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Research Article

Characterizing Radio and Networking Power Consumption in LTE Networks

Álvaro M. Recio Pérez, Almudena Díaz Zayas, and Pedro Merino

University of Málaga, Andalucía Tech, 29071 Málaga, Spain

Correspondence should be addressed to Almudena Díaz Zayas; almudiaz@lcc.uma.es

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Power consumption is a key factor in how final users rate the quality of service in mobile networks; however, its characterization is a challenging issue due to the many parameters involved and the complexity of their dependencies. Traditional battery drain testing in the field does not provide a suitable environment to reach accurate conclusions. In this paper we address this problem providing a controlled environment, more compact and accurate than those currently found in the literature, designed to measure the effects that different factors have on the global energy consumption.

1. Introduction

In mobile networks, traditional conformance testing for User Equipment (UE) covers RF, electromagnetic compatibility, and protocol aspects of the UE. However operators and device manufacturers are also concerned about the performance of applications running on a device. Standardization and certification bodies such as the Global Certification Forum (GCF) have enforced testing initiatives for the certification of applications in order to validate the quality of service offered in combination by the device, the application, and the network.

Battery life is also an important customer experience factor for operators because network settings affect smartphone current consumption and users can detect the difference between mobile service providers [1]. Therefore battery consumption testing is very important for smartphone vendors and mobile operators, as it provides an opportunity for differentiation.

In previous works we have focused on evaluating the impact of mobility issues over the traffic and the quality perceived by final users of a video streaming service carrying out fields tests [2]. With the objective of carrying out extensive experiments where repeatability could be ensured we developed PerformNetworks, a highly realistic experimentation environment, based on emulation equipment, real antennas, and devices [3, 4]. As the testbed is highly configurable, to provide an optimized testing process we need to provide a reduced and representative number of tests. In this paper we focus on defining test cases whose scope is to evaluate power consumption of radio network subsystem and user application traffic. Power consumption profiling is a challenging task because there are many factors which have to be taken into account and that also introduce a certain level of uncertainty even in a controlled testing environment.

In this paper we introduce a test environment and a testing methodology to extensively measure power consumption of data services in order to characterize its impact on the battery life of smartphones.

The contribution of this paper is twofold:

(i) As this methodology relies on the use of integrated digital channel emulation, it provides an advantage over other approaches in the literature, where external channel emulators are used to analyze the impact of the radio channel. Not including such additional equipment reduces the number of interconnections and cabling, thus improving the power accuracy and the spectral flatness of radio signals. In addition, the proposed scheme is suitable for all LTE frequency bands as no frequency selective components such as duplexers are required.

(ii) Using a power analyzer (as in [5]), also provides benefit when compared with interposers [6]. It allows automated long-term testing without requiring battery chargers that would interfere with the power drain measurements.

The paper is organized as follows. In Section 2 we provide the motivation for this paper and a review of literature on VoIP power consumption. Section 3 introduces the proposed methodology and the testing environment. In Section 4 we provide a detailed description of the parameters configured to execute the power consumption tests. Section 5 presents the results of the experiments. Finally Section 6 remarks the advantages of the testing procedure introduced in this paper to provide accurate results in a very realistic environment.

2. Motivation and Background to the Evaluation of VoIP Power Consumption

Voice calls are part of the basic services that users expect from mobile networks. Traditionally, before the arrival of Long-Term Evolution (LTE), voice calls were implemented over circuit-switched networks, in which the resources needed for the call are reserved before the call is made. In contrast, LTE is based on an all-IP, packet-switched network. This poses new challenges, as voice calls must now contend with variable conditions such as fluctuating bandwidth, packet losses and retransmissions, jitter, and delay. Some of these effects have an impact not only on the quality of service (QoS) but also on the energy spent by mobile terminals during a voice call.

Voice over IP (VoIP) is a popular method for the delivery of voice calls over packet-switched networks. In fact, Voice over LTE (VoLTE), a system based on VoIP, is the most promising alternative studied by 3GPP to provide voice calls over LTE networks [7, 8]. Without loosing generality, in this paper, we focus on VoIP solutions based on third-party applications as a popular alternative until VoLTE is widely deployed. Users demand as much battery lifetime from their phones as possible. Maximizing the energy efficiency of the procedures and applications running on mobile phones is therefore critical.

In recent years, we have observed remarkable changes in how people and cellular networks interact. In addition to a great variety of traffic profiles, such as social networking, multimedia streaming, and peer to peer, new paradigms have emerged in mobile networking. Offloading from mobile applications to cloud computing and heterogeneous mobile networks are just some examples of increasingly complex scenarios. Multiple approaches in the literature have addressed the analysis of energy consumption in different types of mobile networking, but to the authors' experience, many results are based on oversimplified unrealistic models or the approach cannot be directly reused when moving to new scenarios of interest. For this reason we have conceived a test environment to reference energy analysis using commercial mobile devices operating under controlled yet realistic RF and networking conditions.

