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Can broadband over powerline carrier (PLC) compete? A techno-economic analysis

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Abstract

Powerline carrier (PLC) communications have been heralded by the FCC as the "3rd wire" to every home, and have matured to the point of field trials and limited deployment. This paper examines the technology from a techno-economic perspective, factoring in regulatory issues and network design (focusing on the United States). Results indicate that PLC does not appear to represent a major disruptive technology, especially from a price-performance perspective. In addition, a baseline stochastic model created for the analysis shows that not only do competition and penetration matter, but locational distribution (i.e., how many consumers can share upstream equipment) is critical in determining PLC's competitiveness.

Keywords: Broadband over powerline (BPL); Powerline carrier (PLC); Techno-economic analysis; Access technologies

1. Introduction

Broadband penetrations in the United States have, especially until recently, lagged behind those of a number of other OECD countries. In Korea, one of the world leaders, not only are most households online, but 96.5% of these have *broadband* connectivity (ITU, 2003). Worldwide, the leading technology used for broadband is DSL (digital subscriber line), followed by cable—which leads in the United States. An emerging technology, powerline carrier (PLC), also known as broadband over powerline (BPL), is envisaged as a new solution that can provide lower costs to

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consumers. PLC is an access solution that transmits data over electricity wiring while simultaneously carrying electricity.

PLC, like most broadband solutions, provides always-on, high-speed connectivity (hundreds of kilobits/s or greater).[1] PLC is viewed as especially attractive because of several characteristics. Electricity service is nearly ubiquitous, and so the theoretical coverage from PLC is close to 100% (at least in the US—and most developing countries have higher electricity penetration than telephony). Most consumers have a reasonable expectation of quality and reliability from their power provider.[2] In addition, PLC can provide an elegant solution for in-home access and networking, since the signal can reach virtually any outlet in the home. This can provide connectivity to almost any location within the house, in a ‘‘plug and play’’ fashion.

For PLC to be successful, it must not only operate successfully from a technology point of view, but also present a viable business case. The two are interlinked, since its market share will depend on its price-performance, i.e., cost as well as throughput. The market space consists of not only well-entrenched alternatives (DSL and cable), but also alternatives such as fiber-to-the-home (FTTH), fiber-to-the-curb (FTTC), and broadband wireless. In addition to an analysis of the technology, and its economic implications, this paper highlights several issues relating to policy. After all, if PLC does not do well in the market, is not that simply a part of the natural competitiveness of the telecom industry? As will be shown, like all issues of telecom, regulation and competition play a vital role.

The next section describes PLC technology and its status, highlighting network (power distribution grid) design and its implications. The subsequent section discusses regulations pertaining to PLC, followed by a description of the model created for analysis. It is worth emphasizing that many of the costing numbers are not publicly available, and there will be differences between systems based on different physical infrastructure and designs. Given the great uncertainty in a number of parameters and variables, a stochastic model was created, using a range of parameters, to provide plausible and useful results. After presenting the results, the paper examines sensitivity and robustness of the variables. The concluding sections cover the implications of the analysis, including PLC’s possible competitiveness in the market.

2. PLC technology

Electricity flows over powerlines at a near-steady 50 or 60 Hz (cycles per second), depending on the country’s standard. If a signal is injected over this network at much higher frequencies, it would present minimal interference with the electricity delivery—somewhat analogous to DSL technologies using different frequency bands for voice and for data over the same copper infrastructure. Utilities have been transmitting communications signals over powerlines for many decades, mainly for control purposes. However, these signals usually operated at kilohertz ranges, and offered only modest transmission capacity, sometimes less than a kilobit per second. A relatively new idea has been to transmit broadband signals for communications purposes, i.e.,

[1] There is no universal definition of or standard for ‘‘broadband.’’ The ITU (2003) terms connections with speeds of at least 128 kbps (kilobits per second) in one direction as broadband.

[2] The August 14, 2003, blackout notwithstanding. This paper focuses on the US, unless stated otherwise.

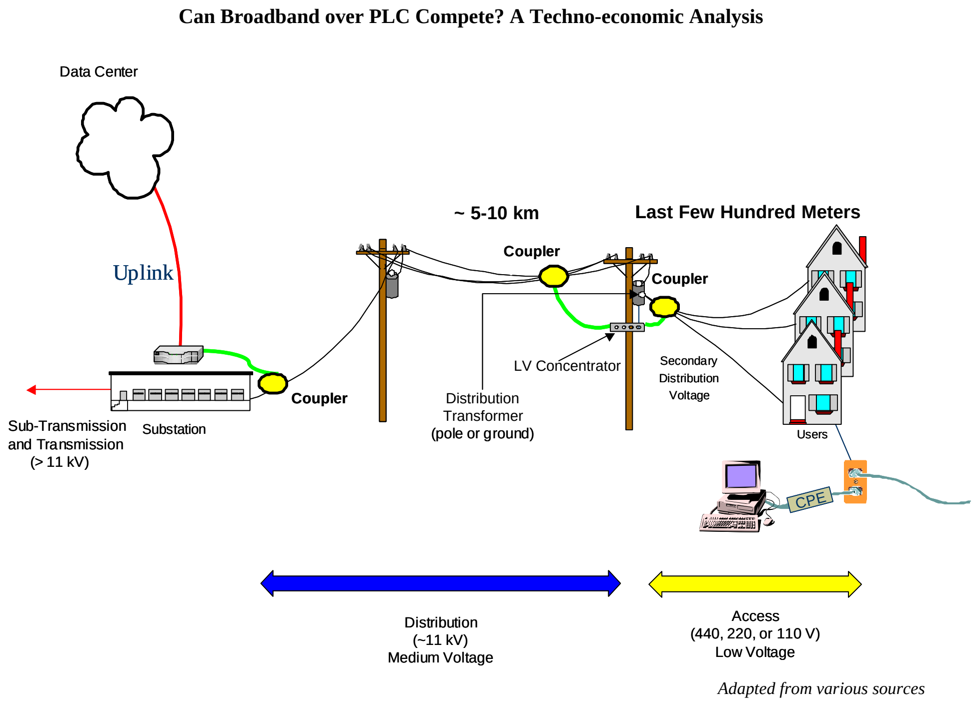

Fig. 1. Generic PLC system network. This is based on PLC being used across both the medium- and low-voltage portions of the network, all the way up to the end-user.

