Feasibility of Full-Duplex Dynamic Spectrum Management for PLC-DSL Coexistence

Gautham Prasad and Lutz Lampe
The University of British Columbia, Vancouver, BC.
Email: gauthamp@ece.ubc.ca

***Abstract*—In this paper, we address the issue of electromagnetic compatibility (EMC) in indoor wired communication systems. In particular, we consider the electromagnetic interference between broadband power line communications (BB-PLC) and digital subscriber line (DSL) networks, and investigate a non-intrusive opportunistic dynamic spectrum management technique to enable coexistence. To this end, we examine the feasibility of power spectral density adaptation at the PLC nodes using spectrum sensing to estimate the DSL-to-BB-PLC interference channel. We consider the use of in band full duplexing to enable power line modems with superior spectrum sensing efficiency to simultaneously transmit PLC data and sense for the electromagnetically coupled DSL signal. We then determine the conditions under which sufficient signal-to-noise ratio of the known DSL pilot signal is achieved at the PLC node to obtain a satisfactory interference channel estimate. Further, we simulate a realistic indoor BB-PLC network and use real DSL-to-PLC interference channel measurement data to examine the viability of a dynamic spectral adaptation approach.**

***Index Terms*—In-band full-duplex (IBFD), broadband power line communication (BB-PLC), digital subscriber line (DSL), dynamic spectrum management (DSM).**

I. INTRODUCTION

A home area network consists of a multitude of communication requirements for applications ranging from low data rate home automation to high-speed multimedia communications [1]–[3]. Power line communication (PLC) provides an attractive alternative for all types of in-home communication demands due to the ubiquitous nature of the electrical wiring infrastructure and the widespread availability of power outlets in an indoor environment. One of the drawbacks of PLC applied in in-home communication networks is the electromagnetic interference (EMI) to and from the PLC signal produced due to the presence of asymmetric (common-mode) components on the unshielded and unbalanced power lines. For example, broadband PLC (BB-PLC) signal egress in the frequency range of $2-100$ MHz interferes with neighboring applications such as, broadcast, amateur, and digital radio services [4, Ch. 3] [5, Ch. 3]. Radiated BB-PLC signals have also been found to cause interference in wired access networks, like digital subscriber line (DSL) communications, where broadband signal on the telephone line is distorted as a result of a common-to-differential mode conversion as in the case of PLC [6]–[8].

A. Smart Notching

A straightforward solution to ensure coexistence in the presence of EMI is to regulate the transmission bandwidth to avoid frequency overlaps of two or more services. For instance, regulatory authorities across the world restrict PLC transmission in the frequencies occupied by the amateur radio bands [9], [10]. Newer standards, such as the EN 50561-1, further accommodate broadcast radio services by including a flexible frequency exclusion mode that allows PLC modems to cognitively use the *white spaces*, i.e., idle frequency bands allocated to broadcast radio operations [11]. Since most BB-PLC devices use multi-carrier modulation techniques such as orthogonal frequency division multiplexing (OFDM), they have accurate control over silencing transmission on intermediate frequencies by turning off the corresponding OFDM subcarriers. To this end, several measurement studies have been conducted in the past to determine spectrum sensing strategies to successfully detect the presence of radio interferences [12]–[14]. These methods traditionally employ a listen-before-talk approach, i.e., a half-duplex operation, where the PLC nodes frequently suspend their transmission to sense the spectrum, leading to an inefficient utilization of the white spaces. Spectrum sensing can instead be performed simultaneously, in a listen-and-talk manner, along with an active transmission, using the in-band full-duplex (IBFD) operation [15]. This allows uninterrupted data transmission in white spaces and enables 100% spectrum sensing efficiency [16].

B. Interference Cancellation

A smart notching, or dynamic spectral notching, is suitable to combat interference that occupies a relatively small portion of the PLC transmission bandwidth. The short-wave and digital broadcast radio services, for example, occupy a maximum of only 5.7 MHz of the 85 MHz of total bandwidth that is used by newer BB-PLC devices [17], [18]. However, recent DSL standards of very-high-data-rate DSL 2 (VDSL2), vectored-VDSL2, G.fast, and XG-fast occupy nearly the entire BB-PLC operating bandwidth [19]–[22]. Thus, dynamic notching to accommodate these services could render PLC completely inoperable.

