IEEE 1901 Access System: An Overview of Its Uniqueness and Motivation

Shmuel Goldfisher, MainNet Communication
Shinji Tanabe, Mitsubishi Electric Corporation

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ABSTRACT

In 2005 the IEEE P1901 Working Group began standardization activities for broadband over power line networks. The process is now in its final stages, and the latest P1901 draft standard is available for sale to the public. The standard is designed to meet both in-home multimedia and utility application requirements including smart grid. The utility requirements and the resulting features that support those requirements were clustered together and form the basis of what is referred to as the utility access cluster. This article explains the aspects of P1901 power line communication technologies designed to address the access cluster. The differences between access and in-home applications, including addressing methods, clock synchronization, smart repetition, quality of service, power saving, and other access unique mechanisms, are also explained.

INTRODUCTION

In June 2005 20 companies agreed to form the IEEE P1901 Working Group (WG) under the sponsorship of the IEEE Communications Society [1]. The resulting IEEE 1901 standard [2] is applicable to both in-home (IH) multimedia and utilities applications.

Access networks usually cover large areas, may consist of hundreds or thousands of nodes, and are usually centrally controlled. There are two main types of access applications offered by utilities: broadband applications and utility applications. Typical broadband applications include providing Internet data access and voice over Internet Protocol (VoIP). Typical utility applications include controlling energy use (smart grid) and building/factory controls.

Utility applications have been getting a lot of attention recently. For example, the IEEE established a dedicated portal for handling this hot topic [3]. There are two primary approaches for implementing utility applications over the power line network:

- A narrowband power line communication (PLC) low-speed approach, for which some solutions are already available
- A broadband PLC (BPL) approach such as the one developed by the IEEE P1901 Working Group.

This article begins by explaining the preference for the broadband PLC approach over a more conventional narrowband PLC approach. Next, we cover the access network's features and requirements (particularly utility systems) and compare them with those needed for IH systems. We then address some of the design differences in detail such as special addressing methods, clock synchronization, repetition, quality of service (QoS), power saving, and centralized time-division multiple access (TDMA) systems for large topology multihopping access systems.

WHY BROADBAND PLC IS NEEDED FOR LARGE-SCALE ACCESS SYSTEMS

The main differences between narrowband (low-speed) and broadband (high-speed) PLC are their bandwidths and the carrier frequencies they use. Figure 1 shows a typical inverter noise spectrum that may be found on the power lines. Narrowband PLC typically uses carrier frequencies below the U.S. amplitude modulated (AM) band (<500 kHz). At these frequencies the high noise floor reduces range and available bandwidth. Broadband PLC requires a much better signal-to-noise ratio (SNR), and typically uses carrier frequencies between 2 and 30 MHz where the noise tends to be less.

Higher-frequency PLC not only improves the data rates but also provides better transmission distances and coupling across circuit breakers and between lines.

Utility applications such as smart grid need 100 percent accurate data communications. The system has to be *commercial-grade* and very robust. Broadband PLC is able to choose the best of many carriers supported by a wider (2–30 MHz) band, a variety of modulation methods that adapt to the channel SNR, and a selective automatic repeat request (ARQ) mechanism in order to achieve a robust link. In addition, when there are a large number of nodes, broadband PLC may be needed to provide even small bandwidth allocations to each node.

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For access applications like VoIP, utility applications, and Internet surfing, several levels of QoS may be required when these applications contend for bandwidth on the same medium. For example, some packet streams are isochronous video or audio streams, and others may be asynchronous real-time data. These data may require much higher bandwidth than utility applications in order to share the same medium.

It is expected that more demanding applications and commercial opportunities will arise in the future. Because utilities traditionally invest in technologies for the long term and have to predict their needs over that term, it is logical to select a broadband PLC solution with more potential rather than narrowband PLC.

The Main Differences between Access and In-Home Systems

In-home networks are relatively simple and small. The distance between stations is generally short, and the topology is typically a star or a tree. A repeating function is rarely required, and if it is needed, most of the time a single repeater between endpoints is enough. All of the devices in the network usually belong to and are managed by one owner.

