Broadband Communications using High Voltage Transmission Lines – A Review

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Abstract - The possibilities afforded by using an existing transmission line infrastructure for the transport of broadband communications are many ranging from (conventional) A-to-B point-to-point links, to integration of Wi-Fi access points mounted at defined network (power and communications) locations, to operation as a fault-tolerant, rollover backup communications fabric (in conjunction with other transport media, such as optical fiber or terrestrial microwave). As stated by RCR Wireless reporter Jeff Kagan – regarding an ongoing in-field demonstration - *"This is so much more cost effective for the company and so much easier for them to deliver an ultra-fast, gigabit speed, wireless internet connection anywhere there are power lines."* The same situation arises for a utility looking to augment or simply deploy a communications fabric in their region via treating the transmission line infrastructure as a communication fabric thereby reducing the cost and complexity of deployment. A circa 2020 review of broadband over powerlines (BPL) is presented.

1. INTRODUCTION

The possibility of using overhead transmission lines for communication transport – more commonly referred to as "broadband over powerlines (BPL)" - has been an area of study and contemplation for over 100 years [1]. Various schemes involving communication transmission levels, carrier frequencies, modulation formats, and essentially all components of electromagnetic (EM) communications have been examined [2]. Numerous trials have been conducted using a wide variety of transmission line physical media. Commercial products have been developed with a few demonstrations having taken place [3]. A frequent issue associated with BPL has been EM interference manifesting itself as radio frequency interference (RFI) in frequency bands in use by numerous public (government), private and military entities [4]. This led to the US National Telecommunications and Information Administration (NTIA) issuing a Notice of Inquiry (NOI) in 2003 [5] seeking information on potential interference from BPL systems and associated changes that may be needed to accommodate BPL systems in the Federal Communication Commission (FCC) Part 15 rules. NTIA was tasked with examining this situation which led to a study of BPL interference in the <80 MHz range. A report entitled NTIA Report 04-413, Potential Interference From Broadband Over Power Line (BPL) Systems To Federal Government Radiocommunications At 1.7 - 80 MHz, Phase 1 Study [6] was released in 2004. A section extracted from the Report's Executive Summary highlights the general spectre of BPL:

As described in the NOI (Notice of Intent), *"access" BPL* systems transmit Internet and other data at radio frequencies over neighborhood power lines and use electrical *outlets in BPL users' premises as data ports for computers and other devices. "In-house" BPL systems use indoor wiring* for networking *within the user's premises.*

In conducting their technical evaluation of potential BPL interference, NTIA executed three two-week measurement campaigns and used Numerical Electromagnetic Code (NEC) software to characterize BPL signal radiation and propagation. Their findings included differences in interference levels based on EM field polarization (not surprisingly, given the cylindrical nature of power line conductors), and associated peaks and valleys in interference levels identified with measurement proximity to the BPL communication transponders (sometimes referred to as "injectors") across their 1-80 MHz frequency range. A number of recommendations for NTIA/FCC and vendors/users were highlighted in the report, such as:

Mandatory registration of certain parameters of planned and deployed BPL systems would enable radio operators to advise BPL operators of anticipated interference problems and suspected actual interference; thus, registration could substantially facilitate prevention and mitigation of interference. BPL devices should be capable of frequency agility (notching and/or retuning) and power reduction for elimination of interference. NTIA further recommends that BPL developers consider several interference prevention and mitigation measures, including: routine use of the minimum output power needed from each BPL device; avoidance of locally used radio frequencies; differential-mode signal injection oriented to minimize radiation; use of filters and terminations to extinguish BPL signals on power lines where they are not needed; and judicious choice of BPL signal frequencies to decrease radiation.

Of key importance to these studies in the BPL architectures being examined. Fig. 1 presents the four architectures studied.