A reactive solution to counter EMI between PLC and DSL communications is to implement interference cancellation at the customer-end DSL modems using a cooperative communications protocol [23], [24]. However, this intrusive technique requires a new physical connection between the DSL modem and the central coordinator (CCo) of the PLC

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network. Given that the CCo could dynamically change among several operating PLC nodes, we potentially require a physical connection between the DSL modem and all available PLC nodes. Furthermore, this protocol also requires PLC to be synchronized with the DSL super-frames. Under non-trivial network load conditions with devices operating under the carrier sense multiple access (CSMA) mode, such a solution presents a significant increase in network latency. In addition, this interference cancellation solution functions only when the PLC modems operate with the delayed acknowledgment scheme [23], which ensures that not more than one PLC node transmits in a given DSL super-frame duration. Hence, it lacks backward compatibility with current and older BB-PLC products, operating with say, the HomePlug AV standard, which only support an immediate acknowledgment procedure [9].

C. *Contributions*

With this backdrop, we investigate an appealing alternative approach to proactively counter the EMI between PLC and DSL communications using dynamic spectrum management (DSM) in the local area network. Along with such a method already being popular in the domain of wireless communications [25], DSM has also been envisioned by the European Telecommunications Standards Institute (ETSI) as a potential solution to ensure coexistence between DSL and PLC in a home area network [26]. To this end, we examine the technique of adapting the power spectral density (PSD) of the transmitted PLC signal on different sub-carriers based on a dynamic PLC-to-DSL interference channel estimate obtained at the PLC node using IBFD spectrum sensing. Since the interference channel estimation accuracy drives the PSD adaptation efficiency, we empirically determine the required normalized mean squared error performance of the channel estimation procedure to approximately preserve the throughput performance of both DSL and PLC systems. Further, we simulate an indoor communications network on power lines and DSL, and use real interference channel measurements data to investigate the signal-to-noise ratio of the DSL signal available at the power line modems for channel estimation. Finally, we also explore the impact of duplexing on DSM to examine its applicability with next-generation DSL standards of G.fast and XG-fast that do not use the traditional frequency division duplexing. We show through our analyses and simulations that a non-intrusive DSM approach, although appealing and widely applied in wireless communications scenarios, has limited applicability in practical indoor environments under both half-duplex and full-duplex PLC operations.

II. FULL-DUPLEX DSM

As a first step toward DSM, an elementary PSD reduction at the PLC modems can be performed on a trial-and-error basis until satisfactory data rates are achieved in the DSL network [26], [27]. However, such a method is evidently inefficient time- and throughput-wise, especially under varying interference channel conditions. Alternatively, a more potent solution is to dynamically estimate the PLC-to-DSL interference channel (PDIC) and selectively reduce the transmit PSD at the PLC modem such that the PLC interference on the DSL transmission is below a pre-defined minimum threshold. Although solely reducing PSD on the PLC network appears to be an unfair power allocation strategy at the outset, the fact that the DSL access network forms the backbone of indoor communications makes the DSL nodes the primary users of the spectral resource, and justifies requiring a higher priority. Furthermore, on short power line links that enjoy conducive PLC channel conditions, PSD reduction does not result in a noticeable decrease in data rates due to adequate signal-to-noise ratios that are guaranteed to the adaptive bit allocation algorithm. To determine the desired PSD reduction, we make use of the known *sync-symbol* that is transmitted in every DSL super-frame, and estimate the DSL-to-PLC interference channel (DPIC) [23]. Since PDIC and DPIC here refer to the indoor wireless channel between the customer-end DSL modem and the PLC node, the channel can be assumed to be reciprocal [27]. As a result, we can compute PDIC at the PLC node simply by monitoring the DSL signal ingress on the power line and estimating the DPIC.

