User Equipment Power Consumption Analysis under NLOS TDL Channel Models for 5G Communication

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***Abstract*—5G networks emerge as a solution for many cellular mobile communication scenarios, demanding new energy consumption requirements. Diverse approaches regarding the base station (BS) have already been discussed in the literature, but little has been debated about the user equipment (UE). In this paper, the objective is to understand in practice how much propagation channels subject to multi-path fading can influence the battery consumption of mobile devices connected to a 5G network. Considering an emulated network in the laboratory, 3GPP NLOS TDL channel models and conditions with different resources allocation are analyzed. Results have shown that the poor-quality channel requires more power from the battery due to a more complex process for demodulating the degraded Physical Downlink Shared Channel (PDSCH) signal and more energy for sending uploading content related to the Physical Uplink Control Channel (PUCCH). Furthermore, fading profiles with longer delays proved to be higher energy consumers.**

***Keywords*—5G, Power consumption, User equipment, TDL models, Propagation.**

I. Introduction

5G New Radio system was developed to meet the demand from specific use cases with distinct and challenging requirements for data transmission rate, latency, and reliability [1]. The eMBB (enhanced Mobile Broadband) scenario, for instance, is focused on applications that require high data throughputs, such as high-resolution video streaming and online gaming, considering different mobility environments. Low latency is a critical parameter in URLLC (Ultra-Reliable and Low-Latency Communication) implementations, such as remote medicine, intelligent transportation, and real-time cloud applications. For mMTC (massive Machine-type Communication), a huge number of connected devices must be considered, where long-life batteries are required. To reach the requirements of such a robust and complex system, minimizing the interval between mobile device battery recharges, it is necessary to project techniques that increase energy consumption efficiency. Several consumption improvements from 4G LTE are considered in the fifth-generation mobile system, such as more accurate algorithms as well as more straightforward and efficient signaling between the user equipment and the network core [2]. It is crucial to minimize energy consumption as much as possible since the energy efficiency in 5G is a significant concern.

5G energy efficiency has received significant attention in the literature aiming to reduce the amount of Watt needed to meet QoS requirements. Solutions to reduce energy consumption considering the network (base station) perspective have been discussed. In 2012, the International Telecommunication Union (ITU) set stages for 5G research activities (IMT for 2020 and beyond) in which two frameworks were established [3]: 1) The ITU-R IMT M2083 Vision stipulates that the energy consumption for the radio access network should not be greater than IMT networks deployed at the time while delivering enhanced capabilities. The network energy efficiency should therefore be improved by a factor of at least as significant as the envisaged traffic capacity increases from IMT Advanced to IMT-2020. 2) ITU-R IMT-2020 explains that it is required that the 5G mobile networks have the capability to support long sleep duration and other energy-saving mechanisms for base stations. The 3GPP (3rd Generation Partnership Project) has also studied the energy consumption theme. TR 21.866 “Study on Energy Efficiency Aspects of 3GPP standards” defines KPIs related to energy [4]. These KPIs cover measurements of energy consumption and efficiency. Parameters are measured at RAN and system-wide level during a predefined time interval.

In [5], the authors discussed the fundamental aspects of 5G energy efficiency. The increased number of small cells implies higher energy consumption. However, it has been pointed out that the individual energy consumption of each small cell is much lower than a macro cell. Furthermore, concerning massive MIMO (Multiple In Multiple Out), which involves the use of arrays with many more antennas at the base station, as massive MIMO technology develops, its energy efficiency may also improve over time. Indeed, the study has predicted that future massive MIMO 5G base stations may consume less energy than fourth-generation (4G LTE) base stations. Due to the spatial multiplexing capacity, the energy consumption is divided up between the users. The possibility of setting the base stations to sleep mode is debated. When there are no active users, the energy consumption is reduced. Therefore, it is expected to reduce energy consumption by almost 90% compared to 4G technology. A study carried out in [6] also discusses the base station sleep mode regarding energy efficiency. According to Bojkovic *et al.*, 5G systems with high energy consumption should always be built on the principle of only being active and transmitting when required since only 15% of the energy is allocated for transmitting bits. The majority of the energy is used for system broadcasts, idle resources, to run cooling systems, and other power supplies. There should be a focus on these aspects to reduce energy consumption.

