Channel Capacity Estimation of Power Grids in Multiple-Dwelling Units

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***Abstract*-Communication channel capacity for the residential power lines within multiple-dwelling units (MDU's) is evaluated to check for the potential use of power grid in shared broadband access. Several measurements of noise and attenuation in the HomePlug band (2 MHz-30 MHz) on actual MDU power grids are measured. Two different grid topologies are considered: Star and bus. They are the foremost grid topologies of buildings in urban, suburban and rural areas. Both in-phase and across-phase performances are measured. The individual effect of electricity meters inherently present across flat-to-flat path is also evaluated. MDU emulator has been built using meters only to measure the end-to-end frequency response of different meter types without cables. Finally, the obtained results are used to calculate the theoretical channel capacity for the different configurations of MDU grid with and without the effect of meters.**

The capacity of power line at all test locations selected is found far above the targeted data rates for broadband distribution and sharing. Capacity in the range of 300 - 400 Mbps is common in MDU's with 2-3 floors span between transmitting and receiving nodes, which implies a total span of 5-6 floors when selecting the position of internet gateway carefully. It has also proved that the decrease in link capacity due to the existence of 2 electricity meters in between sender and receiver has an average value of 14 %, while the effect of normal cable distance within home could reduce link capacity by more than 35%.

Keywords- Power Line Carrier; Shared Broadband Access;Channel Capacityt; HomePlug Applications

I. INTRODUCTION

Statistics in most developing countries still show very low broadband penetration rates [1, 2]. However, the reality is somewhat less pessimistic. Many more people gain Internet access through sharing connection with others [1]. This model of internet access is particularly common in emerging and developing countries. Despite its fast growth, the method of sharing broadband still lacks the appropriate access configurations. Local Area Network (LAN) cables' model implies using a switch connected to the internet gateway (IG), which in this case is a DSL or 3G router. While LAN cables are the most reliable method of BB distribution in terms of link performance and bandwidth, their deployment implies modification in the infrastructure, civil work and time.

On the other hand, Wireless LAN (WLAN) is used where fast network deployment with minimal infrastructure alteration is required. WLAN is also the most optimum in terms of user mobility. Nevertheless, WLAN has its own limitations compared to cables. Free-space path-loss and penetration loss are one of the major factors that limit the usage of WLAN on large distances for indoor applications. WiFi also suffers from a rather more serious problem which is spectral pollution. The WLAN band (2.5 GHz and 5.8 GHz) is used by many incompatible devices and standards like DECT phones, Bluetooth, Wireless LAN's, Wireless sensors, etc. Very simple tests have been performed to show the severity of the problem by measuring the maximum data rate in almost perfect conditions, and have been found far below the standard [3].

Utilizing the existing power grid as a communication medium is a configuration applied for years for its distinctive advantages. The idea dates back to the 80's, and it is generally denoted as power line carrier (PLC). Common PLC modes are confined to two main configurations: Home Networking and Broadband over Power Line (BPL). Home Networking applications include broadband access and home automation, and generally work on the indoor low-voltage power grid [4]. On the other hand, BPL works on the medium voltage transmission lines used in electricity distribution, and it is mainly used as an access technique.

Previous work contains several efforts towards characterizing the power line medium as a communication channel. In [5], a single-parameter deterministic model for indoor power line up to 100 MHz has been demonstrated. The ordinary variance in power line channel characteristics due to variable loading conditions is represented by a single parameter which differentiates between urban, sub-urban and rural areas. The coherence bandwidth and time delay of indoor power line at the frequency range 2 MHz – 30 MHz was evaluated in the second part of this study [6], based on different measurements done at France Telecom lab in Lannion, France.

The results of [5, 6] provide valuable information for modem designers on how to split operating frequency band to a set of coherent sub bands. However, all the measurements are conducted in sites representing single house or apartment. Thus the home-to-home and the effect of electricity meters are not covered in those studies. Also the classification is based on the nature of loads and grid in France, which are generally different from those existing in other developing countries, where nature of buildings, loading profile, regulatory standards controlling appliances noise and grid quality are considerably different.

In [7], an algorithm is proposed to evaluate the channel frequency response on indoor power line. However, the model considers only the impedances of the loads, without consideration of noises arising from those loads, which affect the capacity drastically.

