Crosstalk Measurement and Modeling for 5G Fixed Broadband Access Networks

Diogo Acatauassu, Roberto Menezes and João C. W. A. Costa

***Abstract*— Crosstalk is the main interference limiting high-speed data transmission over short twisted-pair cables, such as the ones planned to be used in the 5^{th} generation (5G) fixed broadband access networks. Due to this fact, it must be accurately measured, characterized and modeled. However, the task of measuring crosstalk coupling functions from short cables is arduous due to the sensitivity of the measurement setup. In this work, we show an application of the Bob Smith termination technique to reduce electromagnetic interference (EMI) in crosstalk measurements using short twisted-pair copper cables. Experiments adopting a typical category 6 (Cat6) cable show that resonant components are reduced from the measured data when the Bob Smith termination is employed in the experimental setup. Then, using reliable measurement data, crosstalk modeling is performed using a 1% worst-case model.**

***Keywords*— Bob Smith termination, crosstalk, fixed broadband, Multi-gigabit fast access to subscriber terminals (MGfast).**

I. Introduction

The continuous demand for data traffic boosts the development of new solutions capable of delivering the required data rates to the final customers. In this scenario, the International Telecommunication Union (ITU) designed the 5^{th} generation (5G) fixed broadband access technologies and defined the Multi-gigabit fast access to subscriber terminals (MGfast) standard [1], [2], which aims at achieving data rates in the order of Gbps using frequencies up to hundreds of MHz and short metallic cables, including coaxial and twisted-pair lines [2], [3].

For the twisted-pair based systems, crosstalk is the main interference limiting communication. It comes due to a capacitive and inductive coupling between neighboring pairs inside a cable and is manifested in two ways: 1) near-end crosstalk (NEXT), that is the crosstalk between transmitter and receiver pairs at the same end of a cable section, and 2) far-end crosstalk (FEXT), that is the crosstalk between transmitter and receiver pairs at opposite ends of a cable section [4], [5].

Due to its harmfulness, crosstalk must be measured, modeled and mitigated. However, the task of measuring crosstalk coupling functions[1] using very short twisted-pair lines at frequencies of hundreds of MHz is not trivial, in part, due to the sensitivity of the measurement setup, which is intrinsically affected by electromagnetic interference (EMI). In this context, dealing with resonant frequencies that move the electrical value being measured to very high/low levels is very common. These resonances disturb the signal integrity and impair the resulting measured data. Hence, any parametric model fitted to these estimates for crosstalk channel characterization may lead to wrong results.

This article presents a crosstalk measurement and modeling technique for 5G fixed broadband access networks. We show an application of the Bob Smith termination technique to reduce resonant artifacts in crosstalk measurements extracted from short twisted-pair copper cables. Experimental results show that the Bob Smith termination provides substantial benefit in terms of reducing EMI in this kind of measurement procedure, allowing obtaining reliable measured data. Consequently, with reliable data, crosstalk modeling can be performed [6], [7], [8], which allows simulation studies to predict the transmission behavior of metallic loops under different conditions. Moreover, crosstalk models can also be used for testing new signal processing algorithms that will directly impact the development and evolution of the modern MGfast network transceivers.

The rest of the work is divided as follows: Section II reviews the network architecture and reference loops adopted in the MGfast standard, emphasizing the usage of short cables. Section III discusses the origins of cable emissions that create resonances in crosstalk measurements from short twisted-pair cables. Section IV briefly describes the Bob Smith termination technique. Section V details the equipment used in the tests performed for validating that the refereed resonances are mitigated from the measured data when the Bob Smith termination is employed in the measurement setup. Continuing, Section VI presents the measurement results, Section VII presents the modeling results, and, at last, Section VIII describes the conclusions.

II. MGfast Standard

A trend for the 5G fixed broadband access networks is providing data rates in the order of Gbps to the final subscribers. Since fiber-to-the-home (FTTH) connectivity is still expensive, the use of alternative architectures is attractive in some scenarios. Therefore, the ITU standardized the MGfast access technology to allow multi-gigabit transmission over metallic media, employing architectures such as fiber-to-the-building (FTTB) and fiber-to-the-distribution point (FTTdp), as well as extending the frequency limit of its predecessor Fast access to subscriber terminals (G.fast) [9].

