Measuring Link Characteristics of Power Line Communication Systems

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***Abstract*—Knowing link characteristics of a network connection is essential for the efficient design, management, and usage of a network. In view of the proliferation of power line communication systems, in this work, we propose a novel measurement approach, called PLC-Probe, to concurrently measure link capacity and available bandwidth of PLC links. PLC-Probe uses 'train-chirps' to probe the network, and it combines the strengths of the packet train and packet chirp approaches for estimation of link characteristics. Using testbed experiment, we evaluate the proposed approach and show that PLC-Probe is accurate, stable, and robust against cross traffic. Moreover, PLC-Probe is simple, effective, and applicable to other multi-rated PLC-like networks.**

I. Introduction

Estimating link characteristics of a network connection is a fundamental research problem in computer networking because knowledge of link characteristics is crucial to the efficient design, management, and usage of a network. The issue has been extensively studied in the recent decades, and several tools have been developed to measure network connections of different link characteristics, such as bottleneck link capacity [1, 2, 4] and tight link available bandwidth [3, 8, 9]. The results of network measurement have shown promises in facilitating a wide variety of network applications/protocols, such as congestion control, multimedia networking, and peer-to-peer networks.

Generally, link characteristics of a network connection are either network-responsive or not. Among them, non-network-responsive characteristics (such as connection path and link capacity) are unchanged when a measurement is ongoing, while network-responsive characteristics (such as latency and available bandwidth) may vary a lot in accordance with network states. The top design goals of network measurement tools are 1) estimation accuracy; 2) algorithm simplicity; and 3) non-intrusiveness (i.e., moderate probing traffic injected to the network).

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Yet, with the quick proliferation of Power Line Communication (PLC) systems, the effectiveness of conventional network measurement tools has been severely challenged. The reason is that PLC adopts a rate adaptive bit-loading algorithm that adapts its modulation scheme to the channel condition and load fluctuation faced [5, 6]. As a result, the probing traffic sent by conventional network measurement tools is too moderate to trigger the highest data rate and thus fail to discover the maximum capability of PLC links.

In this paper, we propose a novel measurement tool, called PLC-Probe, for PLC systems. Unlike conventional measurement tools, PLC-Probe is specifically tailored for PLC-like multi-rated systems and capable of identifying the *minimal probing rate* (MPR) to measure the maximum capability of a PLC link. Moreover, it combines the strengths of *packet train* [1, 2] and *packet chirp* [8] techniques, and it allows concurrent estimation of both link capacity and available bandwidth of a connection path. Using a comprehensive set of testbed experiments, we compare the proposed scheme with the state-of-the-art approaches, and the results demonstrate that PLC-Probe outperforms the existing approaches in terms of estimation accuracy. Moreover, it is simple, stable, and robust to cross traffic over the network.

The rest of the paper is organized as follows. Section II presents the problem statement of this study. In Section III, we presents the proposed PLC-Probe approach for link characteristics estimation of PLC links. In Section IV, we present a comprehensive set of experiments, and the results are discussed in detail. Finally, Section V gives the conclusions.

II. Problem Statement

We consider two basic link characteristics in this study, namely, the link capacity and the available bandwidth. By definition, the *link capacity* of a point-to-point link is *the theoretically maximum traffic load supported by the link*, and the *available bandwidth* is *the residual bandwidth of a link*.

Specifically, we suppose that there are n intermediate hops between a network connection from node a to node b. Let c_i be the link capacity of the i-th link, and r_i be the amount of cross traffic on the i-th link. The end-to-end link capacity,

$C_{a,b}$, of the network connection from a to b is obtained by taking smallest per-hop link capacity among the n links, as shown in Equation 1, and the link that has the smallest link capacity is referred to as the *bottleneck link* of the network connection from a to b.

$$C_{a,b} = \min_{i=1,2,\cdots,n} c_i. \quad (1)$$

Moreover, the end-to-end available bandwidth, $B_{a,b}$, of the network connection from a to b is obtained by taking smallest per-hop available bandwidth among the n links, as shown in Equation 2, and the link that has the smallest available bandwidth is referred to as the *tight link* of the network connection from a to b.