BPL. This has been made possible by advances in communications design and in electronic chips, which can successfully modulate and demodulate information of a carrier signal operating at high-frequency ranges. Most modern PLC systems operate with a carrier frequency range of approximately 1–30 MHz (megahertz). From first principles, Shannon's Theorem (Shannon, 1948) indicates that this bandwidth could theoretically provide many tens of megabits per second (Mbps) of throughput, depending on the signal-to-noise ratio.[3] However, as will be shown in more detail shortly, practical limits on signal levels (regulated by the FCC or other respective regulators) and noise within the power systems limit the throughput.

The power distribution network was not designed or optimized for information delivery, with numerous bridges, splits, taps, branchings, etc., as well as a myriad equipment on route such as capacitor banks and transformers. In addition to being heterogeneous, no two systems are alike. Fig. 1 shows a generic PLC system diagram. Considering the utility network for delivering power, distribution typically begins at a substation, which connects upstream into the high-voltage transmission or sub-transmission system. From the substation, electricity traverses multiple kilometers (on average) at medium voltage (MV) levels (multiple kilovolts), after which point it goes through a distribution ("step-down") transformer (also called a low-voltage, or LV, transformer) to reach the end-users. Most systems have a "tree" design, where multiple end-users tap off from a shared distribution transformer, and distribution transformers themselves branch

[3] Shannon's Theorem relates error-free transmission capacity C, given a bandwidth W (hertz) and signal-to-noise ratio (S/N): $C = W \log_2(1 + S/N)$.

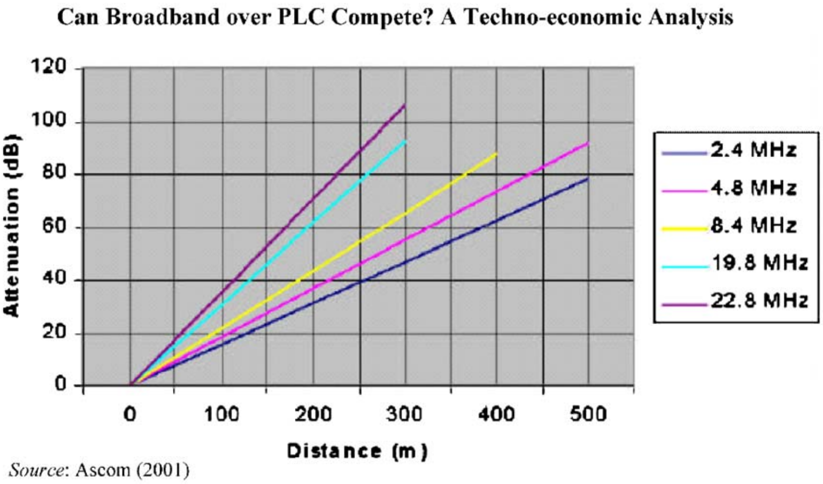

Fig. 2. Average measured attenuation (dB) versus distance for outdoor powerlines as a function of frequency (in Europe). Decibels (dB) are a logarithmic ratio, so the differences are quite dramatic. Lower signals received equate to lower bitrates, limited by channel capacity (Shannon's Theorem—Footnote 3). Three decibels attenuation is approximately halving of the signal.

off from a feeder line coming from the substation. US utilities typically serve on the order of 4–8 end-users per distribution transformer, give or take, and thus are able to use relatively small distribution transformers. In contrast, in Europe and Asia, most distribution transformers feed 100–200 end-users.[4] Of course, different utilities or different consumer mixes can lead to different power network designs. The different power systems and grid designs make PLC standardization—and thus market volume—more difficult, as do the different regulations in different countries.[5]

Based on Fig. 1, data from the Internet can enter (or leave) at the substation level, where specialized equipment generates the data signals that are coupled (physically attached) onto the MV wire. At the other end, the consumer connects their computer(s) to a PLC modem—the Customer Premises Equipment (CPE)[6]—which plugs into a power socket. There are several important technical issues in this simple scheme. For starters, the signal attenuates as it goes over the line, with higher losses at higher frequencies (Fig. 2). Given emission limits that restrict boosting the transmission signal, the only solution is the use of repeaters en-route, increasing the costs. Secondly, the LV transformers act as a low-pass filter, allowing electricity through with low losses but not higher frequencies. This is why most solutions rely on bypassing the distribution

[4] Another difference is in the level of shielded or underground cabling used, which is rare in overhead lines in the United States. This has implications for radiation of electromagnetic signals and interference issues.

[5] Whether the power delivery system is based on balanced loading (like in the US, Japan, and most of Europe) or unbalanced (UK and Australia) strongly affects the radio frequency emissions (Australian Communications Authority, 2003).

[6] The Homeplug Powerline Alliance (http://www.homeplug.com/index_basic.html) has issued a standard for in-home networking based on PLC, to create a LAN. Many broadband access solutions utilize the same equipment as the CPE, which helps lower costs and introduces plug-and-play for end users. Homeplug certified devices are typically rated as being capable of 12–14 Mbps.

transformer (though a few designs have signals go between the two sides of the transformer through ambient coupling). Such a by-pass device (Fig. 1) acts as a natural aggregation or concentration point, allowing statistical multiplexing across the system (sharing the bandwidth). The last issue is that the system is based on shared bandwidth, in part due to the tree design of the infrastructure. While an opportunity in terms of sharing capital equipment costs across users, shared infrastructures also lead to congestion, multiplexing, interference, and security concerns. To overcome these issues, PLC solutions rely on sophisticated signal processing and encoding. Typically, the physical layer and coding is based on orthogonal frequency division multiplexing (OFDM), and sometimes on spread-spectrum techniques. OFDM offers not only spectral efficiency, but also robustness against interference, a major concern in noisy electrical networks. Adaptive encoding schemes allow the nodes to balance signals across different frequency sub-channels, overcoming variances in the infrastructure and its quality as well as unpredictable sources of noise (such as end-user appliances). Because of its shared nature, PLC solutions use medium access control (MAC) protocols like carrier sense multiple access/collision avoidance (CSMA/CA) or variants thereof, as well as other techniques such as time or frequency division multiplexing and protocols such as VLANs (virtual local area networks, defined in the standard IEEE 802.1q). The Homeplug standard as implemented also uses 56-bit (DES) encryption, to assure consumers their data will not be compromised. Realistically, this is only a modest level of encryption, but provides some level of protection. In addition, as only a handful of homes will share a given LV transformer, sharing should not pose significant limitations on the technology, even if other Homeplug devices are also used for in-home (LAN) connectivity.[7] The chipsets for PLC are available commercially from several vendors, notably DS2 and Enikia. Leading designs today offer 45 Mbps of raw throughput (typically asymmetrically—27 Mbps downstream and 18 Mbps upstream), with the promise of 100 or even 200 Mbps capabilities within a year or two. However, this connectivity would be shared by all the users in that segment of the network.