The approach followed in [8] to estimate the channel capacity is the closest to what is demonstrated in this paper. Measurements of transfer characteristics and colored channel noise are provided, and then a water-pouring algorithm is applied to calculate channel capacity. Capacities in excess to 1 Gbps are shown to be achievable with 30 dBm transmitted power over a transmission bandwidth of 99 MHz. Nevertheless, the measurements are conducted at typical cable lengths of 20 meters, as the scope is characterizing the PLC in a single apartment. Also the capacities are calculated over a bandwidth of 99 MHz, which is much larger than the targeted range most used by typical PLC modems (2-30 MHz).

The objective of the current work is to study the possibility of using the power grid within a multi-story building or multiple dwelling units (MDU's) as a medium for broadband sharing. Although the concept appears to be a direct extension to the Home Networking case, the MDU-PLC model differs from the two well-studied aforementioned models in several aspects that justify an ad-hoc study. Firstly, the range to be covered in MDU-PLC configuration is wider than the Home Networking case (50 meters), but far less than the BPL case (3-4 km). Secondly, the existence of electric energy meters across the flat-to-flat paths adds more uncertainty to the behavior of the power grid in the working band. Thirdly, while grid topologies for home networking and BPL are tree-like and point-to-point, respectively, the topology for MDU could be one of two main types: Star and bus. The propagation between flats and floors is greatly affected by the building topology, and consequently the communication performance. Moreover, in broadband sharing, the speed is limited by the speed of the IG, which is in general lower that 4 Mbps in the majority of emerging countries. Therefore, striving to obtain a distribution scheme of speeds above this value doesn't make sense. In other words, speeds that are not acceptable in applications like IPTV and video streaming may be enough for many other less-demanding applications common in emerging countries including web surfing, mail access, and VOIP.

In this study MDU power grid is characterized and analyzed in typical areas where shared broadband model is potentially applied. The characterization process addresses the theoretical limits of the MDU power grid, including all factors that discriminate the model from the other two well-established PLC models which are PLC and BPL. These factors include cable lengths, MDU grid topology, and existence of electricity meters across signal path from flat to flat. Thus, this study serves as a Go-No Go indicator to consider building power grid as a possible candidate for sharing broadband.

The rest of the paper is organized as follows: Section II describes the test setup used as well as test cases and locations where measurements are performed. Section III presents the channel measurement results, together with comments on the major key findings. Effect of electricity meters on the end-to-end characteristics is discussed in details in Section IV, while the capacity calculations for different configurations are presented in Section V. Section VI gives conclusions.

II. TEST SETUP AND TEST CASES

Fig. 1 illustrates the test setup used to characterize power lines within MDU. Due to higher dynamic range and spectral pictorial view, frequency domain measurements are more significant in characterization. Furthermore, channel capacity could theoretically be calculated from only frequency domain measurements [9]. Therefore, time domain measurements are not considered in this study.

The coupling circuit is a key element of both test setups. Its main role is to act as a bidirectional high-pass filter to pass high frequency signals to/from power line, and reject the 220v-50Hz power signal from reaching the device front-ends. The schematic of the coupling circuits used is illustrated in Fig. 2.

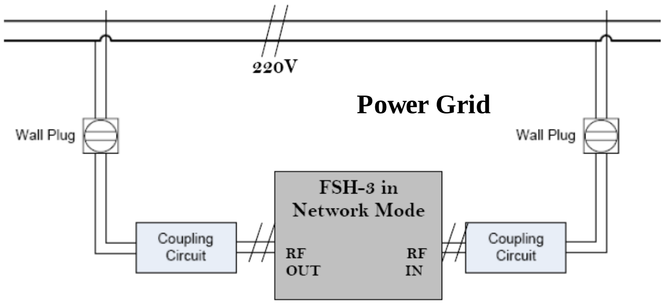

Fig. 1 Test setup for MDU grid characterization

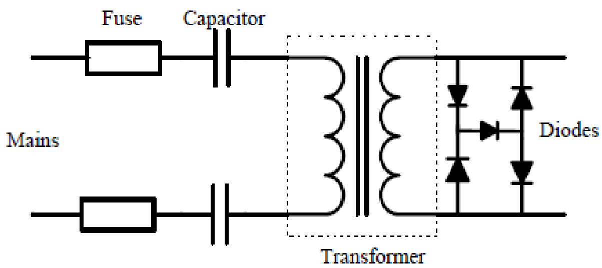

Fig. 2 Schematic diagram for the coupling circuits

Measurements are performed in the following locations and conditions:

1. office environment, light and normal loading.
2. MDU, urban area, normal and heavy loading, In-phase and across-phase.
3. MDU, sub-urban area, normal loading.
4. between 2 flats in MDU, urban area, bus topology.
5. between 2 flats in MDU, suburban area, star topology.

The test setup has been used to measure noise at several wall plugs, as well as transfer characteristics between a pair of plugs in two different locations. Wherever the distance between the two plugs is large, long RF cables are used. A calibration process is followed prior to the measurements of transfer characteristics to account for cable attenuation and self response of the coupling circuits. Instead of tracking the noise generated from each type of loads connected to the line, an averaging approach is used. Each noise and transfer characteristics consists of a time average of 100 measurements at the same location.

III. MEASUREMENTS OF NOISE AND ATTENUATION

Noise measurements are done at test locations in different times and loading conditions. 100 measurements are recorded. At every frequency slot, noise records are marked for the maximum, minimum and average values as in Fig.3

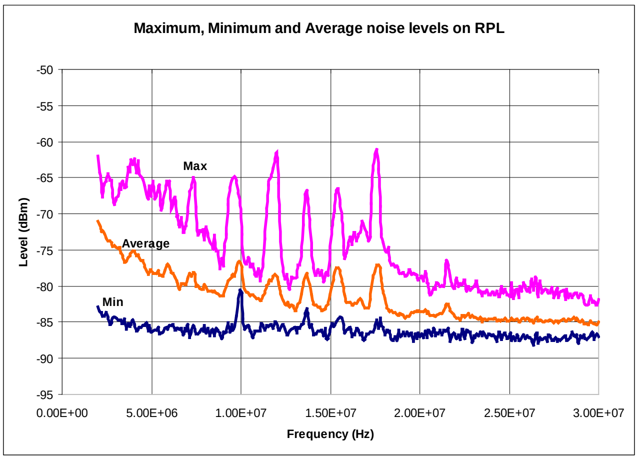

Fig. 3 Maximum, minimum and average of noise at different test locations

From the measured noise traces, the following features could be noticed:

1. Noise at the selected frequency band is a mixture of wide-band noise, and narrow-band noise.
2. Wide-band noise, in general, decreases with frequency.
3. MDU's supplied from aerial grid supply is more prone to pick narrow-band interference (band between 10 and 20 MHz in Fig. 3.) This may be justified by the more susceptibility of aerial lines to act like antennas that receive in-band RF signals.
4. The band between 20 MHz and 30 MHz undergoes the minimum variance of noise level among different locations. Differences less than 10 dB min noise floor, and very low level of narrow-band interference are observed.

To completely characterize the power line channel, channel frequency response should also be evaluated. The objective is to cover the potential configurations of applying the shared broadband model, and predict the performance of those configurations. Therefore, only flat-to-flat responses for both star and bus topologies are considered in this work. Fig's 4 a, b illustrate the two MDU topologies considered for frequency response measurements. In Start opology, all meters exist in one central point, usually at the ground floor, and separate cable connects power to each apartment. In Bus topology, a distribution cable is tapped at each floor and the meter is fixed at the entrance of each apartment. Similar to noise, the magnitude response measurements represent the time averages of frequency responses throughout different loading and grid conditions. Typical magnitude responses are represented in Fig. 5. Only four cases are illustrated for convenience.

For bus topology, it is obvious that increase in span between transmitter and receiver implies increase in attenuation, which will imply decrease in achievable capacity, as will be shown quantitatively on next sections.

