Measurement of Hybrid PLC-wireless Channels for Indoor and Broadband Data Communication

Thiago R. Oliveira, Fernando J. A. Andrade, Luis Guilherme da S. Costa,
Michelle S. Pereira and Moises V. Ribeiro

***Abstract*— This work aims at discussing a measurement campaign carried out in a residential apartment to measure hybrid PLC-wireless channel. The hybrid PLC-wireless channels is the one that allow portable devices and devices physically connected to electric distribution grids to communicate with each other. Also, it is presented a capacitive coupling device designed to carry out the measurement campaign. The analysis of such hybrid PLC wireless channels addresses the magnitude of the channel frequency response and covers the frequency band from 1.7 up to 100 MHz. The presented results show that the hybrid PLC-wireless channels is symmetric and the magnitude of the channel frequency response can vary from -80 up to -10 dB if a omnidirectional antenna is used by the portable device.**

***Keywords*— Hybrid channel, power line communication, wireless, channel measurement.**

I. Introduction

Broadband power line communication (PLC) technology is very attractive for providing telecommunication infrastructure for access networks and smart grid communication because electric power grids are ubiquitous and the cost for deploying a PLC system is between 40% and 60% lower than the costs associated with other broadband technologies [1], such as xDSL, TV cables, WiMAX, and so on. Currently, there are commercial PLC technologies that surpass 500 Mbps at the physical layer. Additionally, PLC could result in lower radiation effects on human being because it can transmit low-power in the frequency band, i.e., from 0 up to 500 MHz.

Electromagnetic interferences, time-varying loads, and impulsive noises are the main problems that must be dealt with to push forward the new and improved generation of PLC technologies. Additionally, we point out that the devices constituting a PLC network (modem, repeater, relay, gateway, etc) must to be physically connected to the electric power grids, what makes impossible the mobility of devices connected to PLC networks. However, if the power lines could be seen as antennas, then wireless and portable devices, which are supposed not to be physically connected to the electric power grids, could eventually transmit or receive data from or to the devices connected to the electric power grids.

In this context, the concept of hybrid PLC-wireless channel arises. The central idea of such channel, as it was firstly presented in [2], is to consider the PLC and wireless channels as only one. In such scenario, a PLC device transmits a signal through the power lines, which are supposed to be unshielded, then the irradiated signals can be sensed and interpreted by a wireless and portable device. On the other hand, the wireless and portable device irradiate a signal that can induce a voltage in the power lines and, finally, be sensed and interpreted by a PLC device. Such idea is illustrated in Figure 1.

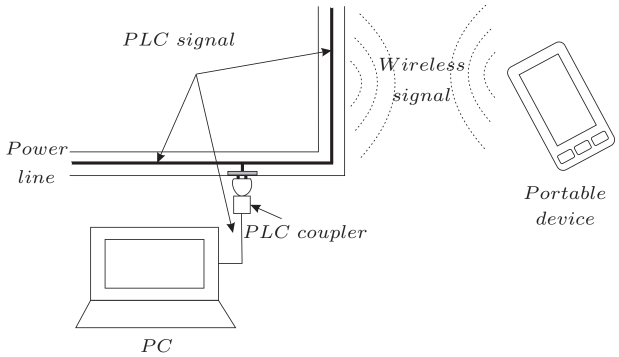

Fig. 1: The hybrid PLC-wireless environment.

We can point out that the hybrid PLC wireless channel is a challenging and interesting issue to be pursued because it can result in a hybrid communication infrastructure that is constituted by fixed and portable devices and it can eventually constitute a telecommunication platform for Internet of things. Although the features of PLC and wireless channels are well-addressed in the literature [3], some efforts are needed to characterize such hybrid PLC wireless channels in order to support the development of hybrid communication systems that allow maximize the use of the available resource among the users.

In this regard, this contribution focuses on a measurement campaign carried out in an residential apartment to characterize the hybrid PLC-wireless channel – by means of the channel frequency response – by covering the frequency band from 1.7 up to 100 MHz. A measurement setup and a capacitive PLC coupler are presented. Also, a statistical analysis of the measured offer valuable insights about the expected attenuation in such kind of channels. Finally, it is shown, different from what was initially presented in [2], that the hybrid PLC-wireless channels are symmetric ones.