Even if there are, say, 5 users sharing the same LV transformer, they would not receive $45 \div 5 = 9$ Mbps of throughput (six down and three up), since upstream, on the MV line, they are sharing the signal with many other users of different LV transformers. The theoretical capabilities of PLC may be high, but the effective throughput depends on the amount of oversubscription and sharing built into the design. In all Internet connectivity solutions service providers typically assume some level of sharing of capacity between users—multiplexing—to take advantage of the non-simultaneous usage patterns of most users and the inherently bursty nature of packetized data communications. Even in DSL deployments, which are point-to-point access solutions, the uplinking includes explicit oversubscription. The main difference between technologies is at which point in the network there is multiplexing, and by how much. Cable Modem broadband is somewhat similar to PLC in that bandwidth is shared amongst users at the access level. However, the total bandwidth of cable is significantly higher, most of which is used for (shared) video transmission.

[7] In countries where many more homes share an LV transformer, there may be more issues with sharing, especially based on Homeplug 1.0 based CPEs (let alone the upcoming next generation of Homeplug, Homeplug AV, which should operate at 100 Mbps). While the number of CPEs using PLC for broadband Internet connectivity would be less than the design limit (usually about 253 homes, based on Network Layer (Layer 3) interfaces), more Homeplug devices used *within* a home might create data congestion or losses at the Data Link Layer, Layer 2 (requiring retransmission—thus lowering the throughput).

The uplinking from the PLC system to the rest of the Internet is typically done through traditional telecom means, through optical fiber or leased line, sometimes to the service provider's data center. Utilities often have some uplinking/connectivity to their substations for control and other purposes, though not at speeds fast enough for broadband Internet provision to consumers. One alternative design to the generic one presented thus far is to utilize optical fiber connectivity deeper into the system, instead of aggregating at the substation. This can increase the throughput for consumers, but depends on the availability of fiber as well as options for housing equipment mid-way.[8] Another variant design comes from Amperion, whose PLC Medium voltage (MV) technology is used to transmit aggregated signals but the last hop to the end-user is through wireless—802.11 technology.[9] This model saves on some of the costs of the transformer bypass, and can potentially allow greater sharing of access in the final drop.

3. Business plans and regulations

Regulations affecting PLC can be categorized into two spheres, technical and business. The former deals with what technologies and power emission levels are acceptable, while the latter determines how businesses can operate on commercial grounds (covering aspects like bundling, open-access, etc.).

The US Federal Communications Commission (FCC) is encouraging PLC systems as an alternative to the duopoly of cable modems and DSL. Their recent rulings seem to indicate they are shifting the emphasis from intra-modal competition (e.g. from Unbundled Network Elements-Policy—UNE-P) to inter-modal competition. In that sense, Michael Powell, the chairman of the FCC, praised recent PLC developments as a "monumental breakthrough in technology." However, this glosses-over a number of issues regarding ownership, open access, cost allocation (affiliate transactions), etc., as well as technical issues relating to radio frequency emissions and interference.

PLC field trials have been operating in the US for over a year—with very recent commercial deployment in a few pockets in Q1 2004—and the basis for the current approvals stems from the Commission's existing rules for carrier current systems ("CCS") (May 2002 Ruling). Technical issues were put off into the future, especially regarding FCC Part 15 (the part of the FCC Rules and Regulations covering radiofrequency emissions), which mandates such communication systems must accept interference from other authorized systems and not cause interference in those (licensed) systems, pending further standardization and international coordination. PLC systems have been categorized as unintentional radiators, since their primary means of communications is through conduction. Given that there are other licensed and authorized users

[8] In general, the cost of fiber (including installation) dwarfs equipment cost in FTTH designs.

[9] 802.11 b technology, also known as WiFi, is a standard unlicensed spectrum wireless technology, operating at approximately 2.4 GHz. Originally created as an LAN technology, it is now being deployed outdoors as an access technology. However, wireless systems have potentially greater issues of interference and security, given that eavesdropping can be done more unobtrusively than with shared PLC systems. In addition, it is unclear how WiFi would perform if there were many users sharing the spectrum, especially ones not part of the system. WiFi is already quite popular amongst users, and being unlicensed, it is hard to control intentional or unintentional interference or congestion.

within the same frequency bands as PLC (such as amateur radio and some public safety systems), much of objections relate to emissions radiated from powerlines and interference with other communications. This was reported to be a major issue with Nortel's NORWEB PLC trial in the UK (especially in conjunction with streetlamps that became antennae for emissions) (eHam.net, 2001), which was abruptly abandoned. The National Organization for Amateur Radio (ARRL) also seeks to limit PLC in the US citing interference issues (ARRL, 2004).

To address these issues, the FCC issued a notice of proposed rulemaking (NOPR) to amend the Part 15 rules (ET Docket 04-37, released February 23, 2004). This proposal sought to balance emission concerns with the need for supporting technologies such as PLC for increased broadband in the US. Based on feedback from their Notice of Intent on PLC (ET Docket No. 03-104, released April 27, 2003), the rulemaking states that PLC technology could overcome emissions and interference concerns through adaptive signaling (varying emissions in specific sub-frequencies). In addition, proponents emphasized rural broadband options and how PLC could help electricity utilities improve operations and performance, including demand side management. The proposed rulemaking seeks additional measurements in situ for emissions, and proposes exemption from *conducted* emissions for PLC, but maintains Part 15 *radiated* emissions standards (FCC, 2004). It is worth mentioning that there are no worldwide standards for PLC emissions, but FCC Part 15 emissions appear more liberal than competing regulations in Europe (such as NB30 in Germany); the difference is estimated to be 10 dB or more (about an order of magnitude) (Electronic Communications Committee, 2003). Indeed, the Ministry of Telecommunications in Japan, after monitoring several field trials for PLC, considers their radio-communication interference risks too high to allow widespread deployment (Australian Communications Authority, 2003).[10]

While all the commissioners supported PLC, as well as proposals for technical fixes to interference issues (such as the use of "notches" for adaptive transmission—frequencies where emissions would dynamically be lowered to prevent interference), there was dissent regarding the non-technical aspects. Specifically, how could PLC be established to ensure universal service, E911, competition, etc., and how should the (separately) regulated power business and unregulated telecom business interact?[11] Given that most power distribution utilities in the US are still regulated, a common expectation is for them to create a subsidiary for PLC and/or other telecom ventures, and many have done so already. This entity could provide retail services (perhaps as a joint venture), or it could only offer the infrastructure on which an Internet service provider (ISP) could offer retail services. From an analysis perspective, if full cost accounting is done, ownership and such issues should not significantly affect the techno-economics.