The network architectures considered to be used in MGfast are similar to those ones used in G.fast [9], where optical fiber

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[1]The crosstalk coupling functions quantify the degree of crosstalk that occurs due to electromagnetic coupling between the conductors.

cables flow from a central office (CO) toward a distribution point unit (DPU). The DPU establishes the connection between the customer premises equipment (CPE) and the rest of the access network through a metallic media and it must be placed near to the customer premises. Hence, the DPUs are usually installed in locations such as external walls, in basements and in the building floor.

In MGfast, the metallic loops employed between the DPUs and the CPEs are designed to range from 30 m to 100 m and the deployments may support both single-dwelling unit (SDU) and multi-dwelling unit (MDU). Moreover, MGfast is designed to coexist with other transmission systems such as G.fast or satellite TV (SAT TV).

In order to give support to simulation, design and performance evaluation tests, the MGfast recommendation presents examples of some wiring topologies and reference loops describing configurations expected to be found in real MGfast deployments. Fig. 1 depicts a possible cable configuration for FTTB scenario, as defined in [1]. In this case, the DPU is in the basement of a building and the pairs to each customer share a common cable duct (vertical riser).

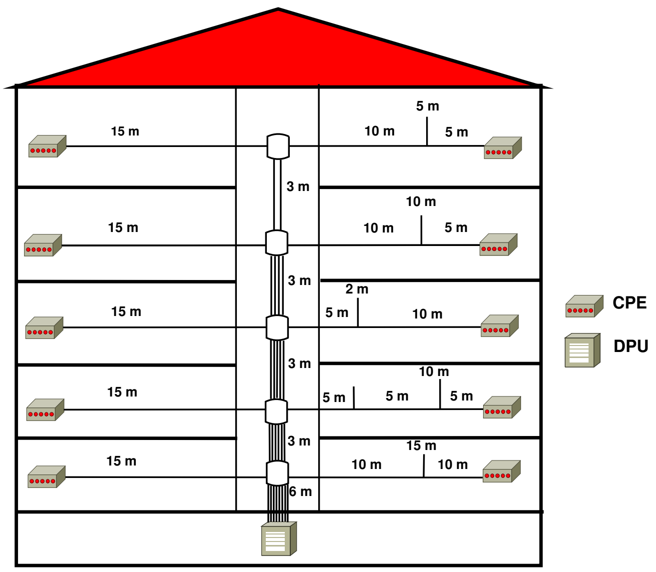

Fig. 1. Reference wiring topologies as defined in [1] for MGfast in FTTB scenario.

It is possible to observe that the reference loops are composed of short cable sections (e.g., as low as 2 m long). Thus, measuring and modeling crosstalk coupling functions of short metallic cables are of great importance for MGfast. However, the task of measuring crosstalk coupling functions from short copper lines (e.g., twisted-pair cables) is arduous due to the sensitivity of the measurement setup and resonances that affect the measured data. The reason for these resonances is explained in the sequence.

III. Resonances in Crosstalk Measurements from Short Twisted-Pair Cables

Radiated emissions from twisted-pair copper cables are mainly due to common-mode (CM) currents. Hence, spurious resonances in crosstalk measurements from short twisted-pair cables may come due to not perfectly matching the CM signals over the lines. In spite of copper cables are intended to carry differential-mode (DM) signaling, CM currents are present in differential transmission due to a number of factors like nonuniformities along the cable [10]. Although the CM current is much lower than the DM one (μA versus mA), it produces very high levels of emission. Thus, proper matching the CM signals is crucial for preventing those signals bounce back and forth and generate standing waves that will be dissipated as radiated emissions [4].

Remark that each pair in the cable has its own differential impedance in addition with impedances that come due to parasitic capacitive effects between other pairs. In general, during the measurement procedures the pairs are individually matched [11], assuming that they are isolated in space. By doing so, the CM impedances become free to generate reflections which will act over some frequency components.

IV. The Bob Smith Termination

The Robert (Bob) Smith termination technique [12] regards an arrangement of loads to be applied to both ends of the cables that aims at matching the cable pairs as a whole with the objective of dissipating CM currents. The proposed arrangement is made up of four loads such that the impedance between any two pairs is about 145 Ω [12]. The Bob Smith termination is important for those wires in the cable that are not connected to signals, since they can act as parasitic elements.