This work is organized as follows: Section II describes the measurement arrangement used in the measurement campaign. Section III provides information about the environment where the campaign was performed. In Section IV some results are presented and discussed. Finally, Section V presents the

Thiago R. Oliveira is with IFSEMG - Federal Institute of Education, Science and Technology of the Southeast of Minas Gerais, Campus Juiz de Fora, Brazil. Fernando J. A. Andrade, Luis Guilherme da Silva Costa, Michelle S. Pereira and Moises V. Ribeiro are with Electrical Engineering Post Graduation Program at the Federal University of Juiz de Fora, , Brazil. E-mails: thiago.oliveira@ifsudestemg.edu.br; fjaandrade@engenharia.ufjf.br; luisgsc@oi.com.br; michelle.soares@engenharia.ufjf.br; mribeiro@ieee.org.

conclusions of this work and some directions for future works.

II. Measurement Setup

The frequency response of the hybrid PLC-wireless channel is estimated by using a technique based on sounding method [4]. Basically, an signal $x(t)$ is injected into the channel input and a signal $y(t)$ is extracted at the channel output. Thus, after applying some signal processing tools in the discrete time representations of the transmitted and received signals, $x[n] = x(t)|_{t=nT_s}$ and $y[n] = y(t)|_{t=nT_s}$, respectively, where T_s is the sampling period, then estimates of the hybrid PLC-wireless channels are obtained.

The discrete version of the transmitted signal is designed off-line to be composed of Orthogonal Frequency Division Multiplexing (OFDM) symbols, in such a way that occupy the frequency band of interest. The procedure for signal generation as well as the signal processing tools applied for estimating the channel transfer function are described in [5].

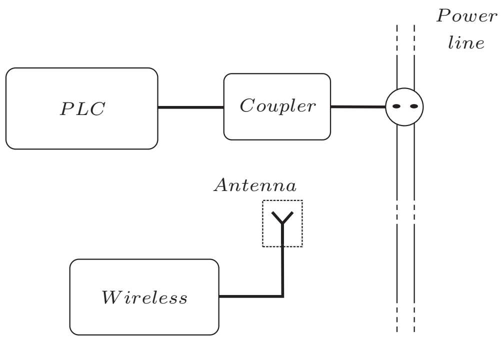

Fig. 2: The block diagram of the measurement setup.

The use of sounding method to estimate hybrid PLC wireless channels requires the development of a measurement setup that, in our case, is constituted by the following equipment:

i) rugged and portable personal computers;
ii) capacitive PLC coupler covering the frequency band between 1.7 and 100 MHz,
iii) data acquisition board with analog to digital converter (ADC) of 16 bits resolution at the maximum sampling rate of 200 Msps,
iv) data generation board whose digital to analog converter (DAC) of 14-bits resolution at the maximum sampling rate of 200 Msps,
v) omnidirectional antenna covering the frequency band between 1.7 and 100 MHz.

The block diagram of the measurement setup is shown in Figure 2.

The data acquisition and generation boards are installed in the personal computers and the PLC coupler as well as the antenna are connected to the channels of the both boards. Furthermore, depending on the data transmission direction ($PLC \rightarrow wireless$ or $wireless \rightarrow PLC$), the wireless and PLC blocks in the Figure 2 represent the data acquisition or the data generation board. The combination of the personal computer, the data generation (acquisition) board and the capacitive PLC coupler acts as the fixed Tx (Rx) device, while the arrangement constituted by the personal computer, the data acquisition (generation) board and the omnidirectional antenna represents the portable Rx (Tx) device.

The generation board is loaded with the discrete time domain representation, $x[n]$ of signal $x(t)$ that was specifically designed to be transmitted. Then, the signal $x(t)$ at the DAC channel output is inject into the channel input, by means of the capacitive PLC coupler or the omnidirectional antenna. The omnidirectional antenna and capacitive PLC coupler that is connected to the data acquisition board provides the signal $y(t)$, which is at the output of the hybrid PLC wireless channel. Finally, the ADC channel offers at its output the signal $y[n]$, which is the discrete time domain representation of the signal $y(t)$. The capacitive PLC coupler designed to interface the boards with the low-voltage and electric power grids is described in Section II-A.

