Impact of Cable Non-uniformities on the Performance of Copper Fronthaul Exploiting the Phantom Mode Transmission

A. A. Ohashi, G. S. Borges, R. M. Rodrigues, A. L. P. Fernandes and J. C. W. A. Costa

***Abstract*— The fronthaul of the future 5G networks is expected to be the bottleneck for coping with the increasing data traffic demand. Despite optical fiber is the preferred alternative for fronthaul, technologies like phantom mode has boosted the data rates over copper lines. Previous works have investigated the application of phantom mode and its interaction with differential channels, but none has addressed the potential impact of the cable non-uniformities on the overall performance of copper-based networks. In this work we carried out simulations in order to investigate such impact on both ordinary differential and phantom channels. The obtained results indicate that non-uniformities must be taken into account for realistic data rate analysis in next-generation networks.**

***Keywords*— Fronthaul, non-uniformities, phantom mode, twisted pairs.**

I. Introduction

The mobile traffic demand is predicted to increase dramatically in the next few years as consumers access and share more and more multimedia content [1]. Additionally, the concept of Internet of Things (IoT) – a purposely interaction among "smart things" through Internet without human intervention – is opening the door for a wide range of new applications like self-driving cars and industrial automation systems. In order to cope with this future scenario, a new generation of wireless communication, called 5G, is under development. The efficient transport of massive amount of data in 5G networks will be greatly dependent on the solution adopted for the mobile fronthaul. The concept of fronthaul is associated to a new type of radio access network (RAN) architecture in which the baseband units (BBUs) are centralized and physically separated from the radio units (RUs). The link connecting these entities is the fronthaul (Figure 1).

Optical fiber is the most promising solution for that due to its transmission capacity. However, the attainable speeds over copper have dramatically increased due to the recent use of physical-layer techniques like phantom mode [2]. This technique exploits the common-mode signaling to transmit data. Ordinary transmissions over copper lines use differential signaling. In this way, the phantom mode allows the transmission of common-mode signals over the differential ones in the same physical channels. This fact increases the transmission capacity of given number of physical channels.

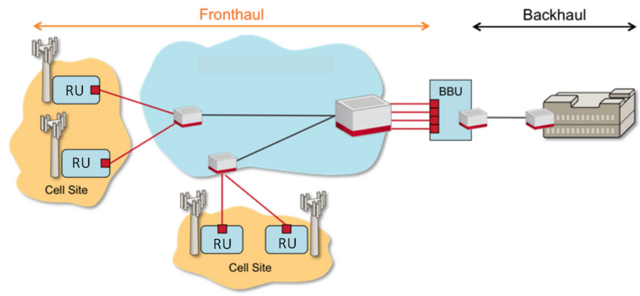

Fig. 1. Radio access network architecture and the fronthaul.

Ideally, a copper network employing regular and phantom channels should experience no interference between these two kinds of signaling. However, the non-uniformities present along copper cables may be a source of signal leakage between them, particularly for high frequencies. From the best of authors' knowledge, it is not completely understood how cable non-uniformities change the interference (crosstalk) between differential and phantom mode channels, and consequently how the overall transmission rate is affected. Previous works addressing phantom mode [3]–[6] did not cover this aspect that is becoming important as the upper bound of the frequency band to be exploited for communication is being pushed away.

In this work, computer simulations are carried out in order to study the impact of cable non-uniformities on the performance of copper-based fronthaul. We show how non-uniformities applied to the geometric parameters of twisted pairs affect the achieved transmission rate for frequencies required by 5G. The remainder of this paper is organized as follows. In Section II, we describe the phantom mode transmission. In Section III, the commonly found cable non-uniformities are presented and how they arise. In Section IV, the employed mathematical modeling as the simulation scenarios are presented. The Section V summarizes the main findings while Section VI provides the conclusions of the present work.