Many studies have focused on the impact of Disconnected Reception (DRX) on energy consumption in VoIP [9, 10] or including VoIP among other applications [11]; however there are few studies about the effect of propagation and channel conditions on energy consumption of VoIP, and they have relied on complex setups involving multiple elements [6]. In [12], an attempt is made to model latency versus energy efficiency tradeoffs in mobile to cloud offloading. In that paper, there is an attempt to analyze the energy and latency from a purely analytical perspective. The underlying assumption is that it is valid to model energy consumption and latency with mathematical expressions that can then be optimized. However, our perception is that this approach seems to be far too simple to derive quantitative conclusions, as too many aspects are missing in the modeling process. For example, assuming that throughput will be constant is fundamentally wrong. One only has to look at the impact of latency variations caused by retransmissions in link level mobile protocols and TCP/IP dynamics reacting to delay variations and packet losses, in order to realize that the throughput may experience noticeable fluctuations.

Other works in the literature, use pure statistical analysis based on preexisting models to derive numerical conclusions, without verifying their suggested contributions in real conditions. In [13], simulations are conducted in MATLAB using analytical expressions derived from a Markov model. However the results are not validated against actual mobile devices nor realistic traffic patterns from real applications. In the test solution we present in this paper, it will be possible to confirm any theoretical results in a totally realistic environment, using commercial devices and applications.

In [14] the outcome of a set of interesting field tests in a set of measurement campaigns in a commercial network is presented. Unfortunately, inherent to the nature of field tests, there is no control on the propagation conditions and network load, thus making it difficult to obtain repeatable results. Additionally, because the driving experiments are limited in time, the statistical relevance of the results could be discussed. In the current contribution, we suggest to complement drive measurements with accurate laboratory experiments where both the network and RF propagation conditions are totally controlled by the experimenters.

In [5] the authors also use a power consumption analyzer; however they focus on the analysis of baseband without linking it to the end-to-end data transmission and without taking into account fading nor AWGN.

In this paper, we present a characterization of the impact on energy consumption of VoIP in a controlled but realistic environment. This allows us to perform multiple experiments under specific radio channel conditions, including support of the emulation of all 3GPP defined channel models and integrated generation of AWGN (Additive White Gaussian Noise). Our research has been carried out as an addition on top of a testbed we have used successfully in previous studies on VoIP over LTE [15].

3. Testing Environment

In this work we have used PerformNetworks [4], a testbed which is part of FIRE (Future Internet Research and Experimentation (FIRE) (https://www.ict-fire.eu/)) initiative

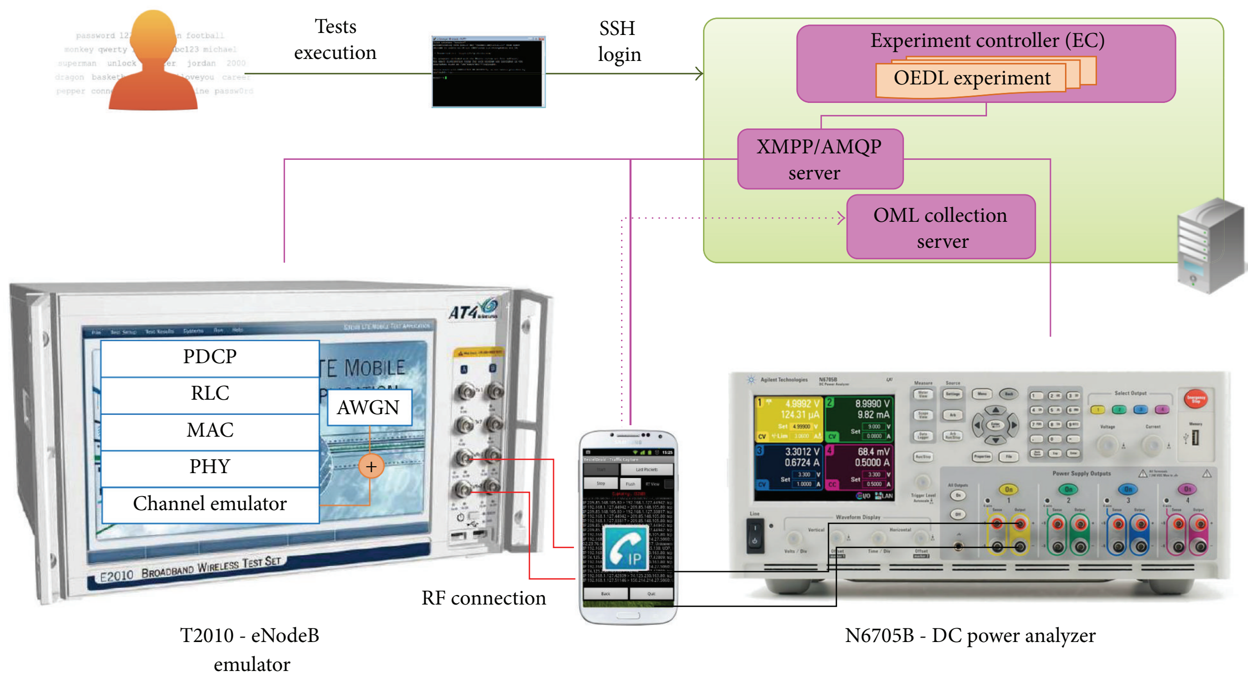


FIGURE 1: Testing environment.

launched and financed by the European Commission. FIRE offers cutting-edge test facilities that could not be accessible otherwise by many researchers.