$$B_{a,b} = \min_{i=1,2,\cdots,n} (c_i - r_i). \quad (2)$$

Generally, the tight link of a network connection is also the bottleneck link, and vice versa. The available bandwidth is equal to the link capacity if there is no cross traffic on the link. To measure the two link characteristics, two of the most popular techniques are

1) **Train-based Method**: This method probes the network using a number of packet trains, and each packet train comprises k equal-sized packets sent in a back-to-back manner ($k \geq 1$). The receiver observes the arrival time of each packet in a train and estimates the link characteristics using different analytic models. Note that this method is identical to the famous *Packet Pair* approach when $k = 2$. Examples of measurement tools in this category include CapProbe [4], Pathload [2], Pathrate [3], and PBProbe [1].
2) **Chirp-based Method**: This method probes the network using a number of packet chirps, and each packet chirp comprises k equal-sized packets that are sent with *exponentially decreased time intervals* between every two adjacent packets, which result in an exponentially increased simultaneous sending rate in a chirp. This method is usually designed for available bandwidth estimation, and examples of measurement tools in this category include pathChirp [8], Thouin's method [10], and schirp [7].

Although conventional network measurement tools have been shown effective over a wide variety of links (e.g., Ethernet, high-speed Ethernet, ADSL, WiFi, and 3G), a detailed and systematic study of network measurement over PLC links is still lacking. In fact, based on our preliminary measurement results, we find that conventional tools are problematic on PLC links because PLC systems employ a multi-rate mechanism that changes its data rate in accordance with its traffic load, and the probe traffic sent by conventional tools is too moderate to discover the full capability of PLC links.

Table I shows the preliminary measurement results of four state-of-the-art tools on PLC links using two identical end devices of different brands/models (i.e., D-Link DHP-307AV and ZyXEL PLA-407). The testbed is separated from the building power system to avoid electromagnetic interference (EMI) using an Uninterruptible Power Supply (UPS), and there are no network flows except the probing traffic. Thus, the available bandwidth of the link is equal to its link capacity. However, we observe from the results that each tool achieves similar results for PLC links of different device models, but, for each PLC device model, the estimation results vary a lot among different tools. The reason is that the four tools probe the network using different traffic patterns[1], and PLC links respond to these flows with different data rates, which result in the diverse measurement results.

TABLE I
COMPARISON OF LINK CAPACITY ESTIMATION RESULTS USING DIFFERENT MEASUREMENT TOOLS OVER PLC LINKS (UNIT: MBPS)

	PBProbe	Pathrate	pathChirp	Pathload
D-Link	95.92	76.15	92.25	85.45
ZyXEL	97.19	74.14	106.53	83.32

To verify our finding, we use packet trains of different lengths (i.e., representing different sending rates) and measure the average dispersion rate (ADR) [2] on the receiver side of a single hop PLC link. From the results shown in Figures 1 and 2, we observe that, regardless the device model used, the ADR curves increase very fast with the sending rates used and start to converge when the sending rate becomes larger than 3Mbps. In contrast, the ADR's standard deviation decreases with the sending rates used and starts to converge when the sending rate becomes larger than 3Mbps too. The results confirm that the path characteristics of PLC links are sensitive to network traffic carried. Moreover, to measure the maximum link capacity of PLC links, it is required to increase the probing rate at least beyond the '*minimal sending rate*' (MSR), which can turn PLC links to the highest data rate mode.

III. PLC-PROBE

In this section, we present the proposed tool, called PLC-Probe, for concurrent estimation of both link capacity and available bandwidth on PLC links. Figure 3 illustrates the operation of PLC-Probe, which is similar to PBProbe [1] except that PLC-Probe probes the network using '*Train-Chirps*'. Specifically, a *train-chirp* is comprised of a number of equal-length packet trains sent at exponentially increased sending rates. We let k be the number of packets in a packet train, and let n be the number of packet trains in a train-chirp. Figure 4 shows an example of a *train-chirp* with an initial inter-spacing time at T and a *spread factor* r.