Traditional half-duplex methods of signal monitoring, or spectrum sensing, require PLC modems to periodically suspend their transmission in order to estimate the DPIC. This leads to a loss in PLC throughput especially for DPIC with low coherence time. However, simultaneous transmission and reception achieved by IBFD allows us to estimate the interference channel without interrupting PLC data transmission [16]. In this case, PLC modems monitor the noise on the power line that is affected by self-interference (SI). Intuitively therefore, the accuracy of the estimated channel is driven by the extent of SI cancellation provided by the IBFD solution.

The state-of-the-art IBFD solution for BB-PLC enables PLC modems with simultaneous bidirectional data transfer using a dual-stage SI cancellation technique [28]. At the first stage, the SI signal is partially isolated from the received signal-of-interest using an active operational amplifier based hybrid circuit [29]. An alternative isolation technique uses all three conductors that are typically available in most in-home wiring infrastructures to achieve signal suppression using the coupling losses [16]. Any remaining SI is then canceled inside the receiver using a replica of the transmitted signal that is adaptively tuned to accurately estimate the SI. These solutions have shown to provide an SI cancellation of about 90 dB [28], through which we can reduce a typical BB-PLC SI PSD of $-50\ \mathrm{dBm/Hz}$ to a benign $-140\ \mathrm{dBm/Hz}$.

Once the residual SI is sufficiently reduced, we then estimate the DPIC transfer function, H_{DPIC}, using well-known channel estimation methods that use a known pilot/preamble sequence, i.e., the sync-symbols transmitted in every DSL super-frame for our application scenario [30], [31]. Accordingly, we reduce the transmit PSD on every kth PLC sub-carrier, $P_{\mathsf{TX,PLC}}[k]$, such that

$$P_{\mathsf{TX,PLC}}[k] \leq \frac{P_{\mathsf{thresh}}[k]}{|H_{\mathsf{PDIC}}[k]|^2}, \tag{1}$$

TABLE I
VDSL2 TRANSCEIVER PARAMETERS [19]

Operating bandwidth	1.1 – 17.6 MHz
FFT Size	8192
Sampling rate	35.328 MHz
Sub-carrier spacing (Δf_{DSL})	4.3125 kHz
Transmit PSD ($P_{\mathsf{TX,DSL}}$)	[19, Table. A7]
Noise PSD ($P_{\mathsf{N,DSL}}$)	-140 dBm/Hz
Max. constellation size ($M_{\max}$)	32768
SNR gap (Ψ_{gap})	9.75 dB

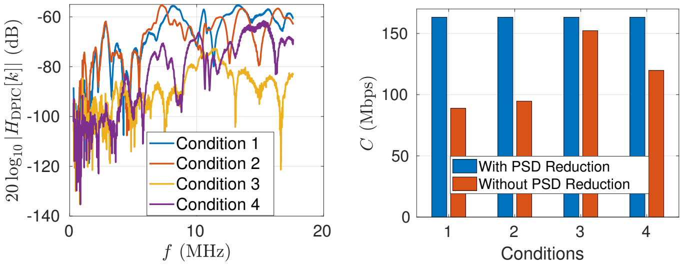
where $H_{\mathsf{PDIC}} = H_{\mathsf{DPIC}}$ is the estimated PDIC transfer function, and $P_{\mathsf{thresh}}[k]$ is a pre-determined interference threshold tolerable on the DSL, which is chosen such that it does not cause noticeable effects on the DSL data rates, i.e., $P_{\mathsf{thresh}}[k]$ is negligible compared to the prevalent DSL noise floor. In this respect, older DSL standards can afford higher values of P_{thresh} due to the effects of far-end cross-talk [32]. On the other hand, DSL access multiplexers (DSLAM) that use vectored transmission render the downstream signals more vulnerable to external interferences, and hence demand lower values of P_{thresh}.