It is a greater challenge to define a solution for access networks since they have no definitive structure. They can also contain tens, hundreds, or even thousands of stations managed by the same logical network manager. Different power line networks may topologically be a tree network, a mesh network, a ring network, or a hybrid structure comprising all three of them. As a result, the optimal Access solution has to be as flexible as possible in order to support all relevant topologies. Automation and optimization mechanisms that make use of the flexibility need to be incorporated into products in order to adapt each station to overcome topology-specific issues and simplify the installation.

The dynamic characteristic of access networks is another challenge. The number of customers, number of end stations, and location of devices (e.g., electric cars) can vary over time. The network itself may also change over time due to electric switches being opened or closed. In addition, the impedance of the line and external interference also affect the usable bandwidth. These challenges require scalable and dynamic solutions that are far beyond the requirements of an IH network.

As a result, the access protocol stack should be designed to support generic topologies, a high number of neighbors and edge station addresses, and fast repetition, and should adapt to dynamic changes.

IEEE 1901 Access System Topology

The access system defined by the IEEE P1901 Working Group has a cell structure. A cell is a group of stations managed and authorized by a single station, usually the head end. The cell is built from stations managed directly by a logical *cell manager* and additional network elements, which are managed indirectly using stations as proxies.

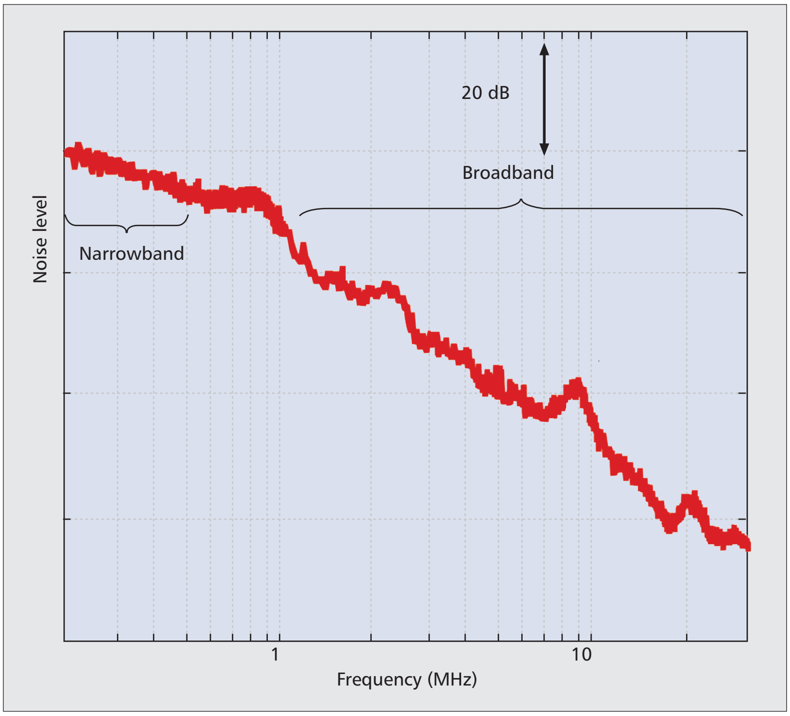

Figure 1. *Inverter noise spectrum.*

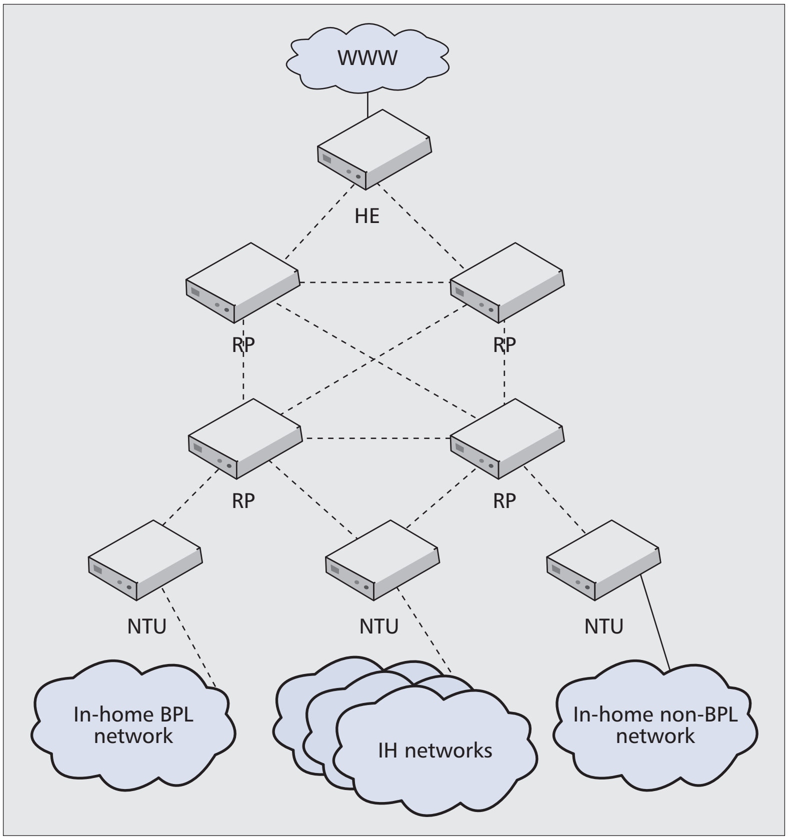

Figure 2. *Elements of a 1901 access cell.*

Figure 2 describes the elements of a 1901 access cell, which includes the head end station (HE), a number of repeating stations (RPs), and network termination stations (NTUs). The HE manages the cell and connects the whole access

In an access network where repeaters are likely to be used, end-to-end communication is defined as the entire communication path between edge stations in the Access Cell, including the repeaters, which are being used between them.

network to the backbone. RPs are stations that can also repeat from one station to another. NTUs are RPs that can also bridge between the access cell network and external customer networks such as IH networks or non-BPL technologies networks, such as IEEE 802.11 (Wi-Fi) and IEEE 802.3 (Ethernet).

Dotted lines in this figure represent the power line links between stations. Solid lines represent other network media.