Note that there is a lot of controversy in literature regarding the load values used to built up the Bob Smith termination. For example, it is stated in [13] that 52.3 Ω is more suitable than the 75 Ω values originally defined in [12], leading the impedance between any two pairs to about 105 Ω, whereas in [14] it is presented experimental results indicating that this difference does not have significant impact on reducing the CM currents. In this work, we bypass this discussion and employed the original values defined in [12].

V. Experiments

In order to verify the benefits of using the Bob Smith termination technique for reducing cable emissions and EMI in crosstalk measurements, experiments were conducted in our Cable Laboratory at the Federal University of Pará (UFPA). We focused on FEXT measurements since NEXT can be mitigated in MGfast time-division duplexing (TDD) based systems [2].

The measurements were performed using a typical 10 m long category 6 (Cat6) cable (4 x 2 x 23 AWG). This type of cable is defined in ANSI/TIA-568 [15] and is commonly used in structured cabling for computer networks, such as Ethernet. It also is specified as reference wire type for MGfast in [1]. The FEXT transfer functions, in terms of the scattering parameter $S_{21}(f)$, of three combinations of pairs within the line (green & orange, blue & brown and blue & orange) were measured in a frequency range from 1 MHz up to 212 MHz using the following: an Agilent Vector Network Analyzer (VNA) E5071C (9 kHz-6.5 GHz), two North Hills baluns 0319NA (100 kHz-300 MHz, 50 UNB-100 BAL), two interface coaxial cables and a calibration kit. Fig. 2 illustrates the equipment. The calibration plan was set after the baluns.

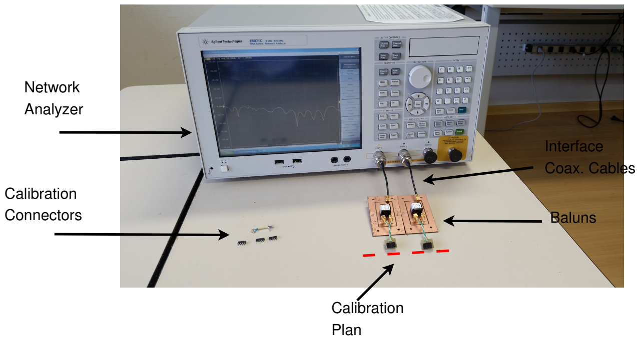

Fig. 2. VNA, baluns, calibration connectors, interface coaxial cables and reference plan adopted for calibration.

The Bob Smith terminations were implemented in a breadboard as illustrated in Fig. 3 (left). The breadboard was employed for simplicity, although its terminal strips of contacts may create stray capacitance that can prejudice the circuit performance. Fig. 3 (right) shows the corresponding schematic (front view) of the symmetric arrangement.

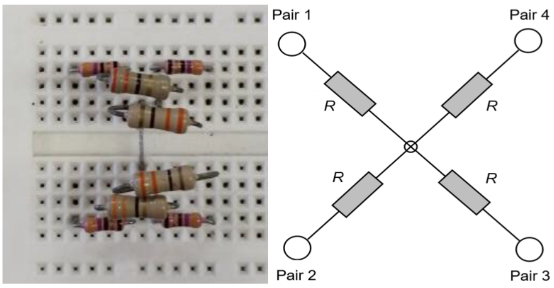

Fig. 3. Bob Smith terminations implemented in a breadboard (left). Schematic (front view) of the symmetric arrangement proposed in [12] (right).

First, measurements were performed connecting the wire pairs under test to the VNA through the baluns and matching the wires that were not connected to signals with the Bob Smith terminations. Later, measurements were performed connecting the wire pairs under test to the VNA through the baluns and matching the wires that were not connected to signals with their nominal characteristic impedance [11]. The baluns are responsible for balance/unbalance signal conversion. The balanced transmission method is used by the copper loop, however almost all measurement instruments have unbalanced input and output ports. Moreover, they also have function to convert the system impedance from 50 Ω of the VNA to approximately 100 Ω of the copper loop. Temperature conditions were kept constant during the measurements. For compensation purposes, the following calibration standards were used: open, short, load and through. The measurements were conducted from a start frequency to a stop frequency, in low-pass mode. It was assumed an uniform sampling of the frequency axis, which means that neighboring points were separated by Δf Hz, which is called frequency resolution.