A. Capacitive PLC Coupler

Usually, the coupling circuit acts as a high pass filter, blocking the main voltage signal (50/60 Hz) that could damage equipment. In fact, the equipment used to estimation of the hybrid PLC wireless channel frequency response were design to deal with very low amplitudes signals, of the order of some hundreds of milivolts. Additionally, it is expected that the coupling circuit present a flat magnitude of its frequency response. By taking both assumption into consideration, then a capacitive PLC coupler that covers the frequency band from 1.7 up to 100 MHz was designed.

This capacitive PLC coupler is composed of a shunt capacitor connected to a $1:1$ RF wideband transformer to provide filtering, protection and galvanic isolation [6]. The capacitor works as high-pass filter cutting the main voltage signal in the electric power grids. Due to the fact the frequency up to 100 MHz is considered, then special attention has been given to design the Printed Circuit Board (PCB) [7] to address electromagnetic compliance, ground plane and transmission line. The prototype of such PLC coupler is shown in Figure 3. Figure 4 shows the magnitude of the frequency response of the designed capacitive PLC coupler.

Fig. 3: The prototype of the capacitive PLC coupler.

III. Measurement Campaign

In this work, the characterization of the hybrid PLC wireless channel was performed in a typical middle-class apartment located in a residential area in the city of Juiz de Fora, Brazil. The scenario is similar to many households in Brazil. The

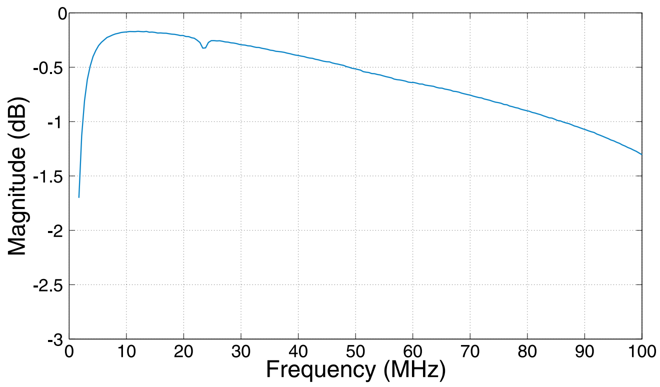

Fig. 4: the capacitive PLC coupler: the magnitude of the frequency response.

total area is about 48 m^2 and includes two bedrooms, two bathrooms, a living room, a kitchen and a service area.

A sketch on a scale ($\approx 1:80$) of the apartment is portrayed in Figure 5. For the sake of simplicity, it is shown only the outlets that were used to connect the measurement setup. These outlets are denoted by A, B, C, and D arrows. The fixed Rx or Tx devices are connected to the outlets.

The portable Rx and Tx devices are positioned in different locations indicated by a circle. Each circle has a letter followed by a number inside it. The letter and the number indicate the corresponding outlet and position associated to the measured hybrid PLC-wireless channel.

IV. Results

For the measurement campaign was assumed that $f_s = 1/T_s = 200$ MHz in the data acquisition and generation boards. The transmitted signal is a sequence of 4096-length OFDM symbols (2048 subcarriers and accuracy equal to 48.8 kHz) and 1024-length cyclic prefix. It is important to mention that each received symbol provides estimates that can be severely corrupted by the noise enhancement yielded by the estimation process. To reduce this undesirable effect, it is applied the technique discussed in [8] because it results in enhanced estimates of the frequency response with respect to the noise.

A. *Frequency response*

Figure 6 presents estimates of the frequency response of hybrid PLC wireless channels considering all outlets, when the signal is transmitted by the portable Tx device and received by the fixed Rx device connected to one of the listed outlets ($wireless \rightarrow PLC$ direction). Figure 7 depicts the magnitudes of frequency responses in the opposite direction.

We note that the hybrid PLC wireless channels show similar frequency responses in both direction indicating that they are symmetric. This results could be attained before because, different from [5], the capacitive PLC channel was very well designed. Except for the case of the outlet B, the hybrid PLC wireless channel is less subjected to attenuation in the frequency band between about 40 and 60 MHz and

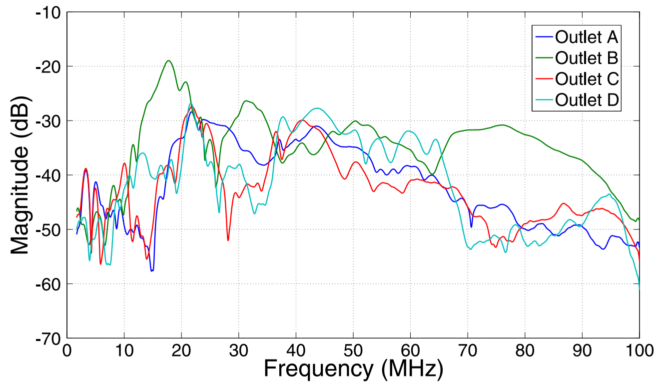

Fig. 6: The estimates of magnitude of the frequency responses of hybrid PLC wireless channels in the $wireless \rightarrow PLC$ direction.