BPL and non-BPL IH networks shown in this figure may be smart grid devices or networks served using the access cell as their backbone.

Specific Functions for Access Systems: Access Station Addressing

Access systems need to be able to address and control more than 1000 nodes. Every station inside the access network requires a unique address. The HEs are given short network identifications (SNIDs). SNID values support a maximum of 63 neighbor networks (63 SNID hexadecimal values, 0x01 to 0x3F, are the network addresses, and the value 0x00 is reserved to mark unassociated stations). Each SNID uniquely defines and logically separates one access cell from its neighbors. Each new station searches for a cell with which to associate and uses the SNID to differentiate between neighbor cells. A station that is already connected will use the SNID to search other neighbor cells if it can improve its connectivity by hopping to a neighbor cell with better performance. If the station cannot hear the HE directly, it will use the RP's repeating ability and associate using another station as a proxy toward the HE.

After the association process ends, the HE allocates a 12-bit address, the terminal entity identification (TEI), to the new station. The TEI and SNID combination will be the address to be used by the station for synchronizing with its neighborhood and transferring information, for bridging, and for repeating purposes.

TEI values support more than 4000 stations in a single access network. This large address range enables different topologies and scenarios for large-scale access installation with low numbers of backbone connection points, and for small-scale access installation with large numbers of backbone connection points. Due to the reality of typical installations, there is no practical limit in terms of addressing for access installation scenarios.

The TEI and SNID combination is what makes each station unique and yet allows it to communicate with its neighbors. Because this address is used for the point-to-point communication, it is also the basic identification tool for higher-layer algorithms such as channel estimation, channel accessing, bridging, routing, and management.

Using the TEI/SNID addressing instead of the unique medium access control (MAC) address of each station is more efficient in terms of address space. The combined TEI and SNID are 18 bits long, while an Ethernet MAC address is 48 bits long. Because each packet includes at least source and destination addresses, TEI and SNID addressing will require only 30 bits (source TEI, destination TEI, and SNID) compared to 48-bit MAC addressing, which requires 96 bits (source Ethernet MAC and destination Ethernet MAC). The result is a saving of 66 b/packet.