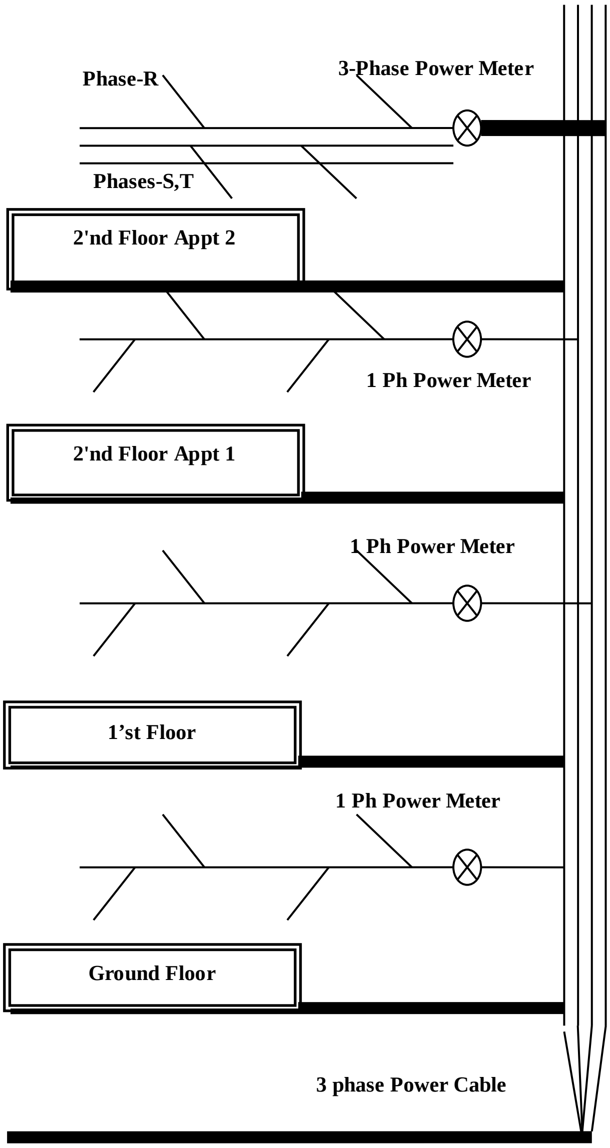

Fig. 4-a Power line topology in a typical MDU's: Bus topology

The results obtained for star topology case are remarkable. The transfer characteristics enhances with frequency, although non-monotonically. This could be justified by the topology of power cables in star case, in which cables for each flat are separate but run close to each other (Fig. 6). Therefore, parasitic capacitances between cables result in enhanced coupling at higher frequencies. In addition, the difference in performance between new buildings (less than 5 years old) and old buildings (more than 50 years old) is found insignificant.