This present paper focuses on power consumption from the UE perspective, considering different channel model configurations in a NLOS scenario. The work is divided as follows. Section II analyses the UE energy consumption perspective, presenting the major issues. Section III introduces the TDL channel models that will be considered in the study. The laboratory methodology for the analysis is described in the Section IV. Section V brings discussions about the results, and finally, conclusions are shown in Section VI.

II. Energy Consumption: UE Perspective

The user equipment, such as a smartphone, is powered by batteries which are usually limited in size and capacity. Therefore, improved energy management must be considered a crucial engineering factor [7]. Modern mobile phones combine the practicality of a small-sized communication device with PC-like capabilities, with diverse functionalities, including voice communication, audio and video services, browsing, message applications, email, gaming, downloads, uploads, and more. All of the above-mentioned functionalities increase the pressure on the battery, requiring a longer lifetime, depending on effective energy management. Hence, it is fundamental to analyze and understand where and how the power is consumed, since the power drawn by various components and different resource schedulings interferes in other ways with the consumption, being critical points for improving power management.

A study presented in [8] analyzes the energy-consuming entities of a mobile device, such as the wireless air interfaces, display, and music player. Data communication measurements were focused on Wi-Fi, Bluetooth, and cellular communication regarding 2G and 3G technologies. It was observed that 3G calls had a higher energy consumption than the same service in 2G. The highest consumption peaks were measured in both download (4.5 Mbps) and upload (700 kB/s) of files, with approximately 12% higher battery usage value for the upload case.

A physical component analysis of a 2.5G mobile device is done in [9], considering the power consumption fluctuation by varying the component usage, such as display, CPU, and RAM. A model of the energy consumption for different usage scenarios was developed, showing how these components interfere with the overall energy consumption and battery life under some usage patterns.

Android operating system is the most popular in smartphones, and studies about it have been carried out [10], [11]. In [12] a hardware-based method for Android smartphones is proposed. An extensive power evaluation is conducted under a predefined set of test cases, identifying the primary power-hungry modules, such as the screen display, GPS, and Wi-Fi modules. Finally, an energy consumption model for these modules was established.

For improving the UE perspective of battery usage, our work aims to investigate the smartphone power consumption related to resource blocks delivered by a 5G network, according to the 3GPP standardized tapped delay line channel models, for emulating NLOS multi-path fading channel scenarios. The main objective is to analyze how the channel's condition can affect the device's battery consumption.

III. TDL Channel Models for 5G Communication

Propagation effects, such as fading, also influence battery consumption in mobile devices due to more complex processes to transmit/receive data correctly. Fading is the variation of signal attenuation caused by time, position, speed, polarization, and frequency. It is often modeled as a random process. Fast fading denotes rapid fluctuations in the amplitude, phase, or multi-path delays of the received signal as a consequence of interferences between multiple versions of the same transmitted signal that reach the receiver at slightly different times and incidence angles. Fig. 1 illustrates the received/transmitted signal considering a smartphone under multi-path fading.