II. The Phantom Mode

The technique called phantom mode increases the number of available channels over the same copper infrastructure. In order to understand how this is accomplished, assume a copper network composed of just two twisted-pairs, where in each pair

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a differential signal is being transmitted (see Figure 2). If one desires to transmit one more differential signal through that network, this can be done by creating a "phantom channel", i.e., the additional differential signal is split in the twisted pairs by applying a common signal to each one. If the common signal in each pair is differentially processed at the far end by a third receiver, the differential signal that runs through the phantom channel can be recovered. In this way, a phantom channel can be thought as an overlay to the regular differential channels.

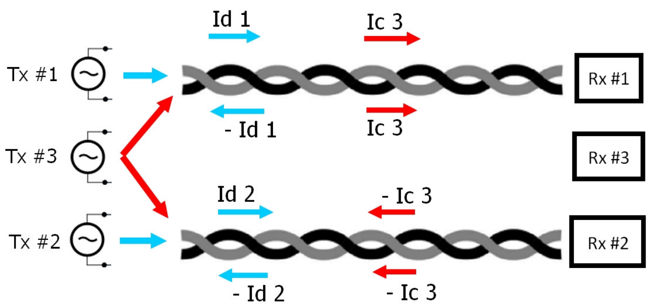

Fig. 2. Illustration showing how phantom mode exploits common-mode signals to create virtual channels over the existent twisted pairs.

This technique can be extended for more pairs, resulting in a number of channels available for transmitting through N twisted pairs as follows: $N_{total} = 2N - 1$. For example, the total number of channels for a CAT5 cable (4 pairs) when one is employing phantom mode will be seven: four differential channels and three phantom ones.

III. Non-uniformities and their influence on cable properties

Imperfections on copper cables may arise due to many reasons, like for instance inhomogeneity of their materials (random non-uniformities), systematic errors on the manufacturing process (periodic non-uniformities), and even after manufacturing (improper handling during deployment). Therefore, a cable free of non-uniformities is unrealistic. Previous works have indicated how non-uniformities can be harmful to the transmission over copper cables, e.g. generating a selective filter-like behavior for specific frequencies [7] and impedance changes [8].

It is well known that non-uniformities cause unwanted mode conversion along the cable (i.e. some amount of the differential signals being converted to common-mode and vice-versa). As a consequence, it is reasonable to think that non-uniformities also influence the level of signal leakage between differential signals propagating through each twisted pair and between differential and common modes. Both kinds of signal leakages can be referred as crosstalk, without loss of generality. In particular, there are two kinds of crosstalk, namely: Far end crosstalk (FEXT) and Near end crosstalk (NEXT). The former can be determined by transmitting at a given input port and measuring at a given far end output port while for the latter the measuring point is a port close to the transmitting one [9].

The cable non-uniformities considered in this work are very common in practice:

1) **Pigtail:** it refers to a piece of untwisted pair(s) at the cable ends. Frequently, it is done intentionally for proper connection to an equipment or adapter. For instance, Ethernet cables employs RJ-45 connectors. To use such connector, it is necessary to untwist the pairs at the ends (Figure 3).
2) **Pair-Center Variation:** it refers to a variation on the distance between the center of the twisted pairs along the cable (Figure 4). This can occur due to cable bending. However, the longitudinal regularity of such distance is mainly related to the quality of the employed cable. CAT6 cables employ a cross separator, keeping roughly constant the distance among the pairs. Therefore, this kind of non-uniformity for CAT6 cables can be considered negligible when compared to the ubiquitous CAT5 cables.

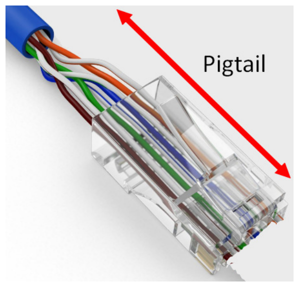

Fig. 3. Example of pigtail in Ethernet cables.