In terms of the business case, this analysis examines PLC on somewhat equal footing to cable modems and DSL systems, on a largely incremental basis. There is no costing for the poles or

[10] The stricter limits on emissions offset many of the benefits from increased sharing possible due to more consumers behind a common LV transformer.

[11] Statement of Commissioner Michael J. Copps Dissenting in Part and Approving in Part [NOPR on PLC]: "Is it right to allow electricity rate payers to pay higher bills every month to subsidize an electric company's foray into broadband?" This is a delicate issue, with significant gray area. A power utility can argue that the telecom infrastructure is for their own operations, including Automated Meter Reading. Cable companies successfully used this argument (the ability to provide pay-per-view and video on demand) as a cover for investments into broadband.

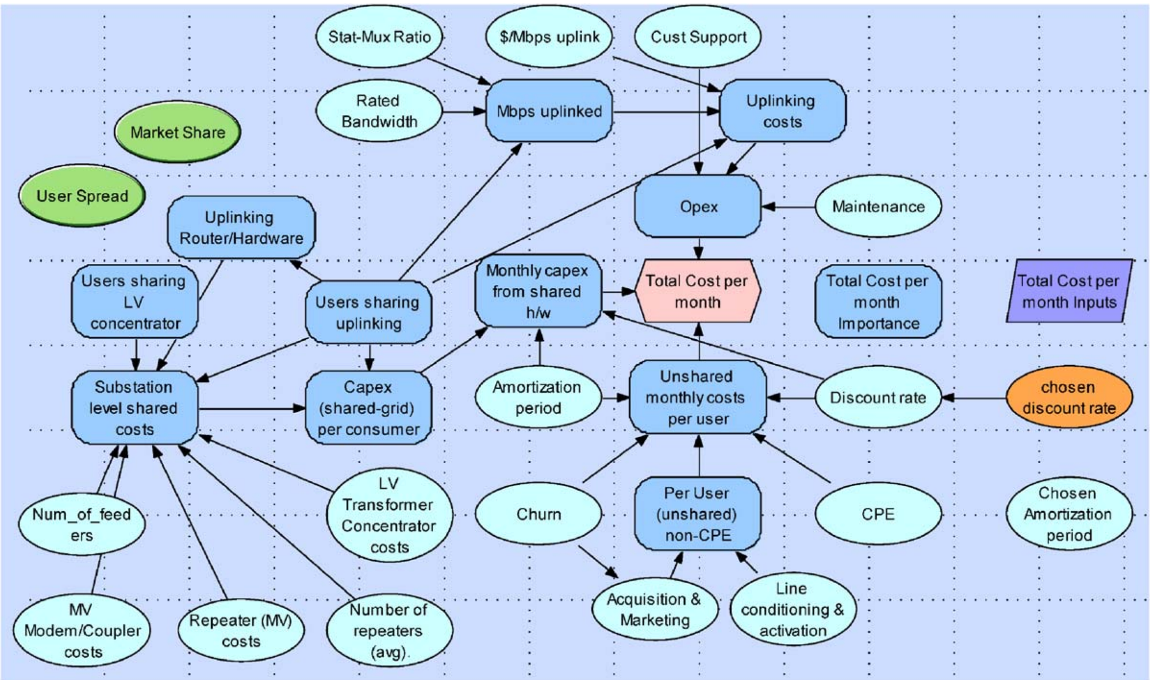

Fig. 3. PLC analysis model (simplified). This model snapshot does not show all the interrelations and correlations between input variables (for clarity sake). The objective function is the total cost per month, consisting of opex, shared capex (amortized into monthly costs), and unshared one-time costs. Given the wide uncertainty in input parameters, the analysis uses a stochastic model, with a sample size of 10,000.

overhead wire; neither are such costs considered when comparing PLC's alternative solutions. On the other hand, if such costs are factored in, solutions such as fixed broadband wireless begin to look more attractive.[12] A fundamental issue is whether PLC will be treated as a telecommunications service (like DSL) or an information service (like cable was classified by the FCC, until the courts intervened in 2003). The former entailed numerous restrictions and obligations like open access. At least for now, it appears that the FCC will not impose cumbersome restrictions on PLC.

4. Model description

Because of the great uncertainty in input parameters, the analysis relies on stochastic modeling to better understand PLC economics. The modeling environment used was Analytica™, and the analysis was performed through a Monte Carlo, or stochastic, simulation (specifically, a Median Latin Hypercube simulation).

[12] Spectrum might or might not be expensive, depending on the frequency and the sale or auction method.

Fig. 3 shows the major components of the model used to analyze a PLC system. The model is for an end-to-end PLC system, covering low-voltage and medium-voltage PLC communications. Required equipment can be shared or individual (such as the CPE[13]), and there are also other one-time costs such as line-conditioning and activation. The shared infrastructure begins at the substation where an uplinking router and other hardware are required as well as a medium voltage coupler/modem. Depending on the number of feeders emanating from the substation, different MV couplers are needed. At every distribution transformer, a concentrator cum transformer bypass is required. This device interacts with the CPE on the low-voltage side, multiplexes the signals, and then transfers the signals to the medium-voltage line, bypassing the transformer. In addition, depending on the distances involved, repeaters might be needed to extend the signal. These are assumed to be on the medium voltage line. In addition to the one-time costs, which are amortized over specific periods, there are also explicit calculations of monthly operating costs. These include customer relations/billing, maintenance, and uplinking. Uplinking costs are the fees paid to the upstream (sometimes backbone) provider, and depend on a number of assumptions including the statistical multiplexing (oversubscription) ratio and the rated bandwidth per consumer. The end result is an estimate of the monthly costs, factoring in a cost of capital.

Table 1 indicates the ranges for the parameters; unless otherwise indicated, because of uncertainty in actual values, the model uses uniform probability distributions across the ranges shown. Providers have been hesitant to release costing information publicly, and so this model relies on realistic ranges based on informal discussions and web reports.