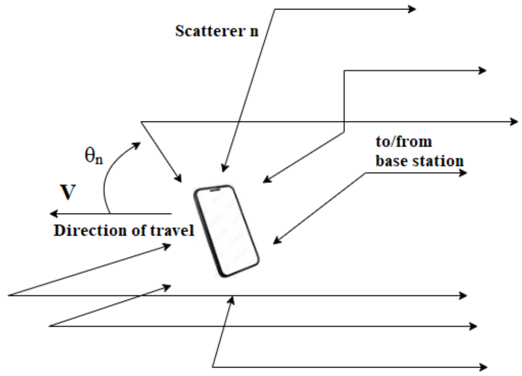


Figure 1: Multi-path Fading

The 3GPP published a technical report on channel models in the frequency range from 0.5 GHz to 100 GHz [13] for evaluating the performance of physical layer techniques. This document adopts the CDL (Clustered Delay Line) and TDL (Tapped Delay Line) models to simulate realistic wireless communication scenarios for 5G systems. The TDL models are simplified evaluations defined considering maximum bandwidth of 2 GHz. Three TDL models (A, B, and C) are implemented to represent NLOS (Non-line of sight) profiles. While TDL-D and TDL-E are indicated for LOS (Line of sight) environments [14], [15]. A TDL model for simplified evaluations can be obtained from the CDL models. Since NLOS models are more realistic in terms of mobile communications, they will be used for emulating the channel effects in this study.

The NLOS TDL models are defined by 23 taps, with an exception for TDL-C, which has 24 taps. The relative power and normalized delays for each tap vary between the profiles. The impulse response of a TDL channel model is shown in Equation 1.

$$H(t,\tau) = \sum_{i=1}^{n} a_i(t)\delta(\tau - \tau_i) \tag{1}$$

Where $a_i(t)$ is the amplitude at τ_i delay time in the ith tap with each tap associating an amplitude characterized by a Rayleigh distribution. Each tap is a point on the delay line corresponding to a certain delay. The signals from each tap are summed and the composite signal represents what a real radio wave might look like as received by a receiver, when subject to multi-path fading. Fig. 2 illustrates a delay line.

Section IV will detail the TDL power delay profiles (PDP) and the methodology adopted in the laboratory analysis.

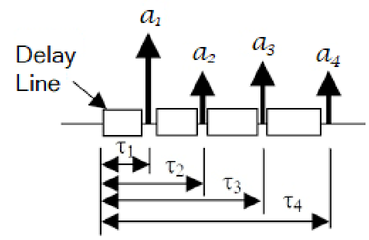


Figure 2: Tapped delay line

IV. Laboratory Analysis and Methodology

The measurement setup is based on modules that create realistic cellular scenarios with parameters standardized by the 3GPP. The Anritsu MT8000A emulates and controls the 5G network and the fading effect over the transmitted NR signal, supported by a server loaded with fading profiles. Since a non-standalone (NSA) architecture has been considered for the analysis, the 4G base station and EPC (Evolved Packet Core) are emulated by a second MT8000A module. Test control is accessed by a software interface (RTD software) in which the campaign is developed and executed. For power consumption measurement, Keysight N6705C DC Power Analyzer was adopted. Measurements were carried out from a DuT (Device under test), which is a 5G smartphone. A downlink single-user SISO system with 1 Base Sation (BS) is considered. The complete setup design is illustrated in Fig. 3.

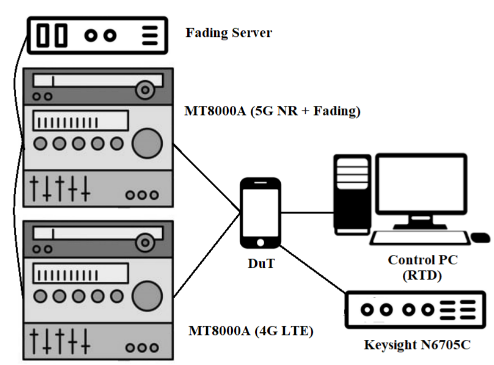
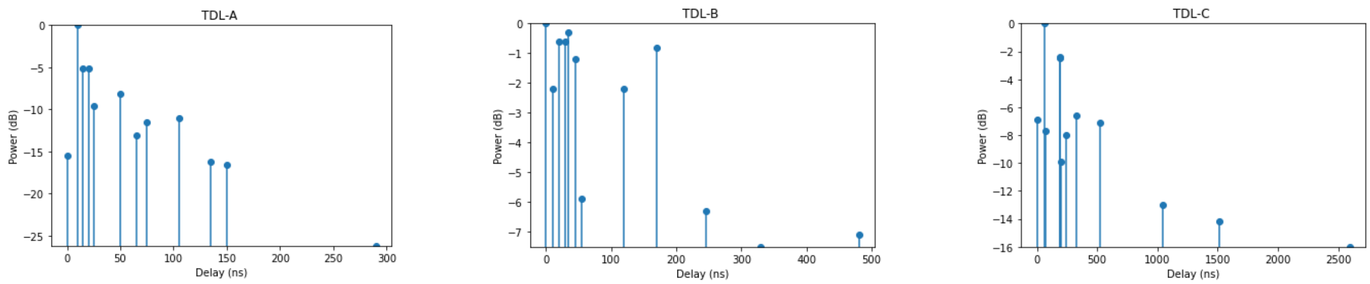