Let L be the packet size, and let λ_i be the simultaneous sending rate between the i-th and the $(i+1)$-th packet trains in a train-chirp. We can obtain the value of λ_i by

$$\lambda_i = \frac{L \times k \times r^{i-1}}{T}, \quad (3)$$

[1]Specifically, in the experiment, PBProbe probes the network with a fixed rate at 35Mbps; and the other three tools probe the network using varying rates ranging from 0.46 to 0.6 Mbps (Pathrate), from 1 to 100 Mbps (pathChirp), and from 45 to 80 Mbps (Pathload).

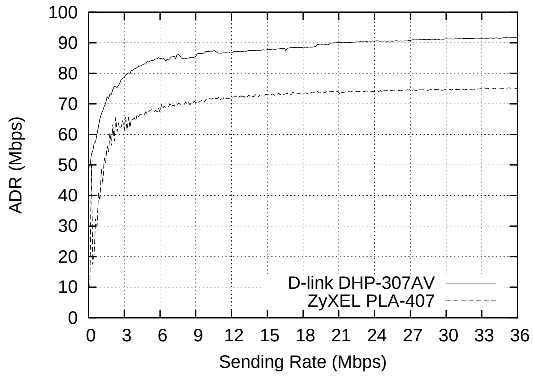

Fig. 1. The average dispersion rate (ADR) achieved by packet trains of different sending rates over PLC links

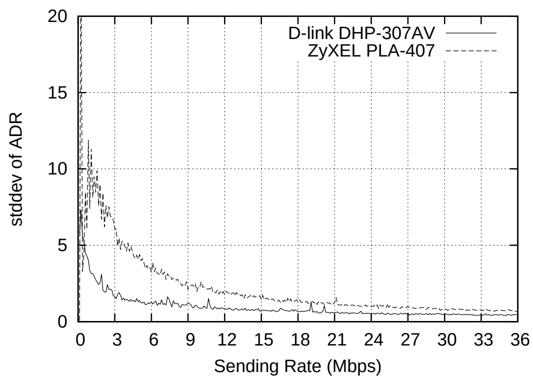

Fig. 2. The standard deviation of average dispersion rate (ADR) achieved by packet trains of different sending rates over PLC links

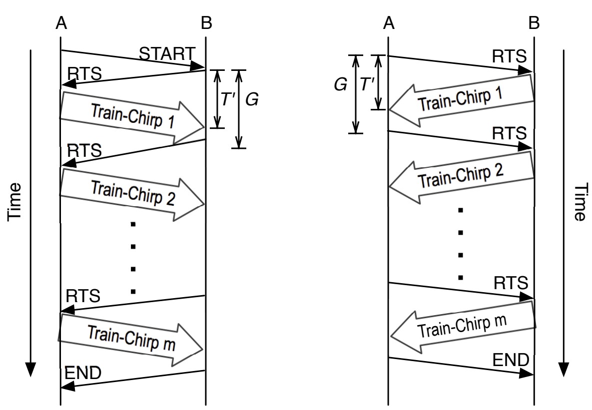

Fig. 3. Illustration of PLC-Probe (a) Phase I: measuring forward direction link capacity; (b) Phase II: measuring backward direction link capacity.

which increases exponentially with the value of i at a rate of the spread factor r.