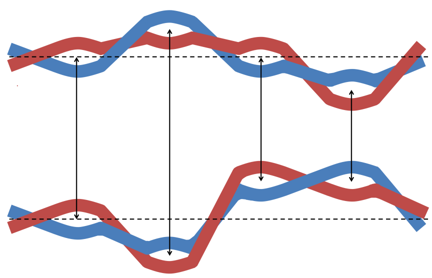

Fig. 4. Variation on the distance between the center of the pairs along the cable.

IV. Configurations and Simulation Scenarios

The computer simulations carried out in this work targeted:

- Quantify the increase in transmission rate when phantom mode is employed and no cable non-uniformities is present (This is our baseline);
- Quantify how much cable non-uniformities degrade the transmission rate via increasing in crosstalk between differential and common modes.

The computational code developed by Bin Lee [10] was used in order to carry out the simulations. Some adaptations on the code like specifications of source and load impedances as well as input current were necessary in order to properly create a scenario with a phantom channel.

Figure 5 shows the input-output voltages for a phantom channel between two twisted pairs. As the transfer function of a channel is generally defined as V_{out}/V_{in}, one can extend that definition for a phantom channel stating that:

$$H_g = \frac{V_{out,1}^{phantom} - V_{out,2}^{phantom}}{V_{in,1}^{phantom} - V_{in,2}^{phantom}}. \tag{1}$$

By defining the "phantom" voltages in terms of the conductors' voltages, the equation (1) can be rewritten as

$$H_g = \frac{(V_{out,3} + V_{out,4}) - (V_{out,2} + V_{out,1})}{(V_{in,3} + V_{in,4}) - (V_{in,2} + V_{in,2})}. \tag{2}$$

Similar approach can be used to derive the FEXT among differential channels and between a differential and a common mode channels as the FEXT is generally defined as the ratio between the voltage applied at a certain input port and the one measured at the far end. Therefore, taking the appropriate voltages, the both kinds of FEXT can be derived.

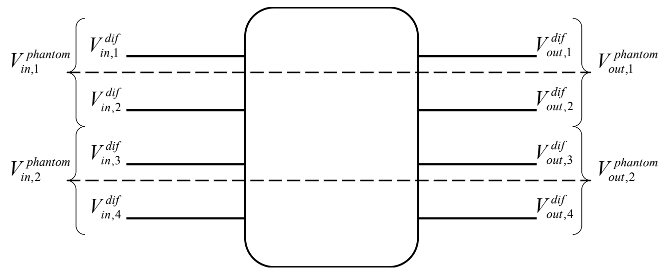

Fig. 5. Input-output voltages relation for the phantom channel.

The aforementioned voltages are generated from the application of the classical transmission line theory – in particular the Multiconductor Transmission Line (MTL) [11] – and the two-port network theory (TPN). The MTL states that each infinitesimal line-segment of the transmission line is described by

$$-\frac{d\mathbf{V}}{dz} = (\mathbf{R} + j\omega\mathbf{L}) \cdot \mathbf{I} = \mathbf{Z} \cdot \mathbf{I} \tag{3}$$

$$-\frac{d\mathbf{I}}{dz} = (\mathbf{G} + j\omega\mathbf{C}) \cdot \mathbf{V} = \mathbf{Y} \cdot \mathbf{V} \tag{4}$$

where **R**, **L**, **G** and **C** are respectively the per-unit-length matrix for resistance, inductance, conductance, and capacitance [11]. The quantities **V** and **I** are the vectors of voltage and current, respectively, both dependent on frequency and position. In turn, **Z** and **Y** are the per-unit-length impedance and per-unit-length admittance, respectively, and they are defined as follows:

$$\mathbf{Z} = \mathbf{R} + j\omega\mathbf{L} \tag{5}$$

$$\mathbf{Y} = \mathbf{G} + j\omega\mathbf{C} \tag{6}$$

From the TPN, the transmission matrix for each infinitesimal segment can be described as

$$\phi(l) = \begin{bmatrix} cosh(\gamma l) & sinh(\gamma l) \cdot \mathbf{Z}_0 \\ sinh(\gamma^T l) \cdot \mathbf{Z}_0^{-1} & cosh(\gamma^T l) \end{bmatrix}, \tag{7}$$

where γ and Z_0 are the propagation constant and characteristic impedance per-unit-length matrices, respectively.