III. DATA RATE GAINS

We now show the potential of IBFD DSM by presenting the DSL data rate gain achieved with dynamic PSD adaptation. Current DSL standards of VDSL, VDSL-2, and V-VDSL2 use frequency division duplexing (FDD) for bidirectional communication [19], [20]. Consequently, to compute the DSL data rates, we only consider the downstream signals that are significantly more prone to PLC interference effects due to the DSL channel attenuation, whereas upstream transmission has sufficient transmit signal-to-noise ratio to be resilient to PLC interference [26]. We calculate the downstream DSL rate as

$$C = \Delta f_{\mathsf{DSL}} \sum_{k\in\mathscr{D}} \min\Bigg[\log_2\left(M_{\max}\right), \log_2\left(1+\frac{P_{\mathsf{TX,DSL}}[k]|H_{\mathsf{DSL}}[k]|^2}{\Psi_{\mathsf{gap}}\left(P_{\mathsf{N,DSL}}+P_{\mathsf{TX,PLC}}[k]|H_{\mathsf{PDIC}}[k]|^2\right)}\right)\Bigg], \quad (2)$$

where $\mathscr{D}$ is the set of all DSL sub-carrier indexes that are used in downstream transmission [19, Annex. A], and H_{DSL} is the DSL channel transfer function from the central office to the customer premise equipment. Please refer to Table I for other notation descriptions, where we also summarize the transceiver parameters that we adopt from the VDSL2 standards [19]. Throughout our analysis of DSL rates, we consider vectoring at the DSLAM that achieves complete far-end cross-talk nullification.



(a) (b)

Fig. 1. (a) PLC-to-DSL coupling channel gains under four different conditions (surrounding environment) from [23], and (b) their corresponding VDSL-2 downstream data rates with and without PLC PSD reduction.

For the purposes of demonstration, we consider a matched 300 meter 26-gauge American wire gauge (AWG) cable with no bridge taps to compute $|H_{\mathsf{DSL}}|^2$ [33]. Further, we use four different H_{PDIC} conditions that were measured in a real in-home environment [23]. With the assumption of perfect H_{PDIC} estimate at the PLC node, we perform dynamic PSD reduction for PLC transmission such that power line interference is negligible compared to the DSL noise. We then compute the data rates using (2) and show the results in Fig. 1. We observe that Conditions 1 and 2, which present relatively higher coupling of PLC signals on to the DSL, produce lower VDSL2 data rates and consequently stands to gain the highest, of up to 80% data rate increase, with the introduction of DSM. Similar analysis follows for the other two conditions, which indicate that DSL communication stands to gain substantially with a lower BB-PLC interference. These results are also comparable with the data rate loss values reported by a comprehensive measurement campaign conducted on 24-gauge AWG cables in different indoor DSL network architectures over various geographic locations [8, Fig. 12].

IV. FEASIBILITY ANALYSIS

We have thus far considered the VDSL2 standard that operates under FDD, where non-overlapping upstream and downstream bands allowed precise PSD adaptation by the PLC modems. At the same time, we also assumed the availability of an ideal channel estimate at the PLC node. In this section, we analyze the impact of PLC noise on the DPIC estimation accuracy, and discuss the effects of alternative methods of duplexing, such as time division duplexing (TDD) and IBFD, that are applied in next-generation DSL standards.

A. Impact of PLC Noise

PLC systems are typically affected by three types of noise, namely, colored background noise, narrow-band noise, and impulse noise [34]. For typical in-home conditions, the noise PSD varies between -80 dBm/Hz and -130 dBm/Hz [35], [36], which is well above the residual SI PSD produced with the IBFD solution of [28]. Hence, the extent of power line noise primarily limits the accuracy of the DPIC estimation at the PLC node under both half-duplex (HD) and IBFD modes.