The testbed has been used to define the experimental methodology and the test cases for carrying out accurate evaluation of power consumption in mobile devices under real radio channel conditions. The specific deployment of the testbed for this work compromises a T2010 eNodeB emulator from Keysight Technologies used for conformance testing, a N6705B DC power analyzer from the same manufacturer, and a Samsung Galaxy S4. Figure 1 shows the final configuration of PerformLTE testbed used during the execution of the tests developed in this work.

The T2010 eNodeB emulator includes a Mobile Test Application which is able to perform RF transmitter and receiver measurements with complete call control functionality as well as end-to-end IP data connections to an external server. This allows the characterization of the RF transmitter and receiver in LTE UEs thanks to its built-in signal analyzer and the embedded protocol stack. The built-in signal analyzer application offers a complete set of RF and modulation measurements. The measurements' default configuration is based on 3GPP TS 36.521-1 [16] specification. Furthermore, full LTE device receiver characterization is possible thanks to the systems integrated BLER measurement suite, with the possibility of adding multipath channel emulation and AWGN to the tests, for maximum realism. Finally, the Mobile Test Application allows users to set up end-to-end connections between the DUT and an external server to test application performance, while retaining the capability to add AWGN interferer and enabling the integrated fading channel emulator. These functionalities have been used in the paper to verify the behavior of power consumption during the execution of end-user applications, while simulating real-life propagation conditions.

For measuring battery consumption the testbed includes an N6705B, a DC power analyzer from Keysight Technologies. The N6705 DC power analyzer is a multifunctional power system that combines the functions of a multiple-output DC voltage source with the waveform/data capturing capability of an oscilloscope and data logger. The data logger functionality includes a continuously sampled mode which samples the voltage and current (the fastest sample period that can configured is 20.48 microseconds, depending on the number of parameters being measured) and stores one averaged value per sample period. The minimum and maximum values per sample period can be also stored.

The UE is a Samsung Galaxy S4 connected to eNodeB emulator via an RF cable connected to the internal antennas of the device. Mobile batteries have typically four connectors: the positive terminal, the negative terminal, the thermistor, which measures the temperature, and a final contact which contains a battery identification code. If the battery is removed and the DC power analyzer is connected directly to the positive and negative connectors the device detects that the battery is not plugged in and does not turn on. The battery must be plugged into the terminal and its positive and negative connectors must be isolated. The UE battery terminals (positive and negative) are then connected to the DC power analyzer as shown in Figure 1.

To configure and orchestrate the execution of the tests designed in this paper we have used OMF (Control and Management Framework), a suite of software components which provides control, measurement, and management tools to support extensive and repeatable experimentation. We have extended OMF to support the control of the eNode B emulator and the DC power analyzer [17]. Our monitoring tool for Android devices, TestelDroid [18] has also been instrumented to support the automatic collections of measurements through the OMF and OML (OMF Measurement Library) experimentation framework [19].

4. Design of Test Cases for Characterizing Power Consumption of Radio and Networking Process

Smartphones have different states. During the suspended state the device is in a low powered sleep mode, the application processor is idle, and only the communication processor performs the minimum activity required to remain connected to the network. In the idle state the device is fully awake, but no application is running. In the active use state the device is performing a task. This is the state where test cases are defined because the measurement tools used to capture IP traffic and network information are running in the background. The screen is set to the minimum brightness.

For measuring power consumption there are two main approaches. The first one is called the component level power measurement and is used in the design phase because it requires access to low level components of the device. The second is the device level power measurement. In this case the power is measured at the battery connection, obtaining a global value of the power consumed. This is the method used in this paper. As we wish to measure the global consumption of the device, we have to meticulously configure the test scenario. In order to avoid unpredictable behaviors, cloud synchronization has been deactivated. Also during the test, the calls are launched programmatically so as to avoid user interaction and thus further isolate the consumption due to radio and networking processes.

Networking power consumption comprises the RF power consumption and that required by the CPU and RAM components for baseband and higher level protocols processing. CPU and RAM consumption is higher for high data throughput. In the setup we use a narrow band code which results in a IP throughput of 80 kbps.

4.1. LTE Radio Channels Models. In order to evaluate how propagation issues impact on power consumption we have defined a set of test scenarios using the LTE channel models defined by the 3GPP.

Signals transmitted on mobile radio channels suffer from different propagation related effects such as "fading."