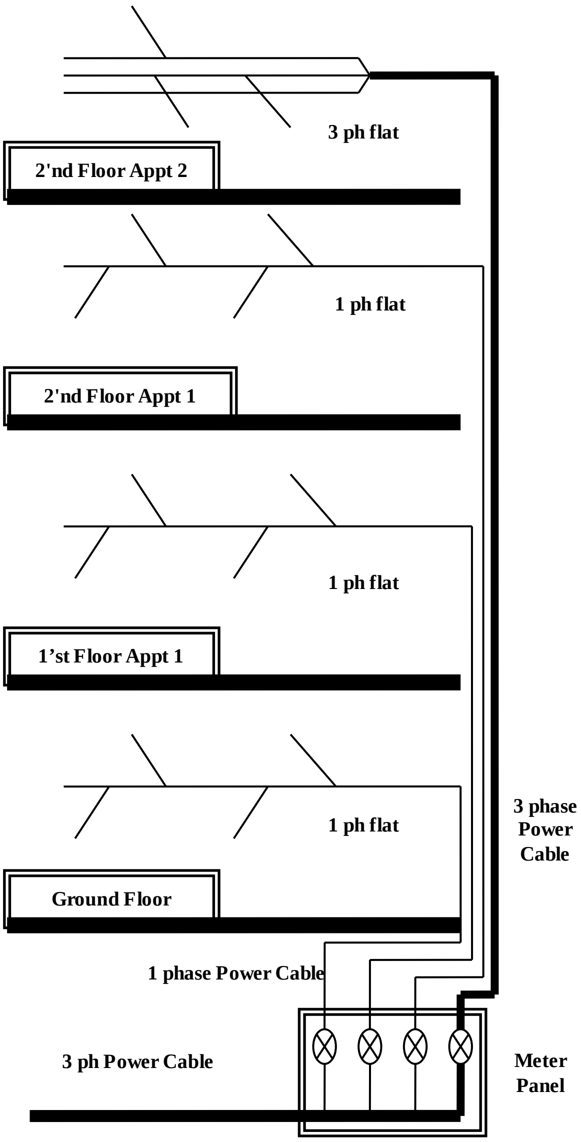

Fig. 4-b Power line topology in a typical MDU's: Star topology

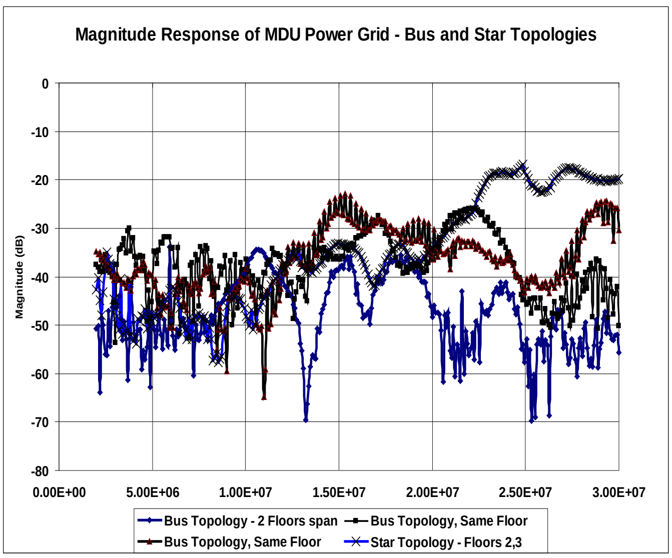

Fig. 5 Transfer characteristics within MDU –Bus and star topologies

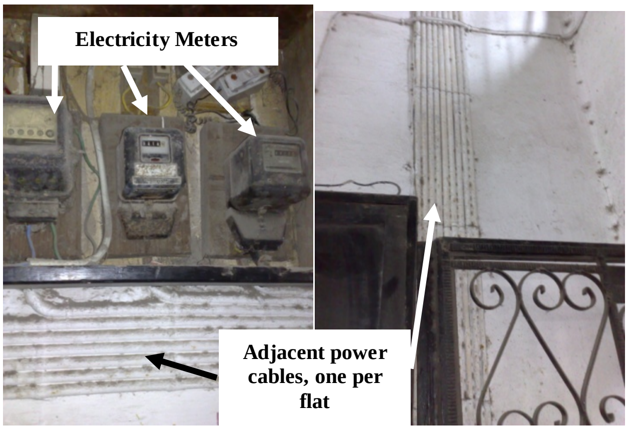

Fig. 6 MDU power distribution in star topology case

IV. EFFECT OF ELECTRICITY METERS

One of the major differences between MDU-PLC and home networking PLC is the existence of electricity meters along the signal path. In shared broadband access, and considering the topologies shown in Fig's 4-a,b the internet gateway (IG) will be installed in one of the flats, and the end users are in some other flats within the MDU. It is clear that CPL signal has to bridge 2 electricity meters while being exchanged between the IG and the terminal of each end user. Therefore, studying the response of electricity meters to the PLC signal is crucial to estimate their effect on signal attenuation and hence the link throughput.

At the beginning of this work, and to validate the concept of using PLC within MDU, several inquiries have been made to the following parties: France Telecom CPL Lab, Devolo, Corinex, Intellon (Atheros) [10] on the impact of electricity meters on the HomePlug signal. The replies imply that the usage of current power line modems at those configurations is not common, and there is a general impression that the existence of meters will severely attenuate the signal. Those non-quantified answers call for ad-hoc study on electricity meters' effect, especially when considering the fact that the types of meters in emerging countries (Mechanical – Disc Type) could differ from that used in Europe and US (digital meters in many cases). We ought to perform tests on the most common types of meters, and measure their contribution on the end-to-end attenuation profile experienced in previous section.

In this section, the contribution of meters to the end-to-end magnitude response between different flats in the MDU will be addressed. A complete test setup for a simple MDU is built using only different types of meters and artificial loads. The end-to-end response has been measured. This response constitutes the *upper-bound* on transfer characteristics appeared within the MDU, as it addresses only the effect of meters and doesn't include the effect of cable lengths. Upper bound for the channel capacity could be calculated using the results of this setup.