One unique characteristic of this model, compared to simple deterministic models, is the explicit treatment of user mix, location, and market share. Given the fact that PLC is a shared medium, it matters greatly how many users lie behind shared equipment. The model uses two parameters to quantify the user mix, location, etc.: ''market share'' and ''user spread.'' While not shown explicitly in Fig. 3, these two parameters are inputs to most other variables in the model. Market share can vary from 2.5% to 7.5%.[14] This is quite aggressive when considering the total broadband share in the United States is only about a quarter of the total households (end of 2003). User spread is a proxy variable for the extent end-users lie behind shared equipment—a zero value corresponds to ''bad luck'' distribution of only one user behind an LV transformer, while a value of one leads to 2–4 users behind the same LV transformer on average, depending on the market share.

This model assumes that the minimum practical equipment required is installed; no areawise blanket coverage is envisaged. This means that the low-voltage transformer concentrator is only costed in when a paying customer lies behind that particular transformer. Of course, the best-case scenario would be when the next customer also sits behind that same low-voltage transformer. In practice, a provider might need to advance deploy all the equipment, to ensure there is no delay in a consumer being able to sign up when they are within the geographic market. While this may raise upfront costs, it might provide an interesting differentiator—a consumer can go to a retail store, buy the Homeplug CPE, and connect almost instantly.

[13] While some deployments rely on the consumer buying the CPE from retail stores (Homeplug compliant devices), the model assumes the provider gives this as part of a contract, similar to what is done for cable and DSL.

[14] This is the overall market share. The share within a region, of course, would be higher.

Table 1
Model input parameters, indicating low, median, and high values used in the simulation

	Units	Low	Median	High	Distribution
Monthly operating expenditure					
Customer support and management	$/mo.	5	6	7	Uniform
Maintenance	$/mo.	3	4	5	Uniform
Uplinking costs	$/mo.				(calculated)
$/Mbps uplink	$ per Mbps/mo.	80	100	120	Uniform
Statistical multiplexing ratio		30	50	70	Uniform
Rated bandwidth (per user—can burst higher)	Mbps	1	2	3	Uniform
Per user unshared costs					
CPE	$	30	40	50	
Acquisition and marketing	$	50	100	150	Function of Market Share and Churn
Line conditioning and activation	$	75	100	125	
Shared costs					
Uplinking router and hardware	$	5000 plus a function of uplink Mbps			
Medium voltage coupler/modem	$	300	500	700	Uniform
Repeater	$	500	1000	1500	Uniform
Number of repeaters (avg.)		2	2.5	3	Uniform
Low-voltage transformer concentrator/bypass	$	300	500	700	Uniform
Other parameters					
Churn (multiplier for amortization)		0.5	1	1.5	Uniform
Discount rate	%	7.5	10	12.5	Uniform
Amortization period	Years	3	5	7	Parametric
Market share	%	2.5	4.0	7.5	Asymmetric
User locational overlap factor (“user spread”)		(dummy variable)			Asymmetric; median below 0.5

Estimated from various sources—off the web as well as through direct communication. All monetary values are US$ unless stated otherwise. Most of the values chosen are plausible, if not optimistic. For example, given the hazardous conditions in power systems, where specialized personnel are required, installation costs have been estimated at US$200–300 for certain deployments in Japan (Sakai, 2003). On the other hand, one trial deployment showed that with volume and expected cost reductions, the installation would be somewhat over US$100 per user (PLC Utilities Alliance, 2004). The numbers shown assume volume deployment, and are not seen today. These are valid for a generic deployment only; variations such as deep fiber would, of course, lead to slightly different results.

The model does not claim to be comprehensive. For example, it does not account for differences between different classes of consumers, even residential versus commercial. However, like TELRIC,[15] it uses forward-looking cost and network impact cost numbers.

[15] Total element long run incremental cost.

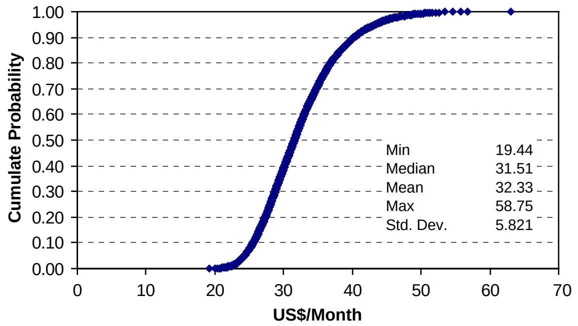

Fig. 4. Cumulative probability distribution for monthly PLC costs. This assumes the parameters as per Table 1.

5. Results

The model indicates that PLC costs might be about US$32 per month (Fig. 4), based on the assumptions shown. Of course, one might disagree with any parameter value chosen, but sensitivity analysis indicates general robustness of the results presented. Given the fact that many such numbers are either unpublished or unknown (and extrapolating from DSL or cable experience might be somewhat misleading—discussed below), this analysis is a first cut at quantifying the costs of PLC. It is important to remember that these are just costs, based on assumed discount rates for capital. Profits and profitability are not yet factored in.

One of the key parameters PLC proponents cite is cost per home passed, with declarations that this is now in the US$100 range.[16] However, given the fact that many potential consumers, even if behind a transformer that has the required equipment, may choose not to avail of PLC, a more important question is how many customers per *serviced transformer* does the company have. Vendors have claimed profitability with just one serviced home per transformer.[17] This model assumes this to be a poor case of user spread, with the best-case scenario with four consumers per LV transformer. Table 2 shows the model calculations, averaging almost 1.7 consumers per distribution (LV) transformer. The total capital costs per consumer (excluding CPE) average about US$85 in the model, assuming an average of 6 homes passed per LV transformer, similar to numbers reported by PLC companies.

Marketing and acquisition costs are treated as one-time unshared costs, for simplicity sake. Churn is used as a multiplier that affects not only marketing costs (high churn equates to higher marketing needs) but also it directly affects the time period for amortization of the CPE (most other equipment can be reused amongst a different user in the system). In addition to the one-time costs, there are operating costs such as bandwidth for uplinking. In the model, assuming 2 Mbps rated bandwidth (with the ability to burst higher, of course, just like with cable networks), the monthly per user uplinking cost comes to US$4.2, close to estimates seen for the DSL industry. One result that is robust across most assumption ranges is that operating expenditures

[16] Stated by industry representatives at CITI's PLC III Workshop, March 20, 2003 at the Columbia Institute for Tele-Information (CITI), New York.