Several channel estimation procedures can be found in the literature that are specifically targeted for preamble-based OFDM systems [31], [37]. In any such method, the accuracy of the channel estimate depends on the signal-to-interference-plus-noise ratio (SINR) of the training signal used. In our case, we use the DSL sync-symbol for DPIC estimation, and we compute its SINR seen on the kth power line sub-carrier as

$$\Psi_{\mathsf{DSL}}[k] = \frac{P_{\mathsf{TX,DSL}}[k]|H_{\mathsf{DSL}}[k]|^2|H_{\mathsf{DPIC}}[k]|^2}{P_{\mathsf{N,PLC}}[k]+P_{\mathsf{TX,PLC}}|H_{\mathsf{SI}}[k]|^2}, \quad (3)$$

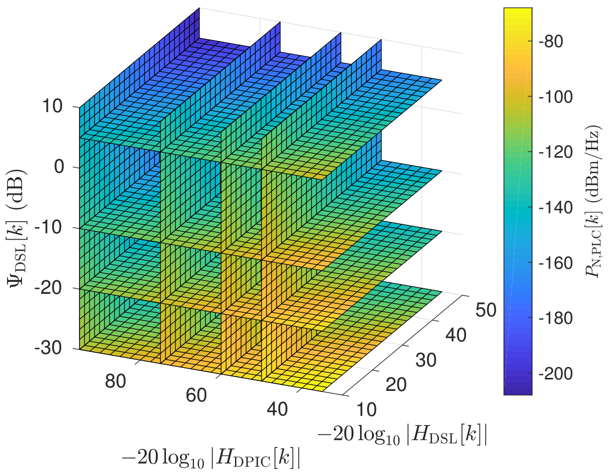


Fig. 2. Heat map showing the required $P_{\mathsf{N,PLC}}$ to achieve different $\Psi_{\mathsf{DSL}}[k]$ for varying DSL channel attenuations and DPIC conditions.

where $P_{\mathsf{N,PLC}}$ is the power line noise PSD and $|H_{\mathsf{SI}}[k]|^2$ is the total SI cancellation achieved by the IBFD solution. It has been shown that the attainable SI cancellation gain is frequency dependent and varies inversely with the strength of the received signal-of-interest [28]. A weaker signal-of-interest enables a more accurate SI estimate, resulting in a higher SI cancellation. Given the DSL transmit PSD, the channel attenuation undergone by downstream DSL signals, and the weak DPIC gains (Fig. 1(a), [8], [23]), we can reliably consider a constant maximum SI cancellation performance of $|H_{\mathsf{SI}}|^2 = 90$ dB across all sub-carriers [28].

With $P_{\mathsf{TX,PLC}} = -50$ dBm/Hz and $P_{\mathsf{TX,DSL}} = -53$ dBm/Hz [9], [19], we plot the PLC noise conditions required to achieve different $\Psi_{\mathsf{DSL}}[k]$ in Fig. 2. We vary the H_{DPIC} axis from 35 dB to 95 dB, which are the statistical minimum and maximum values of H_{DPIC} reported in the measurement campaign of [8] [1]. We present H_{DPIC} slices at 50 dB, 60 dB, and 75 dB, which are found to be the statistical 99th, 90th, and 50th percentile coupling values, respectively [8]. We observe from Fig. 2 that typically seen power line noise conditions between -80 dBm/Hz to -130 dBm/Hz can produce positive values of $\Psi_{\mathsf{DSL}}[k]$ under limited conditions of H_{DPIC} and H_{DSL}. For example, with a 90th percentile coupling of 60 dB, an SINR of 5 dB is achieved only when the DSL attenuation is less than 20 dB even under a low $P_{\mathsf{N,PLC}}[k] = -130$ dBm/Hz. This gives us an indication that the channel estimation procedure could be prone to significant inaccuracies in typical indoor environments.