Neighbor network detection is another aspect of addressing. Access neighbor networks should fairly coexist, communicate, and synchronize by informing each other about their transmission times. In addition, a neighbor network could act as a failover option. The failover option increases the network robustness in case a neighbor network loses connectivity or changes topology to a point where the link does not meet the application's requirements and needs a new path. The first step toward coexistence is the detection of other networks. Using SNIDs, each station will be able to detect its neighborhood activity and sort each transmission to each cell.

1901 Access Cell: End-to-End Communication

In an access network where repeaters are likely to be used, end-to-end communication is defined as the entire communication path between edge stations in the access cell (e.g., the HE or NTU, which are located at the edges of the access cell and may have an external network port), including the repeaters being used between them.

In a typical access network, packets are repeated through stations that are members of the network. However, these stations are not usually the final destination of packets, nor are they usually the initiators of packets. Also, the edge stations in the access cell act as a bridge between external (BPL or non-BPL) network devices to the access network. For example, a PC connected to an IH station may send a packet to the Internet (*www* in Fig. 2). The NTU will bridge this packet to the power line, and the HE will bridge it back to the backbone network toward the Internet.

This concept of access bridged networks has an analogy to a switch with an ingress Ethernet port (e.g., the HE station) and an egress Ethernet port (e.g., the NTU station). From a bridging point of view, this analogy is accurate. Each edge station bridges an incoming packet toward the relevant edge station. The route over which the packet travels toward this edge station is managed by a separate network layer — the routing layer.

In order to allow quick transfer of the packets from one end to the other via repeaters, the access system frame format is built from two headers:

- An external header, which determines the end-to-end communication path and contains the edge devices' addresses
- An internal header created by every repeater in the path according to its path toward the edge device station

The external header handles the end-to-end bridging communication, while the internal header deals with point-to-point communication. The combination of both allows the end-to-end communication from the HE to the NTU using one or more RPs in the path.

Clock Synchronization

Several applications within the access network require accurate clock synchronization between neighbor stations. An example of such a requirement is PHY clock synchronization, which is essential in order to communicate between two stations using higher-order modulations. Another example is the time allocation management reference clock described below.

In established IEEE 1901 IH networks, the clock synchronization process is quite simple. The station that can hear the most other stations is elected and becomes the network manager. This manager synchronizes the IH network to its clock using beacon messages. If one or more stations in the network cannot hear the master, the master assigns one or more proxy masters to forward the beacon clock and information toward these stations.

The access network synchronization is also based on a centralized clock. All access cell stations synchronize on the clock of the HE. The algorithm for this synchronization is more complex than the IH and uses a multihop mechanism. Due to the long distances between the access network's master and the access stations, the beacon period of access networks should be much longer than the IH beacon single-hop synchronization period.

The multihop mechanism used by the HE periodically transmits a beacon message with the network time base (NTB). The NTB is a 32-bit clock maintained by the HE, which indicates the time when the beacon was sent. Another field used in this process is the beacon level (BL), which is always set to zero by the HE. Every station that hears this beacon message synchronizes its clock based on this master clock.

The interval between HE beacons transmission is a function of the maximum interval that allows the network to maintain an accurate clock between neighbor stations.

In order to keep the whole access cell synchronized to the HE clock, each station that hears the HE beacon synchronizes its clock with the HE clock. When the beacon is transmitted by the station, it includes the station's transmitting time based on the station's clock and its inherited NTB. The beacon also contains the BL, which is set to 1 in this case. Only stations that are not synchronized to the HE (BL = 0) synchronize on these beacons.

This process continues for every BL until all the stations in the network have shared and synchronized the same clock value between all stations in the access cell according to their BL.

Given the fact that beacon messages are transmitted using robust but inefficient modulation (in terms of potential line bandwidth usage), the number of BLs is minimized, and is equal or less than the actual number of hops that would be used in an optimal and efficient data transmission path.

Intracell Smart Repetition

The forwarding mechanism described in the IEEE 1901 document has a distributed nature. Each station maintains its own forwarding table and independently makes its forwarding decisions. However, because all stations in an access network need to communicate with their HE, a connection path from the HE toward all access stations has to be established.