Finally, if one assumes that the whole transmission line is formed by a cascade of the per-unit segments, the transmission matrix describing the whole transmission can defined as

$$\begin{bmatrix} \mathbf{V}(0) \\ \mathbf{I}(0) \end{bmatrix} = \phi(l)_1 \cdot \phi(l)_2 \cdot \phi(l)_3 \cdots \phi(l)_N \cdot \begin{bmatrix} \mathbf{V}(L) \\ \mathbf{I}(L) \end{bmatrix}, \tag{8}$$

where L is the cable length and N is the number of cascaded segments. From the transmission matrix both transfer functions for both differential and phantom modes as well as crosstalks can be derived.

Finally, the transmission rate can be derived from the transfer function(s), crosstalk(s) and the frequency range of interest. In particular, the maximum rate of a given channel (C) is provided by [12]:

$$C_i = Wlog_2\left(1 + \frac{S_i|H_i|^2}{\sum_j |FEXT_{j,i}|^2 S_j + N}\right), \tag{9}$$

where W is the frequency range, S is the input power, H is the transfer function of the channel, $FEXT$ is the crosstalk from channel j to channel i and N is the noise figure. The ratio in equation (9) is the Signal-to-Noise Ratio (SNR), i.e., the ratio between the received signal power and the noise power perceived at the receiver. Note that SNR is directly proportional to the transfer functions, but inversely proportional to the FEXT.

In our simulations, two differential twisted pairs were excited to create a phantom channel. The considered cable lengths were 10 m and 70 m (assuming 5G fronthaul for indoor scenarios) and the frequency range is from DC to 500 MHz. Regarding the simulation scenarios, we have defined the following test-cases:

- Uniform copper cable (ideal case);
- Copper cable having one of the following non-uniformities:
  - Pair-center variation along its length of 10 % of the nominal value, assuming an uniform distribution;
  - Pigtail of 1.5 cm at both ends of the pairs.

The specifications assumed in order to simulate a copper cable are summarized in Table I. They are taken from a real CAT5e sample.

TABLE I
SPECIFICATIONS OF THE SIMULATED COPPER CABLE – CAT5E.

Specification	Value/type
Conductor's diameter (AWG)	24
Number of pairs	2
Distance between the pair centers (mm)	24
Twist rate – pair 1 (mm)	12.70
Twist Rate – pair 2 (mm)	13.37
Insulation material	Polyethylene

V. Results

The transmission rates achieved for all simulation scenarios are summarized in Figure 6. One can note that for all cases the rates for the differential channels slightly differs from each other. This is related to the fact that the pairs have slightly different twist rates, causing differences in attenuation and crosstalk. Regarding the phantom channel, its rate changes from case to case and will be analyzed later.

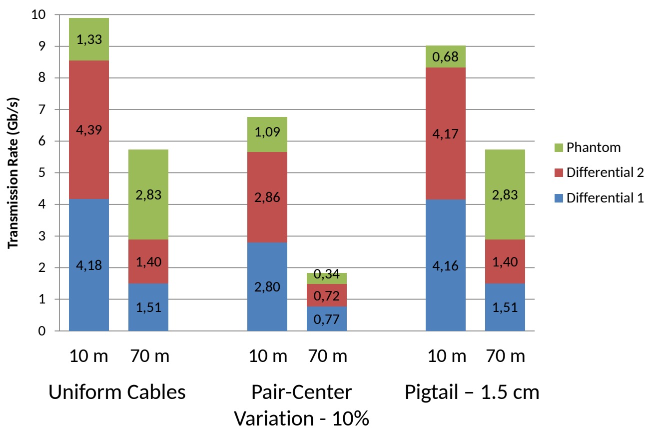

Fig. 6. Transmission rates for the simulation scenarios, cable length: 10 m and 70 m.