Subsequently, we determine how likely useful SINR values are achievable in a realistic in-home communications network. To this end, we use 10 real H_{DPIC} channel transfer functions that were measured in different locations of a residential environment [23], and the same 300 meter 26-gauge AWG cable for downstream DSL transmission. We then compute the average SINR for varying power line noise conditions as $\overline{\Psi}_{\mathsf{DSL}} = 10 \cdot \log_{10}\left(\frac{1}{|\mathscr{D}'|}\sum_{k\in\mathscr{D}'}\Psi_{\mathsf{DSL}}[k]\right)$, where $\mathscr{D}'$ is the set of all BB-PLC sub-carrier indexes lying in the DSL downstream band. We use an open-source cumulative power line noise generator to simulate random PLC noise under two extreme conditions [36]. We then calculate $\overline{\Psi}_{\mathsf{DSL}}$ for 1000 different "high"- and "low"-noise conditions with a randomly chosen H_{DPIC} each time. The empirical cumulative distribution function plot of $\overline{\Psi}_{\mathsf{DSL}}$ is shown in Fig. 3. As expected, we notice poor SINR values under a high-noise environment. But the achieved SINR in lower power line noise conditions also appears insufficient for a favorable channel estimation performance using typical estimation procedures [31], [37]. We therefore ascertain what accuracy of the channel estimate could be considered to be acceptable.

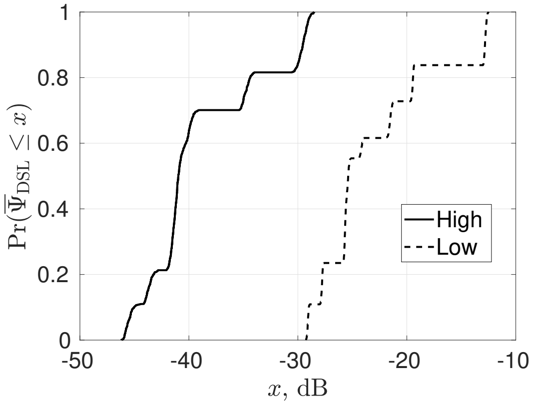


Fig. 3. Empirical cumulative distribution function plot of $\overline{\Psi}_{\mathsf{DSL}}$ observed on the power line under high- and low-noise conditions [36].

The channel or SINR estimation performance can be characterized in terms of the normalized mean squared error (NMSE) of the estimated value. As the NMSE of the estimated SINR, ϵ_{DPIC}, increases, the PSD adaptation accuracy at the PLC node reduces. When $|H_{\mathsf{DPIC}}|^2$ is overestimated, the PLC transmission rate suffers, as the transmit PSD is reduced more than required. Conversely, DSL throughput is affected as a result of under-compensated PSD adaptation by the PLC node when $|H_{\mathsf{DPIC}}|^2$ is underestimated. In order to quantify the exact effect of inaccurate channel estimation on both DSL and PLC systems, we study the impact of varying ϵ_{DPIC} on the PLC transmission rate and the DSL downstream data rate. We denote $\hat{P}_{\mathsf{TX,PLC}}[k]$ and $\widetilde{P}_{\mathsf{TX,PLC}}[k]$ as the adapted PSD for the estimated channel $\hat{H}_{\mathsf{DPIC}}$ and the ideal channel H_{DPIC}, respectively, that are determined using (1). We then compute the achieved PLC transmission rate, $\hat{C}_{\mathsf{PLC}}$, as

$$\hat{C}_{\mathsf{PLC}} = \Delta f_{\mathsf{PLC}} \sum_{k\in\mathscr{D}'} \min\Bigg[\log_2(M_{\mathsf{PLC}}), \log_2\left(1 + \frac{\hat{P}_{\mathsf{TX,PLC}}[k]|H_{\mathsf{PLC}}[k]|^2}{\Psi_{\mathrm{gap}}\left(P_{\mathsf{N,PLC}} + \hat{P}_{\mathsf{TX,PLC}}[k]|H_{\mathsf{SI}}|^2\right)}\right)\Bigg], \quad (4)$$

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[1] The percentile statistics reported in [8] are for the frequency range of $2-100$ MHz. However, Fig. 6 of [8] shows a similar trend of the probability density functions of the coupling levels for the VDSL2 frequency profile of "998ADE17", which is between $1.1-17.6$ MHz [19].