The multipath propagation conditions consist of several parts:

(i) a delay profile in the form of a tapped delay line, characterized by a number of taps at fixed positions on a sampling grid; the profile can be further characterized by the root mean square (r.m.s.) delay spread and the maximum delay spanned by the taps;

(ii) a Doppler spectrum, characterized by a spectrum shape and a maximum Doppler frequency that is determined from the mobile speed;

(iii) a set of correlation matrices defining the correlation between the UE and BS antennas in case of multi-antenna systems.

Table 1: Summary of delay profiles for LTE channel models (3GPP TS 36.803).

Channel model	Number of paths	Delay spread (r.m.s)	Maximum delay
Extended pedestrian A (EPA)	7	45 ns	410 μs
Extended vehicular A (EVA)	9	357 ns	2.51 μs
Extended typical urban (ETU)	9	991 ns	5 μs

Channel models are defined by combining a delay profile with a Doppler spectrum, with the addition of correlation properties in case of a multiantenna scenario. These two concepts will be explained in the following subsection.

4.1.1. Delay Profiles. The delay profiles are selected to be representative of low, medium, and high delay spread environments. The profiles for low and medium delay spread are based on the ITU Pedestrian A and Vehicular A channel models, respectively, originally defined for the ITU-R evaluation of IMT-2000 [20]. The high delay spread model is based on the Typical Urban model used for GSM [21] and in some of the evaluation work for LTE. The resulting model parameters are summarized in Tables 1 and 2. The models are defined on a (10 ns) sampling grid. They can be adapted to any desired sampling grid used in a simulation or test setup using the procedure defined to align sampling grids shown in Annex B of TR 25.943 [22].

4.1.2. Doppler Frequency. A set of three Doppler frequencies spanning the requirement range as high, middle, and low Doppler frequencies are selected in TR 36.803 [23]:

(i) Common high speed scenarios specify mobile speeds moderately high. It is stated in TR 25.913 [24] that high performance should be maintained up to mobile speeds of 120 km/h. The corresponding maximum Doppler frequency for f_c = 2690 km/h is f_D = 299 Hz, where f_c is frequency of the carrier centre and f_D is Doppler frequency. Based on this, the high Doppler frequency is selected as 300 Hz.

(ii) TR 25.913 also states that the E-UTRAN shall support mobility across the cellular network and should be optimized for low mobile speed from 0 to 15 km/h. For testing purposes, very low mobile speeds are not desirable, since testing times may be too long. The lowest Doppler frequency in UTRA propagation conditions is 5.4 Hz, corresponding to between 2.3 and 7 km/h in the existing frequency bands. Based on this, the low Doppler frequency is set to 5 Hz.

Table 2: Tapped delay line models (3GPP TS 36.803).

Path number	Extended pedestrian A (EPA)		Extended vehicular A (EVA)		Extended typical urban (ETU)	
	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)
1	0	0	0	0	0	−1
2	30	−1	30	−1.5	50	−1
3	70	−2	150	−1.4	120	−1
4	90	−3	310	−3.6	200	0
5	110	−8	370	−0.6	230	0
6	190	−17.2	710	−9.1	500	0
7	410	−20.8	1090	−7	1600	−3
8			1730	−12	2300	−5
9			2510	−16.9	5000	−7

Table 3: Uplink Doppler frequencies and corresponding UE speeds (operating band 3: 1710–1785 MHz).

Maximum Doppler frequency	Corresponding UE speed
5 Hz	3.1 km/h
70 Hz	43 km/h
300 Hz	185 km/h

Table 4: Downlink Doppler frequencies and corresponding UE speeds (operating band 3: 1805–1880 MHz).

Maximum Doppler frequency	Corresponding UE speed
5 Hz	2.9 km/h
70 Hz	41 km/h
300 Hz	176 km/h

(iii) An intermediate Doppler frequency can be set at the logarithmic average of the 5 and 900 Hz, being 67 Hz. Based on this, the medium Doppler frequency is set to 70 Hz.

(iv) The LTE requirements for mobility in TR 25.913 state that mobility across the cellular network shall be maintained at speeds of between 120 km/h and 350 km/h (or even up to 500 km/h depending on the frequency band). This special case is called high speed train scenario and it is not contemplated here.

The UE speed that the Doppler frequencies will correspond to will vary between the operating bands. Tables 3 and 4 show the corresponding UE speeds for the carrier frequencies at the centre of each uplink and downlink for band 3. Informative values for the rest of the bands can be consulted in [23].

In accordance with these parameters several multipath models for cellular systems have been specified for low, medium, and high delay spread environments as shown in Table 5.

4.2. Test Configuration. During the tests we configure in the DC power analyzer the logging of current, voltage, power, and their minimum and maximum values. For this configuration the minimum sampled period is 0.12288 ms. This sampling periodicity provides a time resolution of better than 1 ms, which is the minimum transmission interval defined in LTE.

IP traffic is collected at the mobile device by TestelDroid [18], a software tool developed by the University of Málaga.