Fig. 7a shows test setup used to measure end-to-end response in a typical MDU. Three types of meters have been used in this setup, which are selected to emulate the most common types in residential MDU's: Single-phase mechanical, single-phase electronic and three-phase mechanical. The main power supply of the setup is provided from a three-phase distribution panel shown in Fig. 7b. To minimize the effect of noise on those measurements, free connections to the distribution panel have been selected. The circuit diagram for the test setup is provided in Fig. 8.

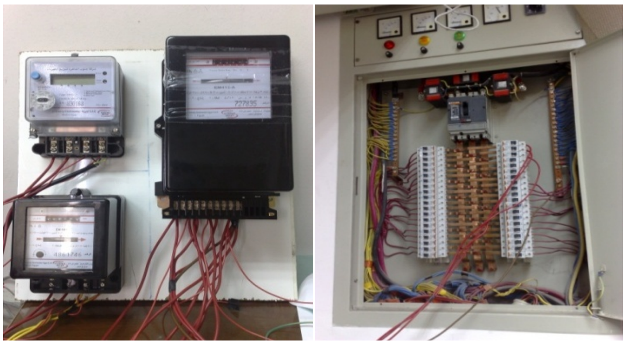

Fig.7(a) MDU emulator for end-to-end test setup, (b) Three-phase supply for the setup

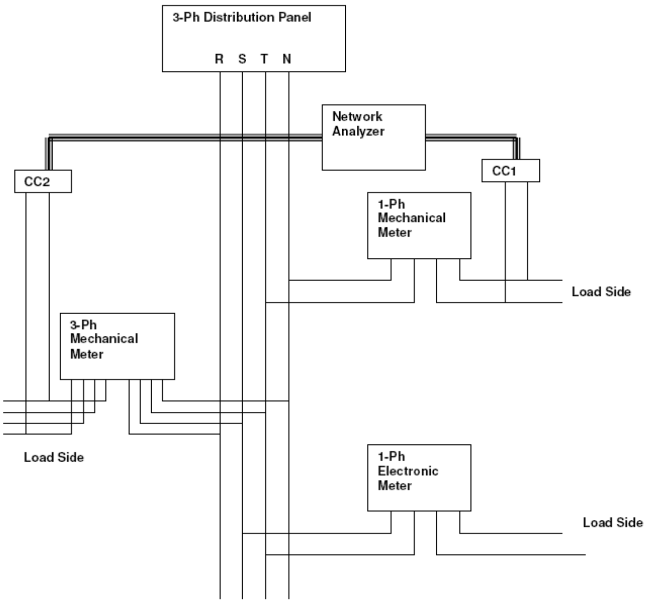

Fig. 8 Test Diagram for measuring meters' end-to-end response

Fig. 9 illustrates the end-to-end magnitude responses measured using the MDU emulator shown above. Also one of MDU measurements obtained before is plotted against end-to-end measurements for comparison. It is clear that the attenuation due to meters is in most cases less than attenuation due to cable distance, and the contribution of meters to the overall transfer characteristics is not major compared to cable attenuation and power splitting to loads. Actually the effect of meter attenuation could be accounted for by installing the modem at the nearest socket to the electricity meter.

V. CHANNEL CAPACITY CALCULATIONS

The measurements presented so far don't clearly reflect direct impact to CPL performance within MDU as a broadband distribution technique. To be more related to what really concerns technology providers, the previous measurements should be used to estimate a single quantitative value that characterizes the "quality" of the channel. This value reflects the utmost performance or an upper-bound of the PLC system operated over this channel. This quantity is the channel capacity. For a given channel of bandwidth B, AWGN of power N and transmitted signal power S, channel capacity is given by [11]:

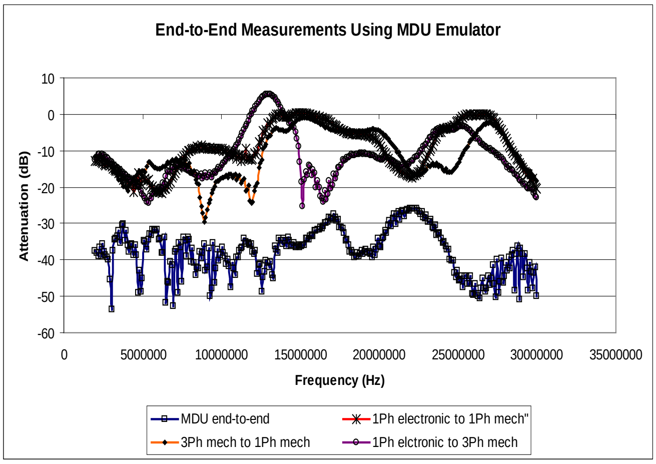

Fig. 9 Transfer Characteristics in end-to-end test using MDU emulator

$$C = B\log_2(1+\frac{S}{N}) \tag{1}$$

If both S and N are not constant allover the operating bandwidth B, the channel is divided into N sub-channels, where S and N could be considered constant with frequency within the sub-channel. In this case, capacity is given by:

$$C_i = B_i \log_2(1+\frac{S_i}{N_i}) \qquad C = \sum_{i=1}^{N} C_i \tag{2}$$

Thus to calculate the channel capacity, both noise and received signal power at each sub-channel should be measured. Maximum allowable transmitted power at HomePlug BW (2-30 MHz) is bounded by the Homeplug standard to -50dBm/Hz [12]. Therefore, the following process is used to get the channel capacity.

1. Band from 2 to 30 MHz is divided into 300 buckets or sub-channels, sub-channel BW= 93333.33 Hz.Transmitted signal power is calculated according to the formula:

$$P = psd \times BW = -50dBm \times 93333.33Hz = -0.3dBm \tag{3}$$

2. Received signal level is obtained by subtracting transmitted power (dBm) from magnitude response (dB).
3. Noise has been normalized with respect to *resolution BW* of the spectrum analyzer to be in dBm/Hz then in dBm again with respect to bucket size.
4. Signal-to-noise (SNR) per slot is calculated and hence sub-channel capacity.

5. Total capacity is summed to give the total channel capacity.

To cover the whole range of possible capacity values, 14 different noise measurements and 25 magnitude measurements are used alternately to give 350 different capacity values. Those 350 calculated values are then classified to five different categories according to the measurement location and conditions:

1. in-Phase (IP);
2. across-Phase (AP);
3. MDU with bus topology grid (MDU-Bus);
4. MDU with star topology grid (MDU-Star);
5. MDU Emulator from load side to load side (E2E).

Another group of capacity (14 values), which is denoted "MAX", is calculated according to each of the measured noise processes. In those calculations, transfer characteristics are considered perfect (0 dB), and only the contribution of transmitted power and noise determines the final capacity. Those values are considered the *capacity ceiling* that could be reached given a certain noise profile. The 350 test cases are classified according to the 6 aforementioned categories, and the different capacities for each category are illustrated in Fig. 10. At all the cases, the capacity is greater than the maximum physical rate announced by HomePlug-AV, (200 Mbps). This means that in more than 9 different test sites and conditions within an emerging country dense area, and with the variant grid status, the channel is still not the limiting factor towards increasing the data rate. Of course this will not be achieved without clever modulation and coding techniques, but at least no theoretical limitations exist to achieve that. Besides, this means that the grids in emerging countries still have room to benefit from further enhancement in HomePlug standard, which are in the research phase now.

The average decrease in capacity at each of the five categories compared to the capacity ceiling is shown in Table I below. The numerical figures are the average values evaluated on the whole measurements for each class. This table contains many remarkable results regarding the effect of each configuration on the resulting loss in capacity. MDU-BUS introduces the maximum loss in capacity. This result is expected as in this case, the effect of meters and cable attenuation are both present, while the cable configuration doesn't imply any overlapping between cables, which doesn't help at high frequency as in STAR case. Due to good coupling at high frequencies, the flat-to-flat response in MDU-STAR is better than in bus case, although going over longer signal path.

The loss value in E2E class obtained using MDU emulator is of special importance. As the emulator accounts only for meters effect, the average loss in capacity due to meters only is about 14%, which is only one third of the loss in MDU-BUS case. This again proves the result that meter effect is not major in terms of inhibiting PLC signal from propagating from flat to flat within the MDU.