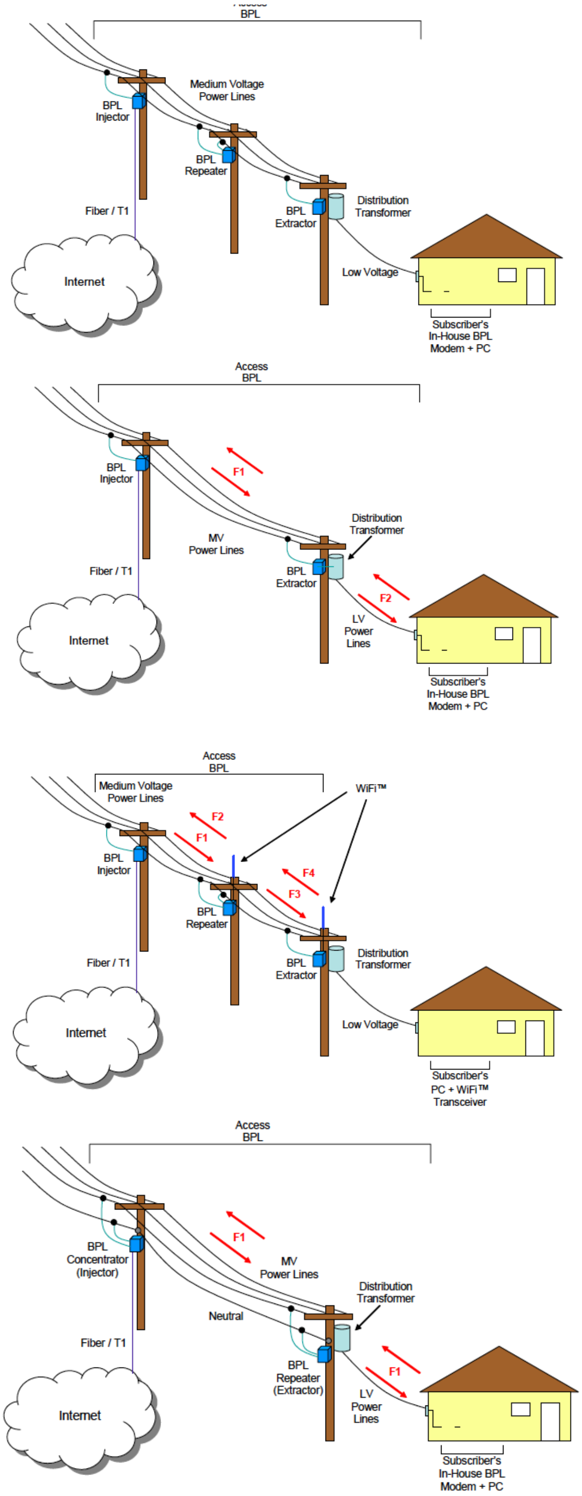

Fig. 1. BPL architectures studied.

The Commission followed the study's recommendations:

Accordingly, NTIA does not recommend that the FCC relax Part 15 field strength limits for BPL systems. Further *based on studies to date, NTIA recommends several "access"* BPL compliance measurement provisions that derive from existing Part 15 measurement guidelines.

2. Continued Study and Contemplation

The NTIA study and associated FCC rulings did not dampen the contemplation of using powerlines for communication signal transmission. What was highlighted is the need for higher frequency operation to avoid the potential interference to a multitude of spectrum users. While not an exhaustive examination of all BPL research since the 2004 NTIA report was issued, a number of relevant activities are worthy of review.

The potential use of BPL for onboard US Navy ship communications was reported in the 2008 MS thesis [7] entitled "Investigation of Broadband Over Power Line Channel Capacity of Shipboard Power System Cables for Ship Communications Networks" concluded that while the estimated channel capacities of the investigated cables obtained from the various simulation studies were significantly less than 100 Mbps with improved channel optimization schemes. Given the widespread existence of these distribution lines in a ship, there is significant potential for the application of BPL technology for use as communication networks for automation in Navy ships.

The 2009 IEEE-Australia paper entitled "Is Broadband over Power-*lines dead?"* [8] examined the case that power-line-carrier (PLC) communications for smart meter, automated meter infrastructure (AMI) and associated low duty cycle, low information bandwidth transmissions present an aggregate bandwidth requirement of <200 kbps. Boundary conditions associated with their Matlab simulation included details such as using a low voltage overhead transmission line operating at distribution utility voltages <7200 Volts, 50 Hz. The conductor chosen consisting of a single aluminum cladsteel (SCAC) cable with three 2.75 mm diameter strands. Their simulation results show that depending on the cable and signal frequency, BPL and PLC can be achieved without causing significant interference – at the radiating carrier frequencies associated with this low data rate.

Schneider's 2009 IEEE Spectrum article entitled "Is This the Moment for Broadband Over Power Lines: Smart grids and the push for rural connectivity" [9] reviewed the continuing intrigue and technical/practical matters associated with BPL.