4.2.1. Base Station Emulator Configuration. T2010 is a generic platform used not only in conformant RF and signaling testing but also for design verification. In addition to LTE signaling and RF connection features, it also integrates channel emulation and digital generation of impairments such as AWGN, which is a critical feature to achieve high accuracy when setting SNR conditions. Standard multipath fading profiles defined by 3GPP are supported so as to emulate reference propagation conditions. MIMO is a key feature in LTE, as it is one of the foundations of the technology's high rates and spectral efficiency. T2010 provides up to 4 × 2 integrated MIMO features, thus increasing the range of test possibilities with interesting network configurations.

As LTE provides a huge flexibility in terms of configuration options, we give the settings we have used to allow a like-for-like comparison.

For this experiment we have used a 15 MHz channel bandwidth. Although LTE standards allow from 1.4 MHz to 20 MHz, 15 MHz is a common value in some Spanish operators.

To keep a tighter control on the quality of the DL signal and minimize the impact of thermal noise, the DL power level has been maintained well above UE sensitivity. The signal-to-noise ratio (SNR) can thus be better controlled by digitally generating additive noise after applying a fading profile in the channel emulator.

In the 3GPP TR 36.803 v1.1.0 the SNR of reference channels is defined with a low SNR and high SNR. For the high SNR channel it is defined as 18 dB.

The Scheduling Request (SR) configuration index has been set to 7, resulting in a SR periodicity of 10 ms. This parameter is closely related to the delay in UL transmissions, as it defines the time slots where the UE may apply for new uplink grants.

Table 5: LTE radio channel models defined by the 3GPP.

Delay spread	Doppler frequency	Model	Comment
Low	Low	EPA 5 Hz	Low delay spread model representing small cell and indoor cases
Medium	Low	EVA 5 Hz	
Medium	Medium	EVA 70 Hz	
High	Medium	ETU 70 Hz	Represents high delay spread environments, with a delay span of the same order as the cyclic prefix
High	High	ETU 300 Hz	

As we are targeting real time services, at the RLC (Radio Link Control) level we have used Unacknowledged Mode (UM) bearers. UM mode provides reordering up to a configurable timer, which has been set to 50 ms. Upon expiration of the reordering timer, all the successfully received messages are delivered to the upper levels even if some previous messages are still missing. In the UM bearers no retransmissions are done at the RLC level, but note that MAC HARQ retransmissions are still in place. HARQ retransmissions provide fast error correction without compromising real time latency, unlike what would happen with AM RLC retransmissions.

The maximum number of HARQ transmissions has been limited to 6 both for UL and DL. Thus the maximum delay of a successful MAC transmission (involving 5 retransmissions every 8 ms) will be 40 ms.

To allow for easier benchmarking and repeatability, we use a fix modulation and coding scheme. If we used DL scheduling based on the UE reported channel quality, a poorly performing UE, detecting a worse channel quality, could grant more resources than one reporting a better quality under the same conditions. However, to monitor the DL quality measured by the UE while minimizing the impact on the power consumption with frequent PUCCH (Physical Uplink Control Channel) transmissions, periodic CQI (Channel Quality Indication) reporting in Mode 1-0 has been enabled with the maximum (160 ms) reporting interval. Periodic RI (Rank Indication) reporting configuration index 484 has been used, which allows for an RI transmission every 8 CQI transmissions.

The UE is also instructed to send RRC level signaling reports of the received power (RSRP) and quality (RSRQ) every 120 ms, with filter coefficient fc4.

With respect to the control region, we have used the minimum number of symbols for PDCCH by setting CFI (Control Format Indicator) equal to 1. This allows a better coding rate for a given Imcs, when compared with larger CFI values. The aggregation level for the user-specific search space has been set to 2. This stands for a relatively low overhead (as the valid values range from 1 to 8) that would allow for a high number of users.

In the PHICH (Physical HARQ Indicator Channel) configuration, normal duration and one-sixth resources have been configured.

The uplink power of the UE has been controlled via open loop power control. The UE adjusts its transmission power based on a signaled target power and on the estimation of the propagation losses. The base station emulator specifies both the nominal power signaled in the broadcast information and the actual power received by the UE, thus effectively controlling the actual path losses. The UE has allowed a relatively high tolerance when it comes to estimating path losses, but the test equipment provides accurate transmission power measurements to confirm the resulting power.

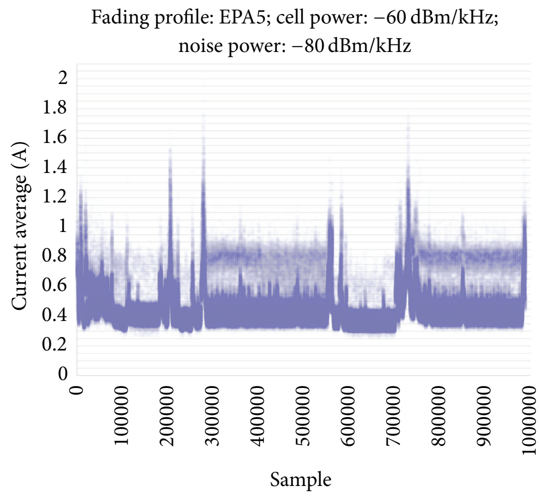
5. Validation: Characterizing the Consumption of VoIP Service over LTE

In this section the results of the test cases are evaluated in order to determine whether or not they provide the accuracy required to characterize the power consumption of radio and networking process.