[17] Stated by industry representatives at CITI's PLC III Workshop, March 20, 2003 at the Columbia Institute for Tele-Information (CITI), New York.

Table 2
Number of consumers serviced per LV (Distribution) transformer

				User spread		
Min	1					
Median	1.578			0	0.5	1
Mean	1.669	Market	2.5%	1	1.5	2
Max	3.762	Share	5.0%	1	2	3
Std. dev.	0.4971		7.5%	1	2.5	4

This is calculated as a function of market share and user spread, which are themselves probabilistic distributions. The calculations to the left are probabilistic, while those on the right are parametric, with other input parameters at their median value as per Table 1.

(opex) are about 45% of the total costs. There are indications that vendors consider operating costs to be higher than capital costs for almost all the access technologies, showing that the costs of equipment and technology have diminished sufficiently. However, it is unclear if installation costs are bundled as capital expenses or treated as operational costs. In addition, the numbers used for maintenance and other operating costs might differ, especially for the case of uplinking bandwidth costs.[18] Given the increased trend in peer-to-peer traffic, it is not unreasonable to expect uplinking costs to remain high.

5.1. Sensitivity and robustness

Given the wide range of monthly costs seen in Fig. 3, sensitivity analysis is very important for determining the robustness of the model. The analysis uses stochastic modeling as well as parametric modeling for this. Fig. 5 shows the results of an importance analysis for the relative importance of the varying input parameters.[19] The most important variable, under the assumptions of Table 1, is the time period for amortization of the equipment. Given the fast-changing nature of the telecom industry, even though the equipment should have a longer physical life than assumed, the median value for economic purposes is assumed to be 5 years. However, in a very competitive environment, instead of the nominal 5 years, equipment might need to be amortized sooner, and the implications are non-linear.[20] Table 3 shows the impact of amortization period on the economics, assuming median values for other parameters.

[18] One study shows higher uplinking costs and lower maintenance costs for cable operators. (Bazinet, Crossman, & Wang, 2002).

[19] Importance is the rank-order correlation (Spearman's rank correlation) between the sample of output values and the sample for each uncertain input. It is a robust measure of the uncertain contribution because it is insensitive to extreme values and skewed distributions. Unlike commonly used deterministic measures of sensitivity, it averages over the entire joint probability distribution. Therefore, it works well even for models where the sensitivity to one input depends strongly on the value of another. (Taken from the Analytica User's Manual (Lumina Decision Systems, 2003)).

[20] A McKinsey study (2001) indicated that by 2005, because of greater competition, the average time period per consumer would decrease to 3.5 years. Of course, most of the other shared equipment can be reutilized for other consumers (except the low-voltage transformer concentrator, depending on the user location). The model accounts for this detail, with CPE costs amortized as a function of churn.

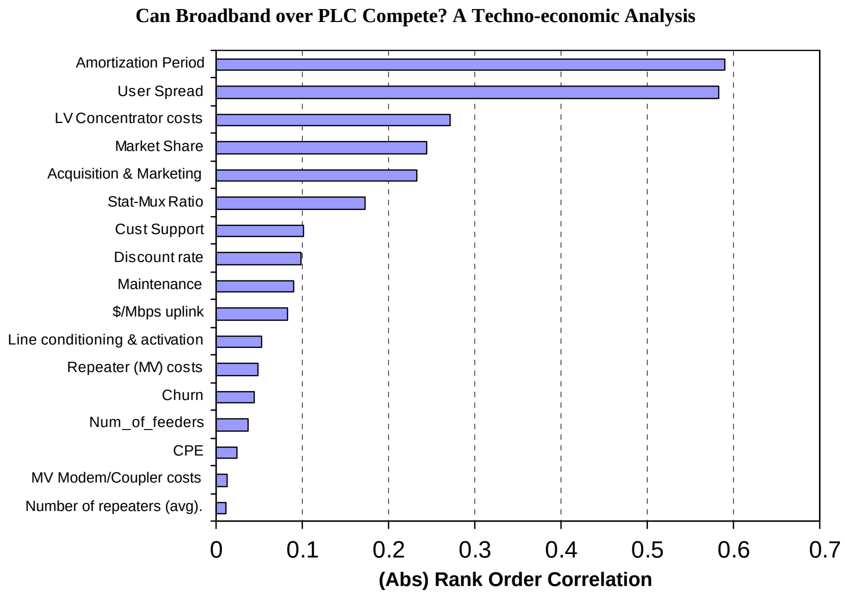

Fig. 5. Importance analysis for input parameters. This shows the absolute rank order correlation for input variables, indicating their relative importance. Of course, there is some interrelation between these parameters, and some variables are not in the hands of the service provider, e.g., market share.

Table 3
Monthly PLC costs (US$) as a function of amortization and user spread

		User spread		
		0	0.5	1
	3	48.6	35.3	31.3
Amortization period (years)	5	36.7	28.0	25.4
	7	31.7	24.9	22.9

The other parameters are chosen at median values, as per Table 1, except market share, which is assumed to be 5%.

As expected, user distribution is one of the most important factors when determining monthly costs, followed by the shared distribution transformer concentrator/coupler capital costs. Other than the LV transformer concentrator capital costs, most other capital expenditures have relatively low impact on monthly costs. The uplink cost is unlikely to be the hands of the PLC service provider, and the statistical multiplexing (oversubscription) ratio is a business decision the provider will need to take depending on the quality and perceived quality for the end users. Of course, in a competitive environment, a service provider will need to ensure high effective throughputs for end users. This is even more important when high-end (video) services are envisaged. Other important factors such as market share, acquisition/marketing costs and even cost of capital all depend on the competitive nature of the business. Given improvements in DSL and cable technologies, as well as emerging competition from FTTH and wireless, it would be safe to expect increasing competitiveness and churn. Churn might likely have implications for

Table 4
Amortized monthly shared capital costs (US$), excluding CPE (US$)

		User spread		
		0	0.5	1
Market share	2.50%	20.1	11.1	8.2
	5.00%	17.4	8.7	6.1
	7.50%	16.1	7.3	5.0

The other parameters are chosen at median values, as per Table 1.

Table 5
Monthly PLC costs (US$) as a function of user spread and LV transformer concentrator capital costs

		User spread		
		0	0.5	1
LV Concentrator Costs	300	32.3	25.8	23.9
	500	36.7	28.0	25.4
	700	41.1	30.2	26.8

The other parameters are chosen at median values, as per Table 1 except market share, which is assumed to be 5%.