The 2009 presentation entitled "Radiation and Attenuation of Single Wire Earth Return Power Lines at LF Frequencies" presented by Kikkert and Reid at the 2009 IEEE International Symposium on Power Line Communications and its Applications [10] addressed the interference issues, again, at low frequencies and low-to-moderate data rates (kbps range).

A novel approach to launching communication signals as surface waves[1] transiting along power line conductors was outlined in the 2011 conference paper by Alam et al entitled "Novel Surface Wave Exciters for Power Line Fault Detection and Communications" [11]. While this presentation concentrated on using surface waves for inspection of power lines (launching waves at frequencies <250 MHz then detecting reflections in a manner similar to a conventional electrical/optical time domain reflectometer), the notion of launching much higher frequency waves (~2 GHz) for communication signal transport was discussed. Of particular note was their statements regarding surface wave communications:

Elmore [12] studied the potential for surface wave propagation on overhead un-insulated power lines for possible power line communication application. By using conical shaped slotted launchers mounted on overhead lines, he was able to achieve a broadband response around 2 GHz. Their work involved the design of (possible) conformal antenna, similar to an inverted L monopole antenna, with accompanying network analysis measurements of surface waves launched down specific powerline cables. Their (initial) proposed designs are shown in Fig. 2.

Lazaropoulo published the paper entitled "Broadband Transmission Characteristics Of Overhead High-Voltage Power Line Communication Channels" [13], where high-voltage overhead transmission lines – as opposed to significantly lower voltage distribution lines – were featured as the communication signal transport mechanism. The author used a transmission line matrix (T-Matrix) approach to investigating the attenuation, dispersion and radiation effects associated with higher bandwidth (i.e., higher communication signal carrier frequency) system design. His conclusions, based on theoretical models, not experimentally verified, include:

Unlike the older models that underestimate the broadband transmission potential of overhead HV lines significantly, the results demonstrate that the overhead HV grid is a potentially excellent communications medium, offering low loss characteristics over a 100km repeater span well beyond 100MHz and guarantees the imminent coexistence of low-voltage (LV), medium-voltage (MV), and high-voltage (HV) BPL systems towards a unified transmission/distribution smart grid (SG) power grid.

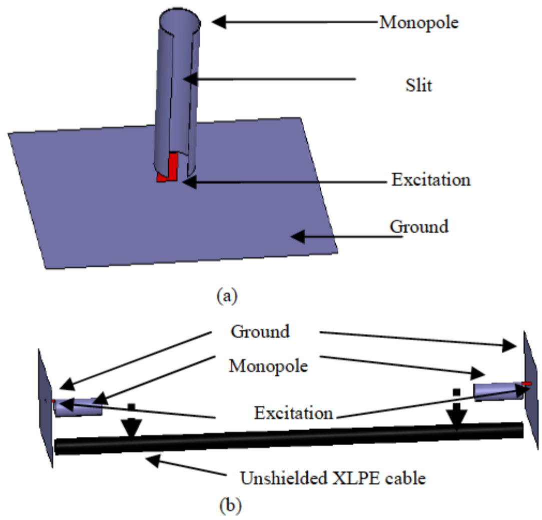

Figure 2. (a) Construction of the vertical wide monopole (b) Signal injection into cable using monopoles, dotted down arrow means monopoles are actually placed on that location of the cable.

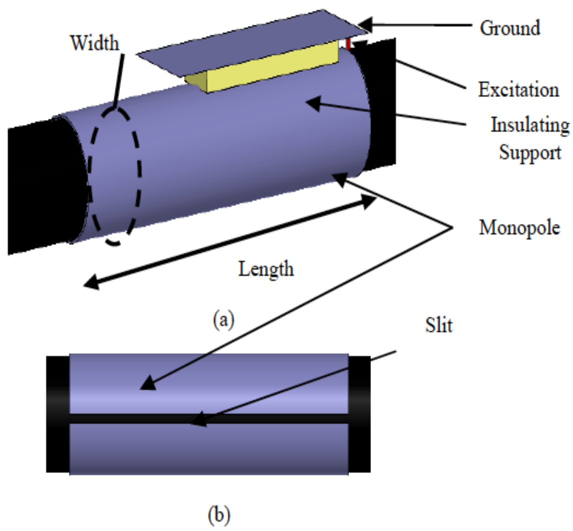

Figure 3. Proposed conformal surface wave exciter- (a) 3-D view (b) bottom view.