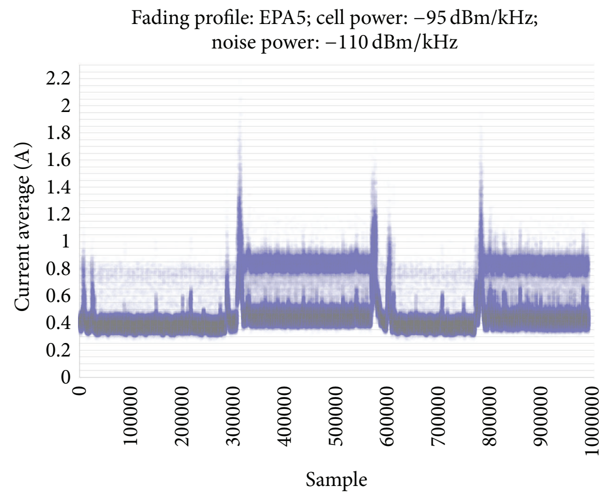
Figures 2 and 3 show the average current consumed during the sampling interval configured in the power analyzer, 0.12288 ms. The test cases have been executed under different conditions of SNR (signal-to-noise ratio) and different LTE channel models, covering pedestrian (EPA5), vehicular (EVA5, EVA70), and urban (ETU70, ETU300) scenarios.

During the experiments shown in Figures 2 and 3, large series of 30 seconds VoIP calls have been carried out every 40 seconds. Voltage provided by the DC power analyzer is set to 3.8 V. Before the call starts the consumption is stable around 0.3 A. The centre of Figure 2(a) shows one. At the beginning and end of each call, large peaks of up to 1.5 A are observed. During the calls, it can be observed that two different current levels coexist. Statistically most of the current values are concentrated around a base current of 0.45 A, while a more spare set of values is associated with a higher level of current, around 0.75, which represents an increase in the current of 0.3 A. Further analyzing the power dynamic in more detail will allow us to understand the dependency of the power on the transmission subframes. For that purpose we correlate the power consumption information with the actual traffic received and transmitted by the UE, as provided by the TestelDroid tool.

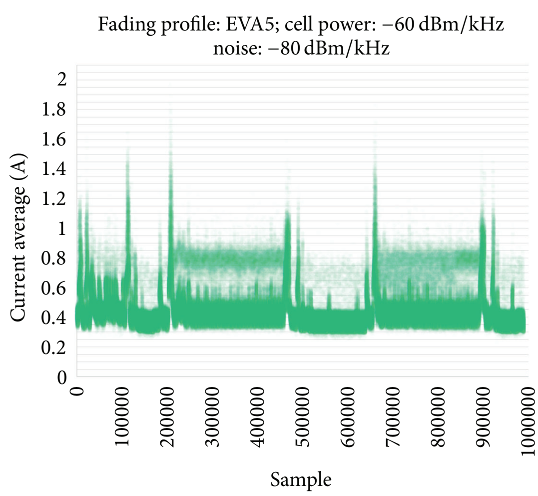
The correlation demonstrates that current peaks correspond to packet transmission. The configuration of this test case depicted in Figure 2(a) represents a pedestrian scenario with a good level of received signal and fair SNR. Comparing this scenario with a scenario where received signal is low (−95 dBm) we obtain a higher density of the points at the second level of current measured during a VoIP call and an increase in the average power consumption of 0.1 A (see Figure 2(b)). The correlation of the energy consumption with the measurements provided by the base station emulator



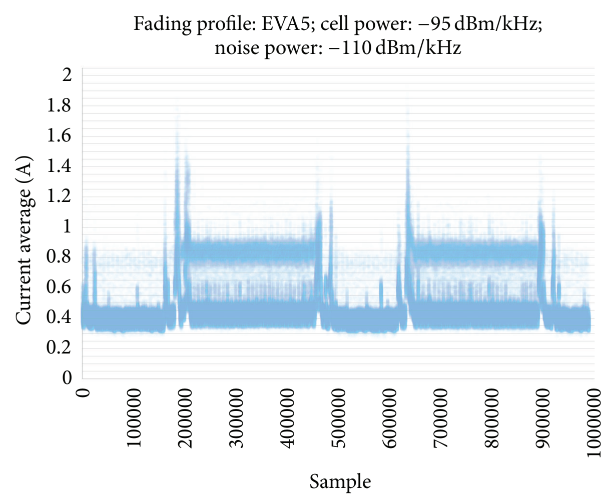
(a) Channel model EPA5: cell power −60 dBm; noise power −80 dBm