VI. Measurement Results

The results presented in Figs. 4, 5 and 6, in the sequence, confirm that the Bob Smith termination provides benefits for reducing EMI in crosstalk measurements. In the plots, the frequency axis is given in logarithmic scale.

Fig. 4 shows the FEXT coupling functions measured from the 10 m long Cat6 cable using the green & orange pairs. It is possible to observe that a resonant behavior near to 2.2 MHz is mitigated from the measured data when the Bob Smith arrangement is employed in the measurement setup. For this specific 10 m long cable, the first natural resonant frequency is expected to occur around 10 MHz, assuming a maximum transmission frequency of few hundreds of MHz [4]. The line resonance is related to the length of the transmission line and the wavelength of the signals transmitted over it. Hence, it can be inferred that the resonant frequency at 2.2 MHz may come from CM radiation, which is reduced by matching the CM impedance of the cable using the Bob Smith termination. Furthermore, it is important to note that such a resonance occurs in a frequency region employed by MGfast systems, and so it is of interest adopting techniques for mitigating its occurrence. In fact, 2.2 MHz is the lowest supported downstream data-bearing subcarrier used in MGfast [1].

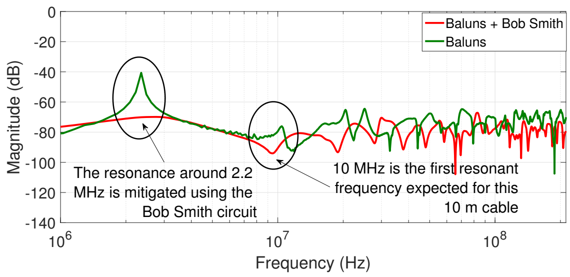

Fig. 4. FEXT coupling functions measured from the 10 m long Cat6 cable using the green & orange pairs. The resonant behavior near to 2.2 MHz is mitigated when the Bob Smith termination is employed in the measurement setup.

Similarly, Fig. 5 shows the FEXT coupling functions measured from the 10 m long Cat6 cable using the blue & brown pairs. Once again, the spurious resonance around 2.2 MHz is suppressed when the Bob Smith termination is adopted in the measurement setup. That is, by matching the termination impedance, the CM energy is absorbed efficiently and does not reflect back onto the transmission line where it forms standing waves that move the electrical value being measured to very high/low levels (in this case, up to near -40 dB).

Continuing, Fig. 6 shows the results for the blue & orange pairs, which confirm the benefits of using the Bob Smith termination for reducing spurious resonances in crosstalk measurements.

In summary, the improvements achieved after impedance matching using the Bob Smith termination were reductions on EMI of about 30 dB, 22 dB and 21 dB for Figs. 4, 5 and 6, respectively. Note that, depending on the configuration, the improvement in dB may not be the same.

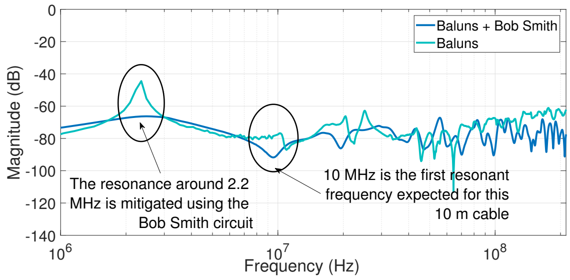

Fig. 5. FEXT coupling functions measured from the 10 m long Cat6 cable using the blue & brown pairs. The resonant behavior near to 2.2 MHz is mitigated when the Bob Smith termination is employed in the measurement setup.

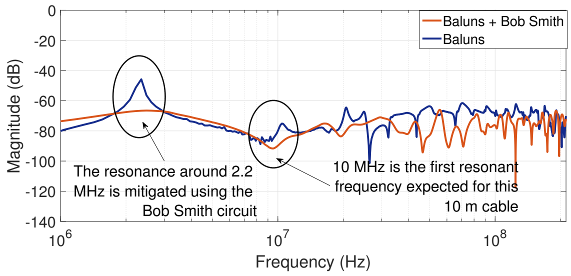

Fig. 6. FEXT coupling functions measured from the 10 m long Cat6 cable using the blue & orange pairs. The resonant behavior near to 2.2 MHz is mitigated when the Bob Smith termination is employed in the measurement setup.