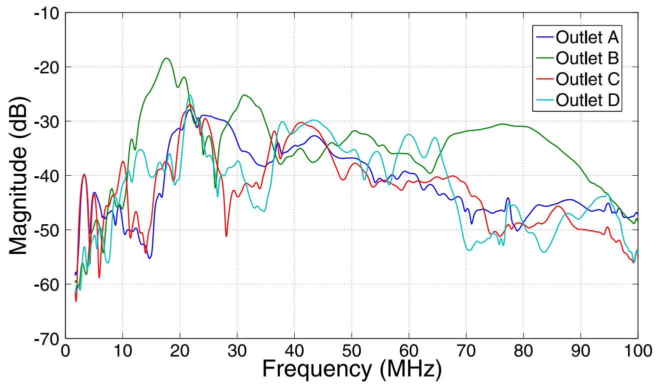

Fig. 7: The estimates of magnitude of the frequency responses of hybrid PLC wireless channels in the $PLC \rightarrow wireless$.

the frequency response is much more flat then in the other frequency bands.

The investigation of the influence of the antenna location is presented in Figure 8 and Figure 9 that show the channel frequency response for the different locations of the antenna and only one outlet.

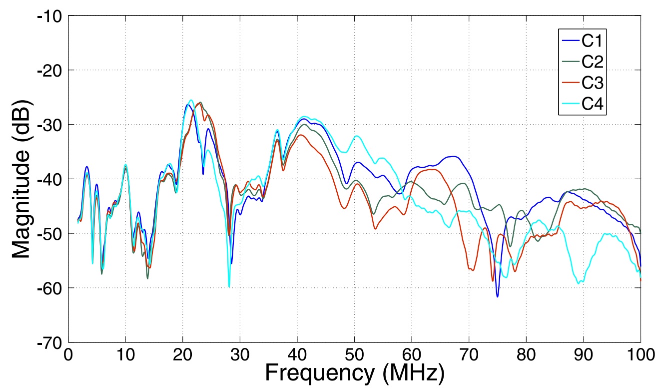

Fig. 8: The estimates of magnitude of the frequency responses of hybrid PLC wireless channels in the $wireless \rightarrow PLC$ regarding the outlet C.

It can be noted that, in so far as the frequency increases, it is

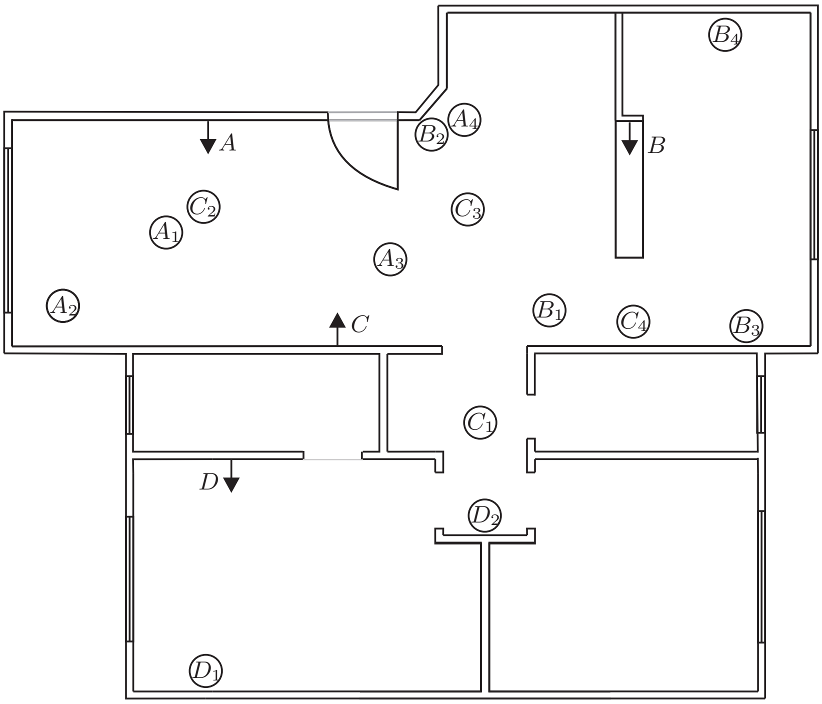

Fig. 5: The layout of the apartment.