TABLE II
TRANSMISSION PARAMETERS OF DSL STANDARDS WHOSE OPERATING FREQUENCIES OVERLAP WITH BB-PLC BANDS [19]–[22]

	VDSL	VDSL2	G.fast	XG-fast
Bandwidth (MHz)	0.13-12	1.1-35	2.2-212	2.2-500
Max. PSD (dBm/Hz)	−60	−53	−65	−89
Duplexing	FDD	FDD	TDD	IBFD/TDD

where $\Delta f_{\mathsf{PLC}} = 24.414$ kHz is the OFDM sub-carrier spacing, and $M_{\mathsf{PLC}} = 4096$ is the maximum modulation order, both chosen as per the HomePlug AV2 standard [18], and H_{PLC} is the PLC channel transfer function. Similarly, we also compute the ideal PLC transmission rate $\widetilde{C}_{\mathsf{PLC}}$ using $\widetilde{P}_{\mathsf{TX,PLC}}[k]$ in place of $\hat{P}_{\mathsf{TX,PLC}}[k]$ in (4). On the same lines, we calculate the achieved DSL downstream transmission rate as

$$\hat{C}_{\mathsf{DSL}} = \Delta f_{\mathsf{DSL}} \sum_{k\in\mathscr{D}} \min\Bigg[\log_2(M_{\max}), \log_2\left(1+\frac{P_{\mathsf{TX,DSL}}[k]|H_{\mathsf{DSL}}[k]|^2}{\Psi_{\mathsf{gap}}\left(P_{\mathsf{N,DSL}}[k]+\hat{P}_{\mathsf{TX,PLC}}[k]|H_{\mathsf{DPIC}}[k]|^2\right)}\right)\Bigg], \quad (5)$$

and the ideal DSL rate $\widetilde{C}_{\mathsf{DSL}}$ with $\widetilde{P}_{\mathsf{TX,PLC}}[k]$ in place of $\hat{P}_{\mathsf{TX,PLC}}[k]$ in (5). We then determine the rate loss in both DSL and PLC systems as

$$\rho_\phi = \frac{\widetilde{C}_\phi - \hat{C}_\phi}{\widetilde{C}_\phi} \times 100 \quad [\%], \qquad (6)$$

where $\phi \in \{\mathsf{DSL}, \mathsf{PLC}\}$.

The empirical values of ρ_{PLC} and ρ_{DSL} are shown in Fig. 4. Each of the PLC transmission rates are computed for a randomly generated indoor PLC channel using [38] and a power line noise condition produced using [36]. Further, we compute $\hat{P}_{\mathsf{TX,PLC}}[k]$ in each case using (1) for a channel estimate, $\hat{H}_{\mathsf{DPIC}}$, that is randomly generated for the chosen ϵ_{DPIC} and an ideal H_{DPIC}. Since typical $P_{\mathsf{N,DSL}} = -140$ dBm/Hz [8], we set $P_{\mathsf{thresh}} = -150$ dBm/Hz over all sub-carriers to limit the impact of PLC-to-DSL interference.

It can be seen in Fig. 4 that we achieve $\rho \approx 0$ for $\epsilon_{\mathsf{DPIC}} \leq 10^{-3}$, which indicates the ideal channel estimation performance that we desire. However, as ϵ_{DPIC} grows, we notice that the rate loss begins to increase, with PLC transmission rate loss increasing faster than that of the downstream DSL rates, as an over-compensated PSD reduction hurts PLC rates more severely than an under-compensated PSD reduction does to the DSL rates due to our chosen P_{thresh}. We can conclude from Fig. 4 that $\epsilon_{\mathsf{DPIC}} \approx 5 \times 10^{-2}$ could be considered to be an acceptable trade-off value that relaxes the required channel estimation performance without significantly impacting the DSL and PLC transmission rates. However, typical channel estimators for OFDM systems indicate such an estimation performance requires $\overline{\Psi}_{\mathsf{DSL}} \geq 2$ dB [31], [37], and Fig. 3 suggests that such conditions are unavailable in our simulated network conditions.