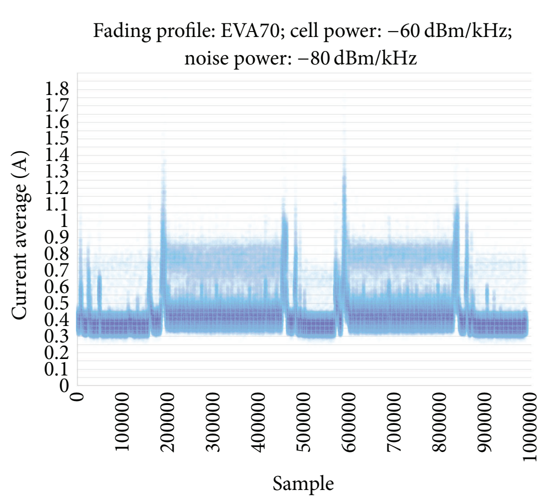
(b) Channel model EPA5: cell power −95 dBm; noise power −110 dBm



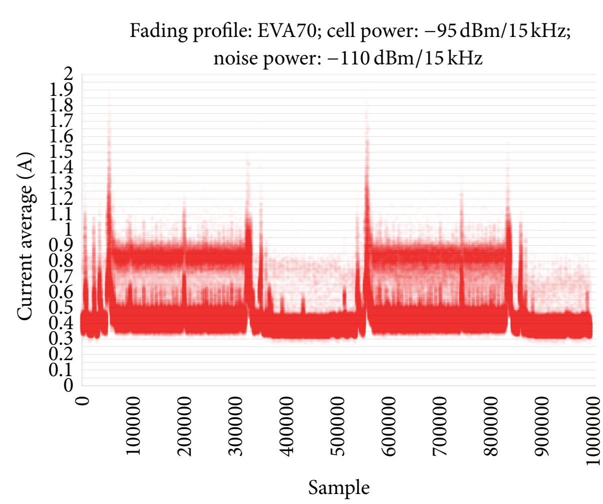
(c) Channel model EVA5: cell power −60 dBm; noise power −80 dBm