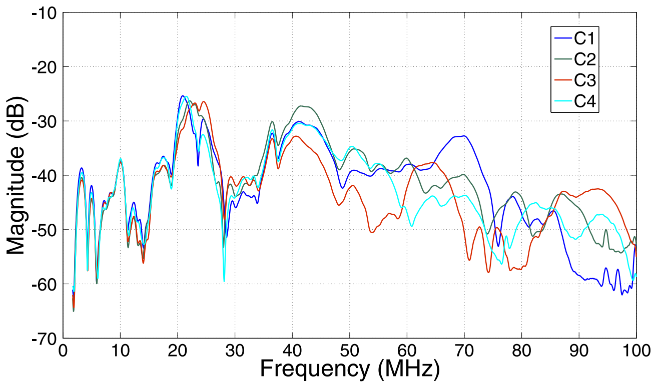

Fig. 9: The estimates of magnitude of the frequency responses of hybrid PLC wireless channels in the $PLC \to wireless$ regarding the outlet C.

clear that the antenna position affects the channel frequency response. In other words, for high frequencies the channel frequency response – in terms of magnitude – becomes completely different when the antenna position is changed. On the other hand, the channel remains the same, for the four antenna positions, in the frequencies below about 30 MHz.

B. Statistics of the channel attenuation

Aiming at analyzing the behavior of different portion of the spectrum of hybrid PLC wireless channels, three frequency bands were considered: 1.7 to 40 MHz, 40 to 70 MHz, and 70 to 100 MHz. More than 1200 estimates of the frequency response were obtained by considering all positions of portable Tx device and of fixed Rx device, which is connected to the outlets. Mean and standard deviation of the magnitude of the frequency response were evaluated considering the three frequency bands. Tables I and II present the values for $wireless \to PLC$ and $PLC \to wireless$ directions, respectively. Also, a discrete probability density function (PDF) was obtained, for each direction, in order to permit to analyze the variation that can be expected in the magnitude of the channel frequency response with respect to each of the tree considered frequency bands. Figure 10 presents the discrete PDF when the signal is transmitted by the portable Tx device and received by the fixed Rx device while Figure 11 presents the discrete PDF in the opposite direction.

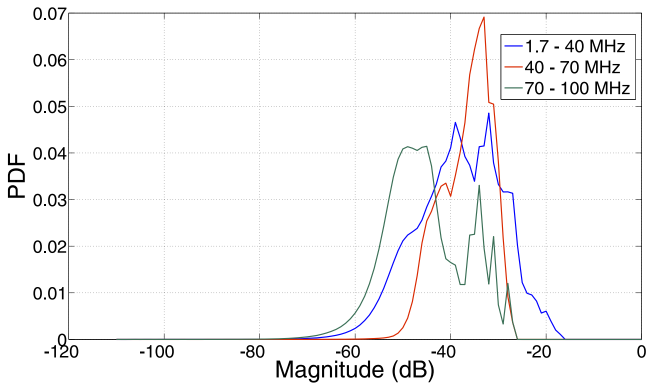

Fig. 10: PDF of the frequency response magnitude for the transmission direction $wireless \to PLC$.