As shown in Figure 3, there are two phases in PLC-Probe. In the first phase, it measures the path characteristics of the *forward* path; and in the second, it measures the path characteristics of the *backward* path. In the first phase, host *A* sends a *START* packet to host *B* to initiate the estimation process, after which *B* sends a *Request To Send* (*RTS*) packet

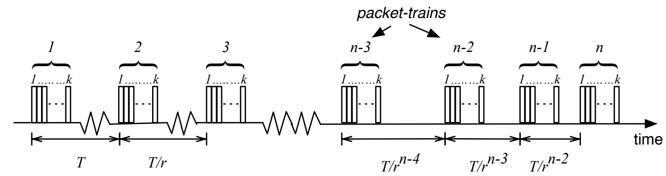

Fig. 4. An example of a train-chirp with the train length equal to k, the chirp length equal to n, and the spread factor equal to r

to A every G time units, where G is a *Inter-Sample Period* factor that is determined by the maximum workload allowed of the probe traffic and the link capacity estimated by far [1]. In each phase, we let $t_{i,j,0}$ be the sending time of the j-th *RTS* packet that triggers the j-th packet train in the i-th train-chirp, and let $t_{i,j,m}$ be the receiving time of the m-th packet in the j-th packet train of the i-th train-chirp. Moreover, we let N be the number of train-chirps sent by PLC-Probe, which measures the link characteristics of the path by analyzing the train-chirps received as follows:

- **Minimal Probing Rate (MPR)**

  For the j-th packet train of the i-th train-chirp sent, PLC-Probe calculates its *Average Dispersion Rate* (ADR) [2], $R_{i,j}$, by

$$R_{i,j} = \frac{(k-1) \times L}{t_{i,j,k} - t_{i,j,1}}. \quad (4)$$

  In addition, for the j-th packet train in all the train-chirps sent, PLC-Probe calculates its mean (R_j^*) and standard deviation (R_j^Δ) by $R_j^* = \frac{\sum_{i=1}^N R_{i,j}}{N}$, and $R_j^\Delta = \sqrt{\frac{1}{N}\sum_{i=1}^N (R_{i,j} - R_j^*)^2}$ respectively.

  Then, the MPR is identified by the sending rate of the u-th packet train in a train-chirp, i.e., $MPR = \lambda_u$, such that

$$u = \arg\min_{j=1\cdots k} [\lambda_j | \lambda_j > (\max_{j=1\cdots k} R_j^*) - R_j^\Delta]. \quad (5)$$

- **Link Capacity (C)**

  We let u be the sequence number of the packet train that is sent at the rate of MPR in a train-chirp. PLC-Probe follows PBProbe [1] and finds the train-chirp (i.e., the v-th train-chirp) that has the *minimum delay sum* [1, 4] for the u-th packet train by

$$v = \arg\min_{0<i<N} ((t_{i,u,1} - t_{i,u,0}) + (t_{i,u,k} - t_{i,u,0})), \quad (6)$$

  where N is the number of train-chirps sent by PLC-Probe. Then, it estimates the link capacity (C) of the path by

$$C = \frac{(k-1) \times L}{t_{v,u,k} - t_{v,u,1}}. \quad (7)$$

- **Available Bandwidth** (B)

PLC-Probe measures the available bandwidth of the path in a similar way to pathChirp [8], except that 1) it considers packet-train pairs in the estimation, not packet pairs; and 2) it considers the fact that PLC links are multi-rated in response to their traffic load. Specifically, for the i-th train-chirp, PLC-Probe calculates the *relative one-way delay*, $D_{i,j}$, achieved by the j-th packet train by Equation 8, and divides the distribution of $D_{i,j}$ for $0 < j < k$ into four types, as shown in Figure 5:

$$D_{i,j} = |(t_{i,j,k} - t'_{i,j,k}) - (t_{i,j,1} - t'_{i,j,1})|, \qquad (8)$$

where $t'_{i,j,1}$ and $t'_{i,j,k}$ are the sending time of the first and last packets in the j-th packet train of the i-th train-chirp.

1) *Under MPR Phase:* In this phase, PLC links adapt their data rates with the sending rates of train-chirps. As a result, $D_{i,j}$ decreases as j increases, since λ_j increases with j; and the higher data rate, the lower transmission delay.
2) *Cross Traffic Appearing Phase:* In this phase, the probe traffic is interfered by the cross traffic, and $D_{i,j}$ increases with j due to additional queueing delay caused by cross traffic.
3) *Queue Relaxing Phase:* This phase comes after the *Cross Traffic Appearing Phase* when $D_{i,j}$ decreases as j increases. The reason is that when network congestion is relaxed, the queueing delay added to each packet train also decreases as a result.
4) *Over Link Capacity Phase:* In this phase, the sending rate of the probe traffic has become greater than the link capacity, and $D_{i,j}$ increase with j because the bottleneck link has been overloaded.