Figure 3: Measurement setup

Considering the setup mentioned above, realistic usage scenarios can be emulated for test campaigns. The results are validated by overall power measurements during throughput data for each NLOS TDL model (A, B and C) with two different channel characteristics, defined by the SNR (Signal Noise Ratio) and the MCS (Modulation and Coding Scheme). The parameters and variables analyzed are summarized in Table I.



(a) TDL-A (b) TDL-B (c) TDL-C

Figure 4: PDP for NLOS TDL Models

Table I: Analysis Parameters

Parameters	Variables
5G Architecture	NSA
NR band/bandwidth	n78 (3500 MHz)/up to 100 MHz
LTE band/bandwidth	b1 (2100 MHz)/20 MHz
NR MCS	18(64-QAM)/27(256-QAM)
LTE MCS	11 (fixed)
Transmission Mode	TM-1 SISO (1x1)
Channel Models	TDL-A/ TDL-B/ TDL-C

Given the parameters shown in Table 1, an analysis of battery power consumption considering different fading profiles based on TDL channel models standardized by the 3GPP for 5G systems will be presented in Section V in order to evaluate how much channels subject to fading can influence the energy consumption of a mobile device connected to a 5G network. Three fading profiles will be evaluated for NLOS communication. The power delay profiles (PDPs), that represent the average power of each propagation path, emulated in the laboratory, are shown in Fig. 4.

We adopted a commercial 5G smartphone with robust hardware configuration (Chipset Exynos 2200/ 8GB RAM) for the tests. The values of power levels reported in this paper have been obtained by running the same experiments several times and then averaging the results.

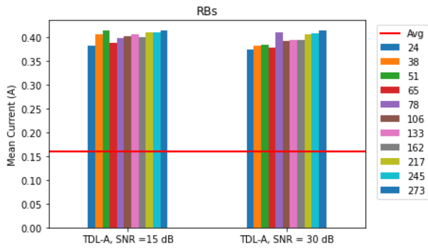
V. Results and Discussion

A. Measured Data

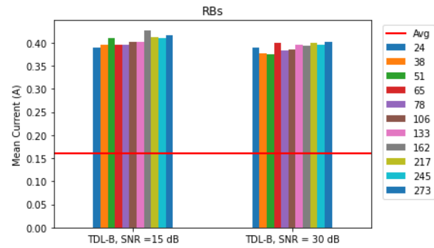
A measurement campaign has been carried out in order to verify the battery consumption of a mobile device (UE) during downlink data throughput. The analysis is based on the variation of resource blocks (RBs) allocated by the network to the user. The central idea is to analyze how multi-path fading and the channel condition affect UE power consumption. Two channels configurations were considered: a) Good condition, with SNR 30 dB and MCS 27 (which, in this case, means 256-QAM), and b) Bad condition, with SNR 15 dB and a modulation and coding scheme equal to 18 (64-QAM). The MCS values were set to achieve BLER (Block error rate) up to 10%, a valid threshold for most applications.