VII. Modeling Results

At last, having suppressed the spurious resonances and obtaining reliable measurement data, crosstalk modeling is performed. We adopted the 1% worst-case FEXT model defined in [6] for this purpose, which is defined as:

$$H_{\text{FEXT}}(f) = \left(\frac{jK_{xf}\left(\frac{f}{f_0}\right)\sqrt{\frac{L}{L_0}}}{1 + jK_{xf}\left(\frac{f}{f_0}\right)\sqrt{\frac{L}{L_0}}} \right) |H(f)|, \quad (1)$$

where L is the cable length in meters, K_{xf} is a cable dependent parameter derived from the FEXT measurements given in dB, f is the frequency in Hz, f_0 and L_0 are the reference frequency and reference length, respectively, which are set to 100 MHz and 1 m considering the cable dimensions and frequency band plans adopted in MGfast [8], and $H(f)$ is the channel transfer function (frequency response) of the disturbing transmitter. The estimation procedure for finding the value of K_{xf} was based on a genetic algorithm routine.

Fig. 7 shows the modeling results considering the blue & brown pairs (from brown to blue). For this specific combination, K_{xf} was estimated as: $K_{xf} = -74.33$ dB. The frequency axis is given in logarithmic scale. Fig. 8 shows results in which the frequency axis is given in linear scale.

It is possible to observe a good match between measured and modeled curves at high frequencies. This result indicates that suppressing the spurious resonances at low frequencies is important for obtaining reliable modeling results at frequencies of hundreds of MHz. Moreover, it is important to highlight that the mismatch at low frequencies occurs since the adopted model has few degrees of freedom and limited slope. The results obtained for the green & orange and blue & orange combinations are similar and are omitted here for convenience.

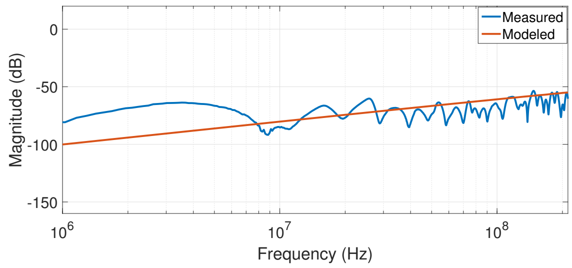

Fig. 7. Measured and modeled FEXT coupling functions for the 10 m long Cat6 cable using the blue & brown pairs. For this specific combination, $K_{xf} = -74.33$ dB.

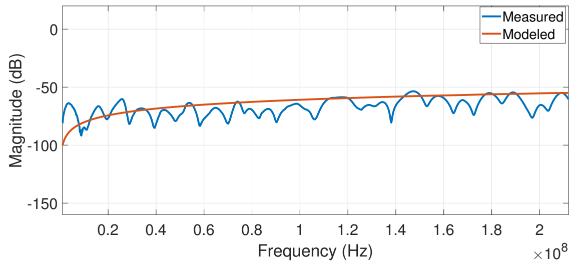

Fig. 8. Measured and modeled FEXT coupling functions for the blue & brown configuration. The frequency axis is given in linear scale.

VIII. Conclusions

This paper presented a crosstalk measurement and modeling technique for 5G fixed broadband access networks. It was discussed an application of the Bob Smith termination for reducing EMI in crosstalk measurements using short twisted-pair copper cables. Experiments indicated that by matching the termination impedance, the CM energy is absorbed efficiently and does not reflect back onto the cable where it forms standing waves resulting in resonant artifacts. In summary, the main contribution of this work is providing a guideline for those measuring and modeling crosstalk coupling functions of short twisted-pair cables at MGfast frequencies. Reducing EMI is crucial for extracting reliable measured data which can be used for refining crosstalk models that can be subsequently adopted in computer based simulations in order to predict the transmission characteristics of these metallic loops under different conditions.

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