Fig. 2. Conformal antenna for launching surface waves onto power line conductors. (source: Alam et al "Novel Surface Wave Exciters for Power Line Fault Detection and Communications").

A wide range of practical considerations are included in this model including factors such as transmission tower design and height, type of electrical conductor wire, voltage levels, etc. Fig. 3 shows the antenna structure used in this analysis.

[1] A surface wave is a wave that travels along the boundary between two different media, such as air and an insulating material.

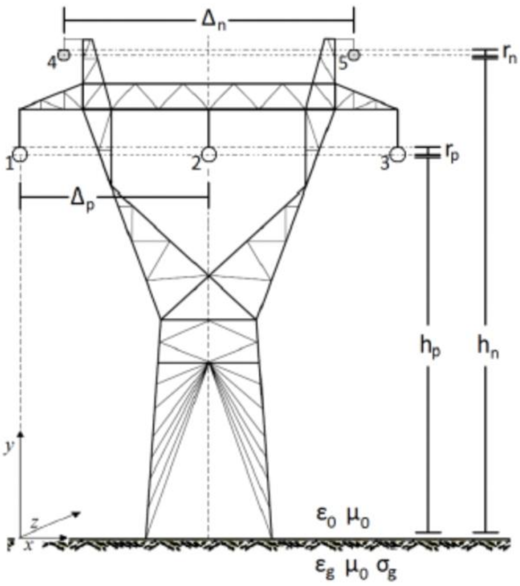

Fig. 3. High voltage (150kV) transmission line tower (from 13).

The paper has an assortment of statements/recommendations based on the simulations, such as:

In most overhead HV/BPL *channels,* "line of site (LOS)" distance rather than multipath is identified as the dominant attenuation factor affecting signal transmission. Therefore, in urban and suburban environments denser overhead HV/BPL networks are preferable. The respective shorter end-to-end connections are primarily affected by multipath.

3. Intellectual Property

During this entire time frame, there have been numerous attempts, worldwide, to find a cost-effective, solution to broadband communications network design that uses transmission lines (power lines) as the physical transport media. Of key interest is a patent awarded in 2015, assigned to AT&T [14], which provides specific details regarding their efforts in bringing a broadband surface wave product for powerline communications to market. Entitled "Surface-Wave Communications and Methods Thereof", the overriding premise of the invention is described in its Abstract:

The system can also include a coupling device that emits the transmission as an electromagnetic wave guided by an outer Surface of a transmission medium. The electromagnetic wave can propagate longitudinally along the Surface of the transmission medium and at least partially around the Surface of the transmission medium.

This patent lists hundreds of prior (USA domestic) patents ranging in date from 1939 to 2015. Similarly, numerous publications and presentations are listed, also over a lengthy timeline. The awarded patent, which in itself was a continuation-in-part of prior filings, clearly states the application space for the described system:

Technical Field: The Subject disclosure relates to wireless communications and more particularly to providing connectivity to base stations and distributed antennas using millimeter wavelength Surface-wave communications.

Note that the AT&T application space involves using the power lines as the transport media to link mobile/cellular base stations, thereby in function acting as a distributed antenna system, operating in the millimeter-wave frequency band (30-300GHz). This point is reinforced in the following section from the patent:

Various embodiments described herein relate to a system that provides a Surface-wave communication system for Small cell deployment and/or a backhaul connection for a small cell deployment. Rather than building new structures, and installing additional fiber and cable, embodiments described herein disclose using high-bandwidth, millimeter wave (30 GHz-300 GHz) communications and existing powerline infrastructure. Aboveground network connections via power lines can provide connectivity to the distributed base stations.

Marketed as Project AirGig, the premise is to provide repeater-cellular base station hardware at locations along an electric power line. A photo of a "node" installed on a distribution pole and crossbar is presented as Fig. 4.

The surface wave launcher design is similar to that described in the 2015 patent [14]. Report of a trial underway in rural Georgia (USA) provides little detail regarding the RF interference issues raised in prior BPL efforts. AT&T is promoting the overall effort – broadband communications with mobile devices – in many media settings (https://www.youtube.com/watch?v=4ApPDP_DbGc). Fig. 5 presents two stills extracted from the YouTube video.