It is also possible to observe that the two transmission directions presented similar behavior. As can be seen, the frequency band between 40 and 70 MHz has the smallest values of standard deviation indicating that the channel is more flat in this band than in the others. Furthermore, the frequency

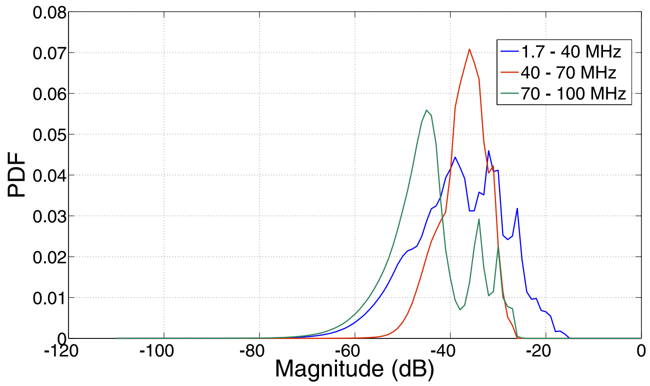

Fig. 11: PDF of the frequency response for the transmission direction $PLC \rightarrow wireless$.

Frequency band (MHz)	1.7-40	40-70	70-100
Mean	−38.2312	−36.8351	−45.3436
Standard deviation	80.2671	27.5524	70.2123

TABLE I: Mean and standard deviation values for the analyzed frequency bands in the transmission direction $wireless \rightarrow PLC$.

Frequency band (MHz)	1.7-40	40-70	70-100
Mean	−38.3787	−37.3447	−44.8457
Standard deviation	91.9547	24.1458	69.0824

TABLE II: Mean and standard deviation values for the analyzed frequency bands in the transmission direction $PLC \rightarrow wireless$.

band from 70 up to 100 MHz constitutes the worst band, in terms of attenuation, if compared with the other ones.

V. Conclusion

This work presented and analyzed measures of hybrid PLC wireless channels in a typical Brazilian middle-class apartment located in a residential area. A measurement setup was discussed and a capacitive PLC coupler was introduced to carry out the measurement campaign of such hybrid channels. The hybrid PLC-wireless channels were analyzed in both directions ($wireless \rightarrow PLC$ and $PLC \rightarrow wireless$) in terms of the magnitude of frequency response.

We could verify that the analyzed hybrid PLC wireless channels are symmetric. According to the statistical analysis, a less attenuated frequency band of such hybrid PLC wireless channels is located between 40 MHz and 70 MHz. Last, but not the least, the influence of the position of the antenna was observed in frequencies above 30 MHz when only one outlet was analyzed.

A future work is to carry out an extensive measurement campaign by taking into account different residential scenarios and to derive an statistical model for this kind of hybrid channel. In this direction, more features will be extracted and analyzed, such as the coherence bandwidth, the delay spread, among others.

Acknowledgment

The authors would like to thank CNPq, CAPES, FAPEMIG, FINEP, P&D ANEEL, CEMIG, INERGE, and Smarti9.

Referências

[1] H. A. Hrasnica H and L. R, *Broadband PowerLine Communications Network Design*. John Wiley & Sons, 2004.
[2] T. R. Oliveira, W. A. Finamore, and M. V. Ribeiro, "A sounding method based on OFDM modulation for PLC channel measurement," in *Proc. IEEE International Symposium on Powerline Communications and Its Applications*, 2013.
[3] S. Guzelgoz, H. Arslan, A. Islam, and A. Domijan, "A review of wireless and plc propagation channel characteristics for smart grid environments," *Journal of Electrical and Computer Engineering*, vol. 2011, 2011.
[4] J. D. Parsons, D. A. Demery, and A. M. D. Turkmani, "Sounding techniques for wideband mobile radio channels: a review," *IEEE Proceedings in Communications, Speech and Vision*, vol. 138, no. 5, pp. 437–446, Oct. 1991.
[5] T. R. Oliveira, M. S. Pereira, C. A. G. Marques, S. L. Netto, and M. V. Ribeiro, "The characterization of hybrid PLC-wireless channels: A preliminary analyzis," in *Proc. IEEE International Symposium on Power Line Communications and Its Applications*, 2013.
[6] O. Bilal, E. Liu, Y. Gao, and Korhonen, "Design of broadband coupling circuits for powerline communication," in *Proc. International Symposium on Powerline Communications and Its Applications*, 2004.
[7] M. I. Montrose, *EMC and the Printed Circuit Board: Design, Theory and Layout Made Simple*. IEEE Press Series on Electronics Technology e Wiley Interscience, 1999.
[8] D. F. Cardoso, F. D. Backx, and R. Sampaio-Neto, "Improved pilot-aided channel estimation in zero padded MC-CDMA systems," in *Proc. 4th International Symposium on Wireless Pervasive Computing*, Feb. 2009, pp. 1–5.