We let $\omega_{i,j}$ be the time interval between the j-th and the $(j+1)$-th packet trains in the i-th train-chirp (i.e., $\omega_{i,j} = \frac{T}{r^{i-1}}$); and let s_i be the smallest sequence number of the packet trains in the *Over Link Capacity Phase* in the i-th train-chirp. Moreover, we let $\delta_{i,j,p}$ be a delta function that returns 1 if $D_{i,j}$ belongs to the p-th phase and returns 0 otherwise ($p = 1 \cdots 4$). Using pathChirp [8], we estimate the available bandwidth of the link by

$$B = \sum_{i=1}^{N}\sum_{j=1}^{k} \frac{(\delta_{i,j,1} + \delta_{i,j,3} + \delta_{i,j,4})\lambda_{s_i}\omega_{i,j} + \delta_{i,j,2}\lambda_j\omega_{i,j}}{\omega_{i,j}}. \qquad (9)$$

IV. Evaluation

We implemented the proposed PLC-Probe approach in C programming language on the Linux platform, and conducted experiments on our testbed as shown in Figure 6. Specifically, on the one side of the PLC link, there are two Linux boxes attached via an 100Mbps Ethernet switch, and the two machines serve as PLC-Probe sender and Poisson cross traffic generator, respectively. On the other side of the PLC link, there is also two Linux boxes attached via an 100Mbps Ethernet and they serve as PLC-Probe and Poisson cross traffic receivers respectively. All the results presented here are based on the average performance of 50 runs.

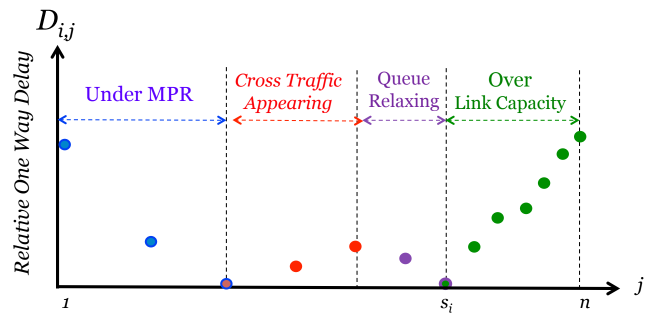

Fig. 5. Illustration of the four phases of relative one-way delays per packet train measured in a train-chirp

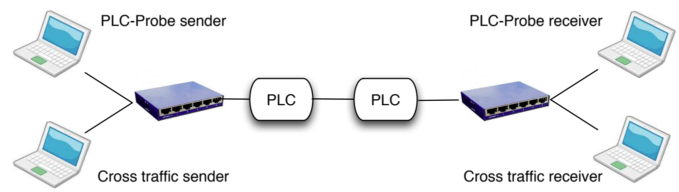

Fig. 6. The network scenario used in the experiment

From the experiment results shown in Table II, there are three observations:

1) PLC-Probe is responsive, in terms of its capability of finding the minimal probing rate for multi-rated networks. For instance, during the experiment, the MPR found by PLC-Probe is about 13Mbps when the cross traffic is below 1Mbps, and it becomes about $1 \sim 1.6$ Mbps when the cross traffic increases from 1Mbps to 15Mbps. The reason is that the cross traffic is generated based on Possion random process, and PLC-Probe is able to take advantage of 'traffic bursty' of the cross traffic and find a 'small-yet-enough' MPR to trigger the maximal data rate of PLC links.
2) PLC-Probe is accurate in link capacity estimation over PLC links even if there is cross traffic over the links. Specifically, it yields capacity estimates between 95Mbps and 98Mbps with a relatively small standard deviation in all test cases. Comparing to our preliminary evaluation results shown in Table I, PLC-Probe is comparable to PBProbe and significantly outperforms the other tools in terms of estimation accuracy. However, we note that PBProbe probes the network using a constant rate, which is not responsive and may not be applied to other multi-rated networks, whereas PLC-Probe is able to find the MPR for multi-rated networks and thus therefore considered more suitable for PLC-like multi-rated networks.
3) PLC-Probe is accurate in available bandwidth estima-