(d) Channel model EVA5: cell power −95 dBm; noise power −110 dBm

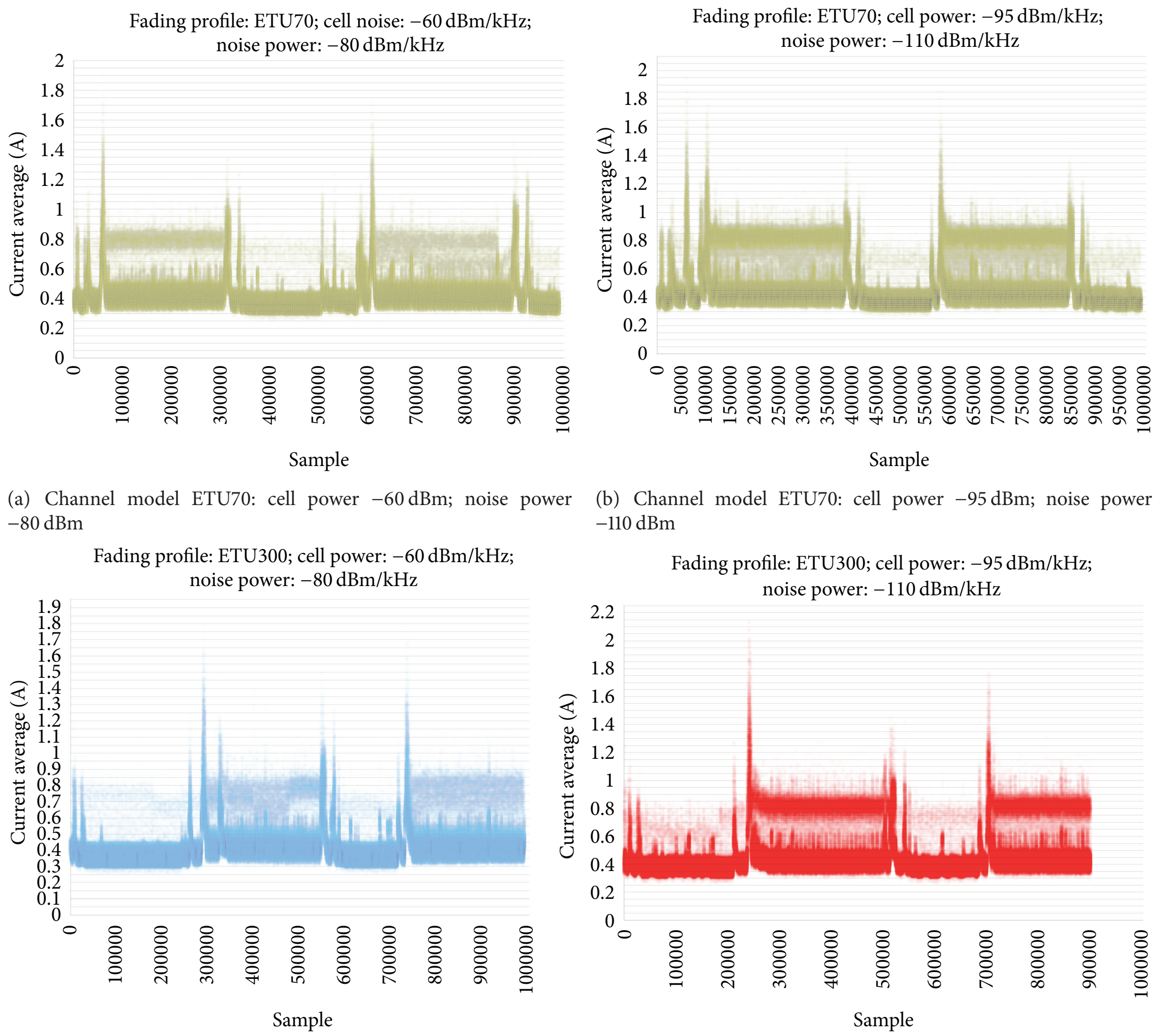


(e) Channel model EVA70: cell power −60 dBm; noise power −80 dBm



(f) Channel model EVA70: cell power −95 dBm; noise power −110 dBm

FIGURE 2: Power consumption profile for VoIP service in pedestrian and vehicular scenarios.



(a) Channel model ETU70: cell power −60 dBm; noise power −80 dBm

(b) Channel model ETU70: cell power −95 dBm; noise power −110 dBm

(c) Channel model ETU300: cell power −60 dBm; noise power −80 dBm

(d) Channel model ETU300: cell power −95 dBm; noise power −110 dBm

FIGURE 3: Power consumption profile for VoIP service in urban scenarios.

enables us to associate the increase in power consumption with a higher average throughput measure at the MAC layer, which denotes retransmissions. This pattern is observed for all the different channel models being tested as shown in Figures 2 and 3.

In Figure 4, a superimposed set of 10 sequences of 100 ms is represented to illustrate the periodic nature of the power consumption peaks.

A base power of 0.4 W can be observed, whereas 5 dominating peaks are shown corresponding to the 20 ms periodicity of the codec being used. The peaks last for approximately 8 samples, corresponding to 1 ms because of the 0.12288 ms power sampling period.

6. Conclusion

In this paper we have introduced a test environment for measuring the power consumption of LTE mobile devices.

The methodology defined has shown that it provides the required accuracy to characterize radio and networking power consumption in the UE. The test cases defined enable isolating, as far as possible, radio and networking consumption evaluation.

The base station configuration introduced in this paper provides a detailed set of parameters and values oriented to enable result comparisons. Finally the results obtained for VoIP traffic show that power consumption measurements can be accurately associated with traffic transmissions. Additionally small increases in current consumption can be detected and correlated with radio propagation issues such as retransmissions.

As this methodology relies on the use of integrated digital channel emulation, it provides an advantage over other approaches in the literature, where external channel emulators are used to analyze the impact of the radio channel. The inclusion of this additional equipment requires additional

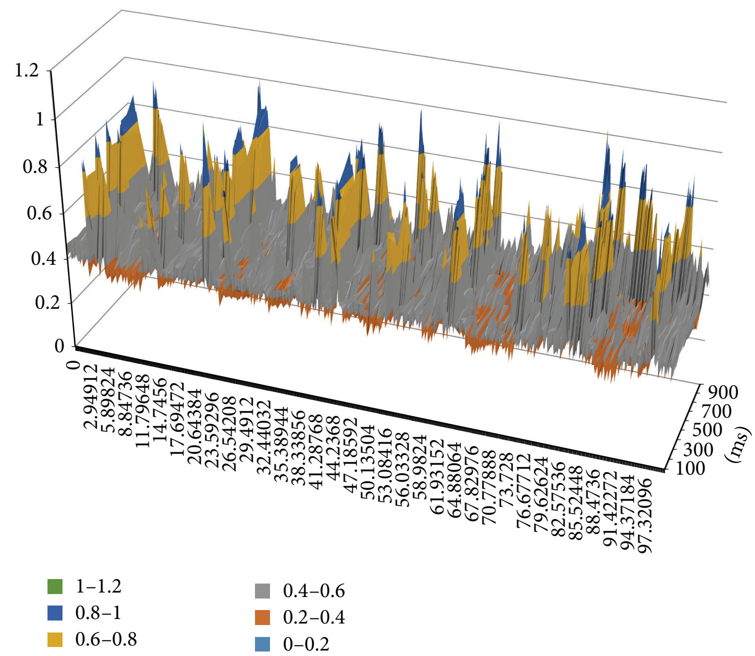


FIGURE 4: Evolution of the power consumption during stationary voice period.

interconnections and cabling, reducing the power accuracy and the spectral flatness of radio signals. Moreover, the proposed scheme is suitable for all LTE frequency bands as no frequency selective components such as duplexers are required.

Competing Interests

The authors declare that they have no competing interests.

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