No information regarding system pricing, costs, and implications for utility deployment has been provided. In addition, nothing related to operation/deployment on high voltage transmission lines has been discussed.

Fig. 4. Aerial view of Project AirGig node.

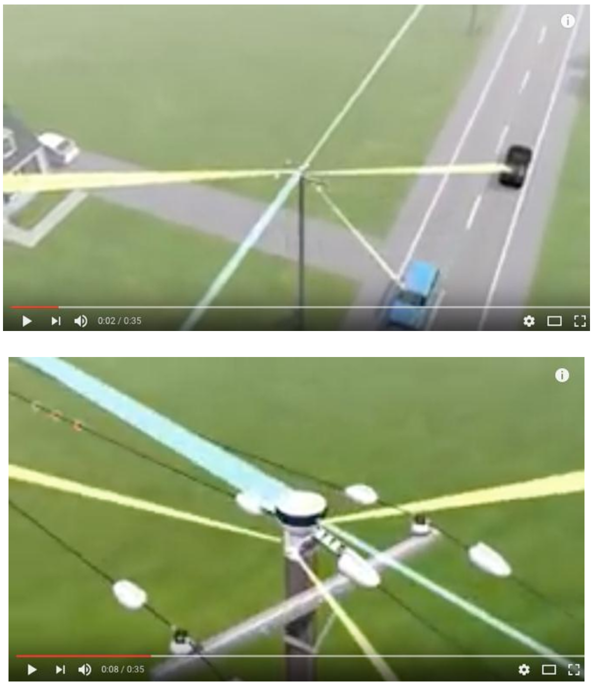

Fig. 5. Scenes from AT&T YouTube AirGig video.

4. Envisioned Future Research

There are a number of key scenarios for validation of HV BPL performance in an operational (utility) setting. It is envisioned that the following research tasks should undertaken:

1. Conduct in-lab, and in-field test of communication/sensor platforms with utility partner, targeting high risk scenarios and locations.
2. Identify possible R&D component development and integration with a partner – data ingest and visualization, utility partner and or commercial partner
3. Incorporation of at-scale collaborative algorithms leading to incorporation within a utility, interconnected regional leading to national scale integrated/hybrid communications design and associated operational model. With accompanying linkage to situational awareness systems.

From a near term perspective – with a nod towards a possible implementation – the following key technical areas should be performed.

1. Investigation into fundamental mechanisms and impediments associated with BPL over high voltage transmission lines.
2. Engagement with controllable field resources such as the National Transmission Technology Research Center and the Extreme Measurement Communication Center (EMC^2) for further evaluation of envisioned HV BPL solutions regarding utilization of high voltage transmission lines.
3. Design an architecture with associated financial model for deployment of a BPL over HV lines for Puerto Rico. Given the state of the island's HV infrastructure it is suggested that the initial focus be on 230KV north-south cross island transmission lines.
4. Investigate enhancements of DOE GMLC [17] developed tools such as Sensor Placement Optimization Took (SPOT) [18] for related communication repeater placement on #3's Puerto Rico lines.

5. Development of distributed communications architectures whose functionalities do not rely on infrastructure availability and provide dynamic networking features, which are resilient to natural disasters; Development of self-healing mechanism to recover certain level of communication to mitigate the impact of damages.

6. Incorporation of developed systems into an existing modular sensor integration platform (such as that deployed at EPB, Chattanooga) with associated proof-of-concept/performance on medium-voltage utility distribution lines.

5. Summary

Broadband over Powerlines (BPL) has been demonstrated for in-home, low-voltage operation with numerous commercial products available. There have been many demonstrations of BPL using distribution-level (<7200 Volts) power lines – with widely varying TRL-level products/instruments [19]. Additional demonstrations involving higher voltage transmission lines have been undertaken with varying results. It is envisioned that future research consisting of a technical and programmatic examination of using high voltage transmission lines for BPL transport with high frequency carriers (thereby lessening the interference issues that have plagued prior BPL activities) be undertaken. The possibility of using overhead transmission lines for communication transport across/throughout Puerto Rico was outlined as a future project. Such a project could include a continual review of academic and private sector activities along with coordination with government-sector related R&D via the Wireless Spectrum Research Development (WSRD) working group [20].

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