average fade duration are metrics not intensive to calculate and measure. Present state of tools explicitly, they do not use these metrics for 5G channel modeling. Establishing a tool to evaluate channel’s LCR and AFD through signal’s passband can improve next generation networks energy efficiency by optimizing flexible transmission schemes used.

Tool presented, yet, leaves wide space for further work and improvements. First, scenario editor can be extended to consider real-map 3D models as in some other tools. Deriving expressions for energy efficiency dependent on LCR/AFD, graphics could be more obvious in terms of optimization. Finally, mapping QoS requirements directly to physical layer metrics as LCR and AFD, can bring reliable intuition about justification for some network configuration deployment.

Acknowledgments
This paper is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, and these results are parts of the Grant No. 451-03-68/2020-14/200132 with University of Kragujevac - Faculty of Technical Sciences Čačak.
References

[1] ITU-R 2015 Recommendation ITU-R M.2083-0: IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond, (Geneva, International Telecommunication Union)

[2] 3GPP 2020 TS 23.501v16.4.0 : System Architecture for the 5G System (5GS) (www.3gpp.org/ftp/Specs/archive/23_series/23.501/).

[3] Kotkamp M, Pandey A, Raddino D, Roessler A and Stuhfauth R 2019 5G New Radio, Fundamentals, Procedures, Testing Aspects (Munich: Rohde & Schwarz) p 285.

[4] Wu J, Rangan S and Zhang H 2013 Green Communications: Theoretical Fundamentals, Algorithms and Applications (Boca Raton: CRC Press, Taylor & Francis Group) pp 520-547

[5] Anjos A, Marins T, Souza R, and Yacoub M 2018 Higher order statistics for the α-η-κ-µ fading model IEEE Transactions on Antennas and Propagation.

[6] Patzold M 2012 Mobile Radio Channels (Chichester: John Wiley & Sons Ltd) p 11.

[7] 3GPP 2019 Recommendation TR 38.901 V16.1.0 : Study on channel model for frequencies from 0.5 to 100 GHz.

[8] MathWorks 2019 5G New Radio Design with MATLAB (www.mathworks.com/campaigns/offers/5g-technology-ebook.html?elqCampaignId=10588).

[9] Jaeckel S, Raschakowski L and Thiele L 2019 QuaDRiGa - Quasi Deterministic Radio Channel Generator, User Manual and Documentation (Berlin: Fraunhofer Heinrich Hertz Institute).

[10] Qualcomm Research & Technology AB 2020 (www.qamcom.se/research/5gsim).

[11] Zaidi A, Athley F, Medbo J, Gustavsson U, Durisi G and Chen X 2018 5G Physical Layer: Principles, Models and Technology Components (London: Academic Press, Elsevier).

[12] Zanella A, Verdone R 2012 Pervasive Mobile and Ambient Wireless Communications: COST Action 2100 (London: Springer Science & Business Media).

[13] Nurmela V 2015 METIS Channel Models (https://metis2020.com).

[14] Sun S, McCartney G and Rappaport T 2017 A novel millimeter-wave channel simulator and applications for 5G wireless communications (Paris:IEEE International Conference on Communications (ICC)).

[15] Tan Y 2020 Statistical Millimeter Wave Channel Modelling For 5G and Beyond (Edinburgh: Heriot-Watt University, School of Engineering and Physical Sciences).

[16] Eldowek B, El-atty S, El-Rabaie E and El-Samie F 2017 Second-order statistics channel model for 5G millimeter-wave mobile communications Arabian Journal for Science and Engineering.

[17] Jaksic D, Bojovic R, Spalevic P, Stefanovic D, Trajkovic S 2017 Performance analysis of 5G transmission over fading channels with random IG distributed LOS components International Journal of Antennas and Propagation.

[18] Panajotovic A, Sekulovic N, Bandjur M and Stefanovic M 2017 Second-order measures of performance of dual SC macro-diversity system with unbalanced BSs exposed to CCI in composite fading channels IEEE Journal of Research 64.

[19] Sassan A 2019 5G NR: Architecture, Technology, Implementation and Operation of 3GPP New Radio Standards (London: Elsevier).