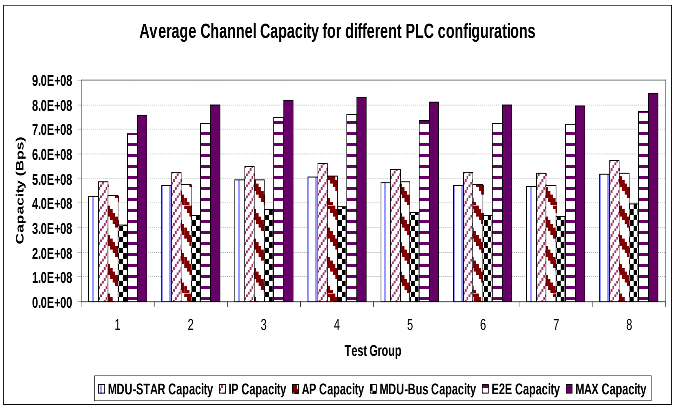

Fig. 10 Calculated channel capacity for different MDU PLC configurations

TABLE I CAPACITY DECREASE COMPARED TO THE CAPACITY CEILING IN EACH CLASS

Class	Capacity / Maximum Capacity
MDU-STAR	0.611589002
IP	0.635179853
AP	0.571166185
MDU-BUS	0.524237089
E2E	0.864100232

Another figure obtained from the results is related to the distribution of the capacity over frequency. The total capacity is the summation of all sub-channel capacities covering the range from 2-30 MHz. The capacity of each sub-channel depends on its own noise floor and received signal power. Thus addressing the contribution of each frequency band to the total capacity is important. Of specific significance is the percentage of the capacity gained in the BW from 20 MHz to 30 MHz relative to the total capacity, as it represents the gain expected from using HomPlug AV modems compared to HomePlug modems, as the later operates up to 20 MHz only. This analysis has been done on each of the 5 categories, and the results are collected and illustrated in Table II below. Note that in MDU-STAR buildings, the channel response enhances at higher frequencies. Therefore, capacity from 20 to 30 MHz, which is almost one third of the total BW under test, carries almost half of the total capacity. In terms of commercial PLC modems, we can predict great enhancement in performance when using HomePlug-AV compared to HomePlug, as the later works up to 20 MHz only.

TABLE II PERCENTAGE OF CHANNEL CAPACITY IN THE BAND 20-30 MHZ TO TOTAL CAPACITY

Class	Capacity (20-30 MHz) / Capacity (2-30MHz) %
MDU-STAR	47.130602
IP	41.43409644
AP	41.23243001
MDU-Bus	36.61891883
E2E	37.90174039

VI. CONCLUSIONS

In this paper, the electrical grid of multiple dwelling units (MDU's) is characterized for use in power line communications (PLC). The medium is checked for possible usage of the building electrical grid for broadband sharing using HomePlug and HomePlug-AV modems. MDU-PLC is considered a more efficient and less expensive alternative to WiFi and LAN cables in broadband sharing. The study can lead to the following conclusions:

1. MDU-CPL is a configuration for distributing broadband access over a building using the building power grid, as an alternative to Wi Fi and LAN cables. It has the advantage of fast setup time, no access to infrastructure, and consistent performance.
2. MDU's powered from aerial cables are likely to pick up higher power line noise than under-ground cables. However, noise between 20 MHz and 30 MHz is almost flat and has a minimum variance with location.
3. MDU-STAR has better transfer characteristics than MDU-BUS for the same umber of floor spans due to the parasitic capacitance associated with building grid topology.
4. Across-phase performance is so close to the in-phase performance, which reflects good coupling between phases.
5. Contrary to the initial impression, meters have little impact on performance of HomePlug modems. Only 14% average decrease in system throughput is expected.
6. The main limiting factor of MDU-CPL is the attenuation due to cable distance. This will gradually decrease system throughput as the distance between IG modem and end user increases.
7. HomePlug-AV is expected to give higher performance compared to HomePlug modems in both MDU-STAR and MDU-BUS buildings. However, the difference in performance is expected to be more in case of MDU-STAR.

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