Table 6
Monthly PLC costs (US$) for optimistic capital cost parameters

		User spread		
		0	0.5	1
Amortization period (years)	3	36.5	27.9	25.4
	5	28.1	22.5	20.8
	7	24.5	20.1	18.8

This assumes optimistic values for all the capital costs, both the shared and unshared, as well as all other factors that are dependent only on the PLC provider (maintenance, customer service, and line conditioning/activation). The remaining parameters that are not in the hands of the provider (such as uplinking costs) are chosen at median values, as per Table 1, except market share, which is assumed to be 5%.

marketing costs, but this model, in the absence of data, does not account for that. The impact of market share and user spread on monthly amortized capex can be seen in Table 4.

Examining the sensitivity to two important factors, user spread and LV concentrator capital costs, Table 5 shows wide variation in monthly costs based on the assumptions. A similar importance of market share was also seen in a DSL and cable model by Fryxell (2002), where low market shares could lead to a fourfold increase in annualized capital costs. Even considering an optimistic case for capital costs within the near term, the monthly cost of the PLC system is unlikely to be dramatically lower than US$25 per month (Table 6).

The results, of course, have the expected provisos attached to them. For example, if there is significant signal interference, providers would have to adjust the signal strength, reducing the throughput or requiring further repeaters. If users consume more bandwidth than projections infer (e.g., due to increased peer-to-peer applications, or video/video-conferencing), this impacts uplinking costs and might even require a redesign since the MV line running PLC has limited total bandwidth. However, technology costs could fall dramatically, especially with higher volume. In addition, within a region or niche market, the competitive pressures might be much lower, allowing for higher market share and greater sharing of equipment, marketing, and maintenance costs amongst subscribers.

5.2. Cable, DSL, and competition

Many comparative analyses suffer from *Parmenides Fallacy*, which is comparing the future to the present, instead of comparing it to alternative futures. At CITI's PLC III Workshop, an industry representative, when questioned about economics, said PLC does not need to be cheaper than the alternatives, it just needs to be profitable at offered prices. This appears short-sighted in that entrenched alternatives can easily lower their prices to compete. Cable has similar data bandwidth today, also shared, but companies justified their Internet services rollout and investment of billions of dollars due to the large base of users for video services.

There are many indications that the prices for cable and DSL will fall dramatically in the next few years and their performance will continue to improve. Already, DSL has cut its prices to US$30–35 per month in many regions, driven by competition from cable systems. In addition, the capital expenditure for a DSL system is dropping dramatically, and is now well below US$100 per user, including the CPE (DSL Prime, 2004). (In the analysis model, such capital costs would lead to amortized capex costs of a quarter of the baseline PLC capital costs, or just US$2.2 per month! Of course, these are equipment capital costs only, excluding any installation or line conditioning charges.) Examining DSL prices in Japan and Korea, these are already below US$25–30 per month retail, that too for *much* higher speeds.[21] These systems are based on pre-standard VDSL, offering tens of Mbps per user. Use of such variants of DSL in the US is some time away due to both longer distances and the physical plant design. But, if and when DSL upgrades its speeds, these would be unshared speeds at least in the access portion of the network.

Total bandwidth is important when considering the applications and services consumers demand from their providers. Given competition amongst access technologies, many analysts believe the "triple play" of services (voice, video, and broadband data) is important for not only gaining customer loyalty and traction, but for justifying the investments required for upgraded speeds. Of the three major technologies, cable systems offer the highest bandwidth, albeit shared. However, with newer standards, such as DOCSIS 1.1 and 2.0, cable is now ready to offer voice services. DSL, by definition, is geared to providing voice services, but typically lacks the bandwidth to offer even switched video (especially in the US). Considering 2–6 Mbps requirements for compressed video, only newer DSL variants can offer appropriate bandwidth.

[21] Wholesale prices are especially lower, perhaps due to differences in accounting requirements and methodology (Sakai, 2003).

To offer voice services, PLC would require quality-of-service (QoS) mechanisms that are today not standardized, but this can be expected shortly. However, the total shared bandwidth might be constrained for widespread video usage. Cable systems, though also shared, can increase the effective throughput through several means, including reducing the physical sharing of the system, changing some bands used for TV into data, and also opening higher frequencies on the cable through newer technology equipment. In the interim, cable systems have faced difficulties with consumers overusing shared bandwidth, an issue that might plague PLC as well.[22] PLC will likely take at least one or two more years to reach 100 Mbps of shared bandwidth in deployment. In addition, switched video is likely to raise operating and uplink and costs, compared to best effort data connectivity and high-quality unidirectional broadcast for video through cable.

This raises the issue of timing and window of opportunity. At one level, PLC providers would want to wait until the technology is slightly more robust and the raw speeds have increased to at least 100 Mbps. On the other hand, cable and DSL continue to gain deployment and penetration. The window for PLC becomes more limited when analyzing the longer-term horizon, which includes FTTH or FTTC. While in the United States FTTH is some years away, in Japan it is already an emerging competitor, and expected to become mainstream within a few years. FTTH offers an order or two of magnitude more bandwidth, and greater future proofing. Its main limitation is on the physical infrastructure—laying fresh fiber is expensive, and greenfield FTTH deployments are estimated at capital investments of over US$1,000 per user (conventional wisdom). On the other hand, there might be synergies between the so-called deep fiber and PLC, whereby a utility/provider could use PLC as a last-hop solution. This makes even more sense if there is a major service provider looking to expand the broadband market while not being beholden to the incumbents (ideal candidates include Yahoo/MSN/Earthlink or long-distance companies who lack local physical presence such as AT&T or MCI).

6. Implications

Given the estimated monthly costs of PLC of around US$35 per month (factoring in profitability), it is unclear whether there is a compelling business case for PLC in the near term based on *price* for the end-user. Of course, economics is not the only factor in determining the success of PLC or any other broadband technology. User satisfaction, customer loyalty, branding, and competition (alternatives) are all important factors as well, and the main challenge will be in smooth execution. However, there is increasing evidence that users are price-sensitive, not only in terms of whether to use broadband, but to choose between providers.[23] Turnover rates are higher, and increased competition will only increase the churn. The cellular telephony market gives clear indications of this trend, where incentives and promotions (including free phones—the CPE) are balanced mainly through contractual user lock-in. Indeed, if PLC were to enter the market solely on a price basis, the incumbents are likely to not only match the price, but beat it.