TABLE II
EXPERIMENT RESULTS OF PLC-PROBE ON A PLC LINK UNDER CROSS TRAFFIC OF DIFFERENT POISSON RATES (UNIT: MBPS)

Poisson Cross Traffic Rate	0	0.5	1	5	10	15
Minimal Probing Rate (MPR)	13.13 ± 1.29	13.13 ± 1.56	1.13 ± 0.56	1.02 ± 0.07	1.04 ± 0.13	1.61 ± 0.97
Link Capacuty (C)	96.49 ± 7.92	95.23 ± 4.69	95.06 ± 5.72	96.22 ± 5.44	97.38 ± 1.25	95.67 ± 8.21
Available Bandwidth (B)	95.14 ± 3.21	95.12 ± 1.44	95.04 ± 2.89	90.88 ± 5.71	87.61 ± 7.57	83.12 ± 9.78

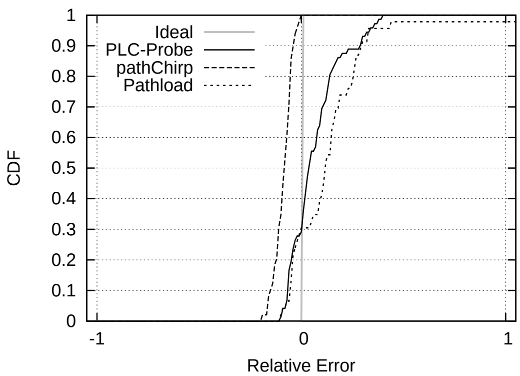

Fig. 7. The cumulative distribution function (CDF) curves of *D-Test* results under different available bandwidth estimation tools

tion. In our experiment, it always yields an estimate that is about the link capacity minus the cross traffic, while keeping the standard deviation small in all test cases.

To further investigate the accuracy of PLC-Probe in available bandwidth estimation, we apply *D-Test* [9] that 1) measures the available bandwidth to get B_1; 2) injects cross traffic at a rate of $S = 0.5 \times B_1$; 3) measures the available bandwidth again to get B_2; and 4) calculates the *relative error* by

$$\text{Relative error} = \frac{S - (B_1 - B_2)}{S}. \qquad (10)$$

Figure 7 shows the cumulative distribution function (CDF) curves of *D-Test* results under different available bandwidth estimation tools, where the ideal relative error is 0. We observe that PLC-Probe is comparable to pathChirp, and both of them outperform Pathload in the experiment results. However, we note that pathChirp is designed for available bandwidth estimation only, whereas PLC-Probe is capable of measuring link capacity and available bandwidth concurrently. Thus, PLC-Probe is considered more suitable for measuring link characteristics of PLC-like multi-rated networks.

V. CONCLUSION

We have studied a classic problem of link characteristic measurement for power line communication systems, and have proposed a novel approach, called PLC-Probe, for concurrent estimation of link capacity and available bandwidth using *train-chirps*. Using real-world experiments, we first identify the measurement issue of PLC-like systems that are multi-rated in response to traffic load, and propose a simple algorithm to estimate the *minimal probing rate (MPR)* that can trigger PLC links to the highest data rate mode. Then, it combines the strengths of packet train-based approaches for link capacity estimation, and packet chirps-based approaches for available bandwidth estimation. Using a comprehensive set of testbed experiment, we show that PLC-Probe is simple, accurate, and effective in measuring link characteristics of PLC links. Work on conducting large-scale Internet experiments is ongoing. We hope to report the results in the near future.

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