The base station shall be able to transmit and receive from a single or multiple UEs bandwidth parts smaller than or equal to the number of maximum resource blocks on the RF carrier [15]. Each numerology defines the minimum and maximum number of RBs. Hence it is possible to calculate the minimum and maximum channel bandwidth. For the n78 NR band, a sub-carrier spacing of 30 KHz was adopted, with a maximum bandwidth of 100 MHz. Fig. 5 shows the result of the power consumption from the UE battery regarding the variation of resource blocks allocated by the network for each TDL model. The RBs values are standardized by the 3GPP, from the minimum value of 24 (8.64 MHz) to the maximum of 273 (99 MHz), considering the guard band. An increasing trend is observed for power consumption. Some outside peaks in the analysis trend appear due to some interferences in the measurement process.

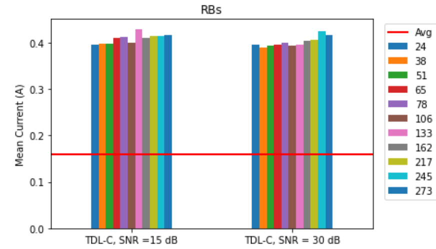
From the graphs in Fig. 5, there is a significant increase in battery consumption when the cell phone is in throughput mode. This information is measured by observing the red line at 0.16 A, which represents the average consumption when the cell phone is not in throughput mode (only RRC connected state). As more resources are allocated, greater throughput is achieved, requiring more power to perform the process. FOr the TDL-A, in Fig. 5(a), an average consumption of 0.402 A is verified for this fading profile when considering a lower-quality channel (SNR = 15 dB). When the received signal has a better SNR value (30 dB) and consequently a higher MCS, the average was 0.394 A. Even with a lower throughput due to lower order modulation, the consumption of the lower SNR scenario proves to require higher battery consumption. This result is because more complex processes are needed to demodulate the received information from the degraded channel, and more transmission power



(a) TDL-A



(b) TDL-B



(c) TDL-C

Figure 5: UE power consumption for TDL Models considering different channel conditions

(uplink) is needed to maintain the connection.

A similar measurement campaign was carried out for the TDL-B model, with the consumption profile shown in Fig. 5(b). As in the previous channel model, we noticed an upward trend in energy consumption as more resources were allocated. In this case, with an SNR equal to 15 dB, the average consumption of the RBs variation was 0.405 A, while for an SNR equal to 30 dB, the value obtained was 0.39 A.

The TDL-C channel model is the one that most differs from the previous channel models because it has components in its PDP with more significant time delays, as can be seen in Fig. 4(c). In terms of battery consumption, this is translated into a slight power consumption increase compared to the TDL A and TDL B models, caused by more interference from delayed copies of the transmitted signal, with a more complex procedure to demodulate the signal in the reception correctly. Fig. 5(c) shows the measured values according to the number of resource blocks. For an SNR of 15 dB with MCS 18, the average consumption was 0.41 A, while for an SNR equal to 30 dB and MCS 27, which emulates a good channel condition, the average value was 0.407 A. Those values are slightly higher than those related to models A and B.

B. Linear regression for consumption estimation

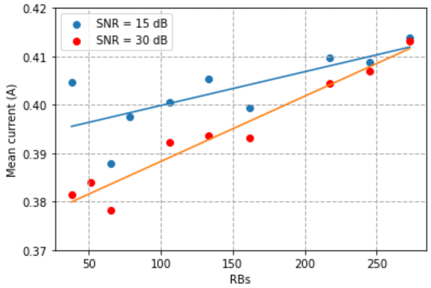
In order to compare the power consumption of the TDL channel models, a simple equation can be defined for the UE battery usage analysis. A regression model is a statistical technique that estimates the relationship between a dependent variable and one or more independent variables using a line (for one independent variable) or a plane (in case of two or more variables). For predicting battery consumption, linear regression is considered according to each TDL model. This form of analysis estimates the linear equation coefficients such as Equation 2.