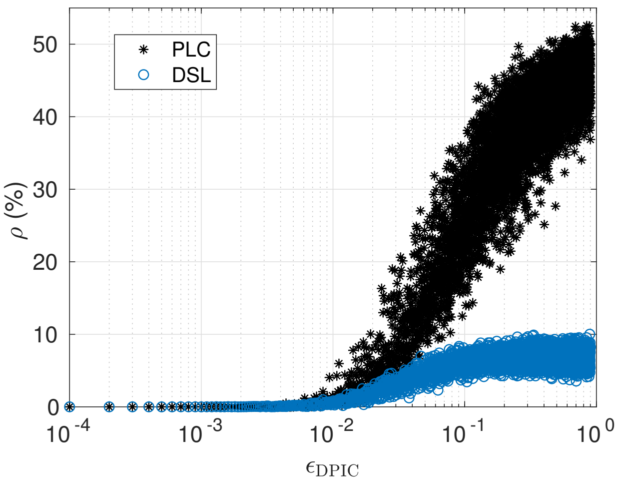

Fig. 4. Percentage rate loss of PLC and downstream DSL communications in the downstream DSL bands.

Further, recall that we have considered a matched 300 meter copper cable with no bridge taps for our simulations. But typical VDSL2 loops span longer lengths (e.g., about 1.5 km [8]) with multiple bridge taps in between that introduce greater channel attenuation and higher frequency selectivity. Additionally, greater bandwidth profiles of VDSL2, such as the “998ADE35” profile, restrict $P_{\mathsf{TX,DSL}} \leq -76.7$ dBm/Hz above 30 MHz [8]. Furthermore, newer standards of G.fast and XG-fast also use lower $P_{\mathsf{TX,DSL}}$, as tabulated in Table II[2]. This signifies that the attainable $\overline{\Psi}_{\mathsf{DSL}}$ is further reduced, leading to poorer values of ϵ_{DPIC}.

B. *Effect of Duplexing*

Implementing dynamic spectral adaptation on PLC devices over the downstream DSL bands is straightforward for FDD systems, such as VDSL, VDSL2, and V-VDSL2, due to the non-overlapping orthogonal nature of the bidirectional frequency bands. However, the recent G.fast standard specifies the use of TDD to accommodate bidirectional data streams [21]. This requires PLC nodes to be synchronized with the G.fast devices to implement DSM during downstream G.fast data transfer. Furthermore, duplexing through IBFD is being considered for the future XG-fast standard [22], which demands a PSD reduction by PLC nodes on all frequency bands at all times.

C. *Outcome*

We have thus learned that while PLC-to-DSL interference is large enough to cause a significant loss in downstream DSL data rates, the DSL-to-PLC interference is hardly noticeable on the power line, thereby limiting the DPIC estimation accuracy. We therefore require more effective channel estimators that are capable of operating under harsh SINR conditions. Thus, we conclude that the practical applicability of dynamic spectral adaptation is limited, irrespective of the operating mode (HD or IBFD) on the PLC device, despite the potential benefits

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[2] The specifications of XG-fast are not publicly available yet. −89 dBm/Hz is the transmit PSD used in an initial hardware proof-of-concept [39].

it presents at the outset over its competitor EMI-management solutions [26].

V. CONCLUSION

In this paper, we have addressed the issue of EMI between indoor communication systems over power lines and DSLs. We have investigated the use of dynamic spectral adaptation in PLC systems to reduce its EMI on DSL communications. To this end, we considered the use of a full-duplex spectrum sensing approach that allows power line modems to estimate the extent of PLC-to-DSL interference while simultaneously transmitting PLC data. However, our feasibility analyses showed that such a non-intrusive spectrum sensing based PLC-DSM approach potentially suffers from severe drawbacks, in both full- and half-duplex modes, due to the harsh effects of power line noise and the substantial EMI reduction demands of newer DSL standards operating over extended bandwidths. This suggests that, in spite of its drawbacks, a customized interference cancellation implemented on the DSL customer premise equipment could be more suitable in practice.

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