For the ideal test-case, the achieved aggregate transmission rates for 10 m and 70 m were 9.9 Gb/s and 5.75 Gb/s, respectively. It can be observed that the rates decrease as the cable length increases, but the phantom channel has a gain in performance. Such behavior can be explained from the gap between the transfer function (H) and the FEXT. When the cable length increases, it is expected that both H and FEXT curves decrease. However, one can see in Figure 7 that the decay for FEXT is larger than that for H, resulting in a larger gap between H and FEXT for 70 m. This fact increases the SNR, yielding a higher transmission rate for the phantom channel at 70 m.

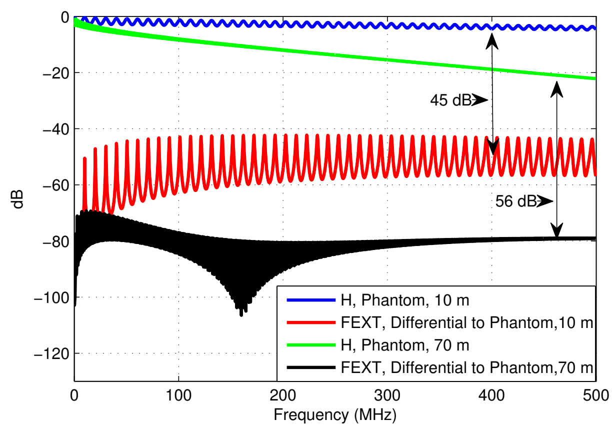

Fig. 7. FEXT curves from the differential channels to the phantom one for 10 m and 70 m, for uniform cables.

A variation on the center of the pairs causes a transmission rate reduction for both 10 m and 70 m (Figure 6). Such reduction is more prominent for 70 m when compared to the ideal case. This is expected because the impact of this kind of non-uniformity is proportional to the cable length, i.e. it is an accumulative effect. This effect also can be analyzed from the FEXT curves. The Figure 8 shows the electromagnetic coupling from the differential channels to the phantom one, where it is observed that the 70 m scenario is more affected than the 10 m one. It is important to point out that the Figure 8 presents a smoothed version of the FEXT curves as the original ones have oscillations due to impedance mismatch, making hard the analysis.

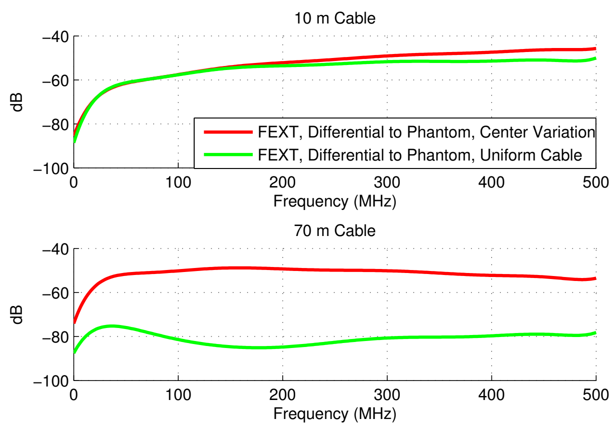

Fig. 8. FEXT curves from differential channel to phantom one for 10 m and 70 m – uniform cables and pair-center variation cases.

For the pigtail non-uniformity, its effect is negligible for 70 m when compared to the ideal case. This behavior is expected as the length of the untwisted part of the cable is a small fraction of the whole length. For 10 m it is noted that this kind of non-uniformity does not impact severely the differential channels, differently from the phantom channel. Other way to understand this is to check the FEXT curves from differential channels to the phantom one – Figure 9, which shows a smoothed version of the FEXT curves.