$$Y_1 = \beta_0 + \beta_1 X_i \tag{2}$$

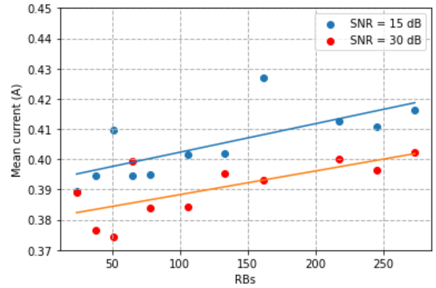
Where Y_i is the dependent variable, which is the current measured for the throughput process. The X_i is the independent variable related to the resource block quantity allocated by the network. The linear regression aims to stipulate the β coefficients. The line that best fits this linear relationship is the least-squares regression line, which minimizes the vertical distance from the data points to the regression line. Fig. 6 shows the linear regression applied to the NLOS TDL models after sample filtering to optimize the estimation for both channel conditions analyzed in this study. It can be observed that, as it was cited previously, a more degraded channel condition requires more power from UE battery. Fig. 7 compares the consumption lines for the three TDL models, considering SNR equals 30 dB and MCS 27. By analyzing the results for the TDL channel models, it is possible to conclude that in poorer condition scenarios, the channel profile that performs most efficiently (less battery consumption) is the TDL A. Profiles with higher multi-path concentration (and longer time delays) require higher energy expenditure by the UE. TDL-C is the model with the highest power consumption, which is explained by the analysis of its PDP and its level difference between the taps. For lower RBs allocation, the resulting consumption lines for TDL A and TDL B are positioned close together, while for TDL C are more distant. Once again, the study confirms the most significant current flow extracted from the battery when the UE operates in degraded channel conditions under multi-path fading.

VI. Conclusions and Future Work

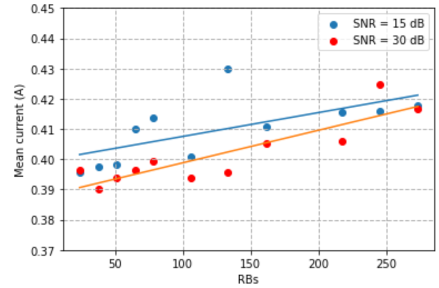
In this work, we analyzed the battery consumption from a smartphone under the effect of multi-path fading channels, considering the Tapped Delay Line models for 5G communication without direct line of sight (TDL-A, TDL-B, and TDL-C), that realistically emulate practical conditions inherent to cellular mobile communication. The consumption profiles differ one from another due to different multi-path configurations. Fading profiles with longer delays proved to



(a) TDL-A



(b) TDL-B



(c) TDL-C

Figure 6: Linear regression for TDL models power consumption

be higher energy consumers. Therefore, TDL-C is the model with the highest power consumption, which is explained by the analysis of its PDP. In addition, better channel conditions imply less battery usage because less complex processes are performed for the correct demodulation/decoding of the PDSCH at the reception side (UE side) and for the PUCCH transmission. Linear regressions were modeled to achieve an efficient power consumption comparison. For future works, we intend to analyze higher-rank configurations, such as 2x2 and 4x4 MIMO, and their influence on power consumption and on throughput/BLER performance.

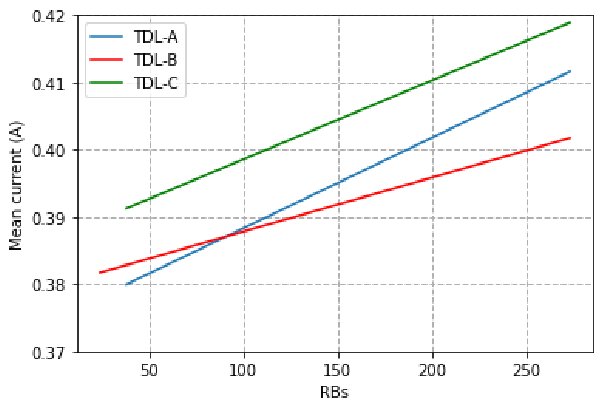


Figure 7: Linear regression comparison for NLOS TDL channels

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