[22] Recently, cable companies have issued notices to some users effectively asking them to curtail their use, claiming their usage pattern violates their user-agreement (which disallow commercial servers, peer-to-peer networking, etc.) (Manjoo, 2004).

[23] Forty-five percent of households in a survey required broadband prices under $30 per month (Bazinet et al., 2002).

The ubiquity of power into American homes and businesses lead some to believe it can offer greater coverage than alternatives, especially for underserved areas. However, it is quite likely that the alternatives have already targeted the more viable (urban) areas, and the theoretical penetration from DSL and cable is quite high.[24] DSL is considered a weak competitor in the US because of its distance limitations. However, DSL technology is improving and in the future deployments could choose either extended distances or higher speeds. In particular, rural areas might be technically feasible for PLC systems, but economically unviable (the same argument would hold for many alternatives). This is because of the need for repeater technology, as the signal attenuates rapidly over long distances. Rural power networks suffer from not only longer distances but also lower densities of users sharing physical equipment (like the LV transformer). Data from Ascom (2001), the European PLC equipment provider, indicate that the drop-off with distance is very pronounced for the higher frequencies, many tens of times dB higher than for lower frequencies (Fig. 2). There are limits to increasing the signal strength based on emission regulations.[25] However, even with the poorer economics, PLC providers may choose to target rural or underserved areas precisely because they would be the only game in town, and thus free to charge the (required) higher rates.[26] However, if one looks into the near future, the one to three years timeframe, it is feasible that broadband wireless (based on IEEE 802.16 technology, also known as WiMax) will prove cost-effective for rural and other underserved areas, especially considered its efficient sharing of infrastructure.

When considering the penetration of PLC, on a total household basis, PLC is unlikely to gain a market share greater than a few percent in the next few years because of the head start that cable and DSL systems have and also the modest penetration of broadband into US homes. There are over 20 million broadband subscribers in the US (Q2 2003) of which almost two-thirds are cable modem subscribers (Cable Datacom News, 2003). At a recent workshop on PLC technologies, the author asked industry representatives how long it would take for PLC systems to gain traction, or one million users.[27] Their response, 3 years, was regarded as optimistic, given estimates of 1 year just to begin full-fledged commercial deployment. In addition, since the technology is less standardized and power systems vary across utilities (mandating extensive field-testing), there is great variance between utilities in their ability to deploy PLC systems—both technologically and in a business sense. Even if PLC reaches 1 million users in 3 years, during the same time, cable and DSL might have improved significantly, growing by perhaps 30–50% over their existing base.[28]

[24] Of 109 million households in the US, over 80% have broadband available (cable and/or DSL). A little under half (53 million) have access to both cable and DSL (Bazinet et al., 2002). Thus, while PLC might offer competition in some areas, it would suffer competitive pressures on pricing itself from the incumbents.

[25] Indeed, even though the recent NOPR allows PLC from a signal strength (emission) perspective, the second part of the regulations relates to interference. If broadband PLC is found to interfere with other users, it will have to be curtailed or even shut down.

[26] While the model showed lower importance for the number of repeaters, this was based on the low range in the parameter assumptions. It also did not factor in lower user densities or other differences in rural power system topologies.

[27] CITI's PLC III, March 20, 2003 at the Columbia Institute for Tele-Information (CITI), New York.

[28] Q1 2003 saw growth of nearly 10% in just one quarter, for cable and DSL. This is actually a sharp decrease in growth rates, possibly because of seasonal variations, and increasing market saturation (Leichtman Research Group, 2003).

If the commercial picture for PLC is truly so uninspiring, why not let the market decide who the winners and losers might be? If PLC vendors are able to execute well, and bring down costs further than modeled in the analysis, they indeed might have a viable solution. However, reliance on PLC as a means for inter-modal competition might distract from the reality that the broadband market is not fully competitive—evidenced by higher prices in the US than other countries. In addition, the bulk of power distribution utilities are regulated entities; policies must try to ensure that ratepayers as well as stockholders will not be burdened by any overly optimistic ventures into PLC broadband. Even if a subsidiary/standalone entity is created, regulators need to pay careful attention to the allocation of common costs. When accounting for affiliate transactions, balancing non-discrimination with attempts to bundle is difficult. In both cable and DSL, providers often offer lower rates for bundled services.

In the absence of a compelling business case, will utilities (or investors) shell out the hundreds of millions if not billions of dollars required to roll out PLC services? After the recent blackout, it is likely that power utility executives will prioritize the electrical aspects of their network. PLC has been touted as useful for utilities to help their own operations, both in control and automated meter reading (AMR), but this might be misleading. Data needs for utility functions are much lower in bandwidth, and could be optimized with a leaner and cheaper design.[29] If the power system evolves to include real-time pricing, PLC need not be the only mechanism for conveying pricing information to users—any always-on connection can be utilized, including cable modems and DSL (with the appropriate software and conversions as well as gateway). In addition, utilities are considered risk-averse, and they also dislike significant capital expenditure in a deregulated environment. According to some critics (Morgan & Lave, 2003), this was one of the factors that led to recent under-investment in transmission, which led to the 2003 US blackout. This mindset is considered one reason AMR has not taken off in the US. In contrast, Europe is pushing ahead with AMR (but not based on broadband PLC solutions).

Even if not economically compelling per se, some utilities might pursue PLC with power markets in mind. In a deregulated power system, the ability to bundle PLC might be a differentiating factor and help create branding or user loyalty. However, regulators must ensure that incumbents do not gain an unfair advantage at the expense of new entrants. At the same time, it appears unfair to restrict utilities from offering telecom services (like the case for some municipalities), especially when there is a compelling business case or synergy. In addition, there are unanswered questions regarding the business model from the utility perspective. Should the utility just be a "wires" company, a wholesale ISP, or a retail ISP? The next few years will show whether PLC can compete in the broadband market.

7. Further work

Given the non-public nature of much of the capital equipment (costs), it is difficult to fully validate the parameters. Using wide ranges, the results are expected to be robust. As more and more costing numbers become available, the next iteration of the analysis can factor in much

[29] The other argument made in favor of PLC, ease of use and customer self-install, also holds true for many other technologies, especially DSL.

greater granularity, especially down to the distribution transformer level. In addition, the model will be expanded to include alternative grid designs, which include wireless, deep fiber and other telecom/access solutions. One variant that needs further examination is rural deployment, a market PLC proponents claim they can serve better than the alternatives.

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