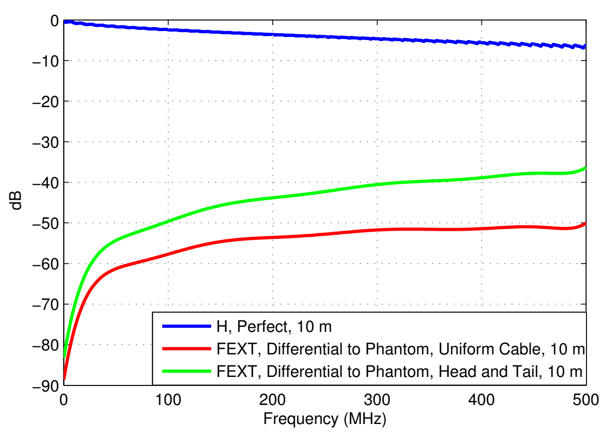

Fig. 9. FEXT curves from differential channel to phantom one for 10 m, for uniform cable and pigtail cases.

VI. CONCLUSIONS

This paper presented a study about the impact of cable non-uniformities on twisted pairs employing phantom mode. The analysis focused three scenarios using two non-uniformities: pigtail and pair-center variation. The obtained results indicate that a realistic data rate analysis for fronthaul should take into account the impact of cable non-uniformities.

For the ideal case, an increase on the aggregate rate was achieved for phantom channel, particularly for longer cables, which presents a better performance than that for differential channels. However, when non-uniformities are present the impact on performance is more evident for the phantom channel. Regarding the scenarios considering a variation on the center of the pairs, the data rates are more impacted for longer cables. On the other hand, the pigtail case impacts more on short-cable scenarios.

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REFERENCES

[1] 5G Radio Access, Ericsson White Paper, https://www.ericsson.com/res/docs/whitepapers/wp-5g.pdf, April 2016, last accessed Dec. 15, 2016.

[2] P. Lafata, "Estimations of G.fast transmission performance over phantom modes," *TSP, IEEE*, Prague, Czech Republic, July 2015, pp. 1–5.

[3] D. A. Gomes, G. Guedes, A. Klautau, E. Pelaes, and C. Lu, "DSL Phantom Mode Transmission: Cable Measurements and Performance Evaluation," *4th IEEE Latin-American Conference on Communications*, Cuenca, Ecuador, November 2012.

[4] M. M. M. Freitas, B. P. T. Sousa, D. D. Souza, D.D. Sales Junior, J. C. W. A. Costa. "Performance analysis for transmission in phantom systems in corporate environments," *XXXIV Simpósio Brasileiro de Telecomunicações - SBrT*, Santarém, Pará, 2016.

[5] W. Foubert, C. Neus, L. V. Biesen, and Y. Rolain, "Exploiting the phantom-mode signal in DSL applications," *IEEE Transactions on Instrumentation and Measurement*, v. 61, pp. 896– 902, April 2012.

[6] T. Gabara. "Phantom mode signaling in VLSI systems," *Conference on Advanced Research VLSI*, pp. 88-100, 2001.

[7] G. S. Borges, R. M. Rodrigues, J. C. W. A. Costa, A. Santos, and A. Fertner. "Effect of periodic cable nonuniformities on transmission measurements," *2015 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Pisa, Italy, May 2015, pp. 315–319.

[8] G. S. Borges, R. M. Rodrigues, V. D. Lima, K. Ericson, A. Fertner and J. C. W. A. Costa. *"Simulator of Nonuniformities in Twisted-pair Cables"*. Journal of Microwaves, Optoelectronics and Electromagnetic Applications, v. 13, pp. 29–38, 2014.

[9] P. Golden, H. Dedieu, and K. Jacobsen, *Fundamentals of DSL Technology*. Auerbach Publications, New York, USA, 2006.

[10] B. Lee, J. M. Cioffi, S. Jagannathan, K. Seong, Y. Kim, M. Mohseni, and M. H. Brady, "Binder MIMO channels," *IEEE Transactions on Communications*, v. 55, No. 8, pp. 1617–1628, August 2007.

[11] C. R. Paul, *Analysis of Multiconductor Transmission Lines*. Wiley-Interscience, NewYork, NY, USA, 1994.

[12] C. E. Shannon. "A mathematical theory of communication," *IEEE Transactions on Intrumentation and Measurement*, v. 27, pp. 379–423.