To make it easy to learn the connection path, each station listens to beacon messages carrying the neighbors' connection level information. Each station that receives a beacon message gathers the connectivity level information from all its neighbors. After taking into consideration the connection level difference between it and each of its neighbors, and the connection level every neighbor has between it and the HE, the station chooses the optimal neighbor to use as a repeater toward the HE.

Because each station constantly optimizes its route toward and from the HE, the result is a dynamic and optimized repeating tree network structure. Every change in link degradation or link improvement may add, remove, or reroute a hop from the previous route. This supports dynamic physical topology changes such as that caused by closing a power circuit or opening a different power circuit (very common in mesh power line networks).

It is important to emphasize that the optimal forwarding tree is usually different than the BL tree described in the clock synchronization section. The beacon-based tree is a function of the simple ability of the stations to hear beacons. There are a relatively small number of BLs. The forwarding tree, however, is optimized based on finding the maximum bandwidth path between edge stations, which usually favors shorter distances and better SNR.

Figures 3, 4a, and 4b summarize the topic of BLs and repetition level. In these figures the connection points of the BPL stations are marked with two adjacent circles. This symbol emphasizes the fact that BPL stations are connected to an existing power line network.

Figure 3 demonstrates the physical topology of an access network. In this scenario the HE has two adjacent stations (RP 100 and RP 101) that have good connection levels (marked with solid blue curves). Stations RP 103 and RP 202 are examples of stations that have bad connections (marked with dotted red curves). These stations have links to the HE, which is good enough for synchronization but not sufficient for high-rate bandwidth usage. Good and bad connection levels between other stations in this cell are marked in the same fashion (Solid blue for good links and dotted red curves for bad links).

Figure 4a and 4b show two network trees built according to the connection levels in Fig. 3. The beacon tree in Fig. 4a is created by the beacon time synchronization mechanism, which relies only on the ability to connect and does not take into account performance — it simply requires a minimal ability of low modulation reception. The repetition tree in Fig. 4b is created by the optimal forwarding mechanism, which

Several applications within the access network require accurate clock synchronization between neighbor stations. An example of such a requirement is PHY clock synchronization, which is essential in order to communicate between two stations using higher-order modulations.

considers the connection level and the bandwidth between the stations in order to achieve optimal performance.

Each station in the trees is marked with its hierarchical level (starting from the HE, which is Level 0). Notice the level changes between beacon tree connections and repetition tree connections.

The difference between the Fig. 4a and 4b trees is that beacon trees require only connectivity between different levels, while repetition trees require finding the optimal path in terms of bandwidth and service from the HE toward each station and vice versa. For example, the connectivity between RP 103 and NTU 303 is enough for beacon passing (synchronization) but (in this example) not good enough for higher-bandwidth transmission. Better performance was achieved using RP 203 as a repeater in the middle.

POWER SAVING

Most access systems are outdoors and consist of more than 1000 nodes. If a smart meter consumed 1 W-h, the total would be a large load on the system. In order to save power and minimize noise emissions, the access *sleep mode* feature is introduced.

The main challenge of supporting sleep mode in access networks (compared to IH networks) is the distance between the stations. The complexity and signal delay make it hard to schedule the sleeping periods and their duration.

In order to support sleep mode and at the same time ensure availability to the network infrastructure, the access system sleep mode works in a hierarchical manner. It starts from the HE and moves toward the edge stations through the RPs in a method similar to the beacon clock synchronization mechanism. Whenever a station intends to go to sleep, it publishes its sleep duration information using beacon messages. The stations located under it in the tree hierarchy will be able to synchronize their sleeping period to their parent's sleeping time. This will ensure that the stations below the parent will be awake in time to get updates and synchronization messages.

In addition, the system is able to define an *exclude list* of stations that are either essential to the proper work of the access cell or serve applications that are sensitive to latency. The HE will create the exclude list and publish it throughout the access cell (using beacon messages). Stations may also use the exclude list to keep their parents awake if they require full-time service.

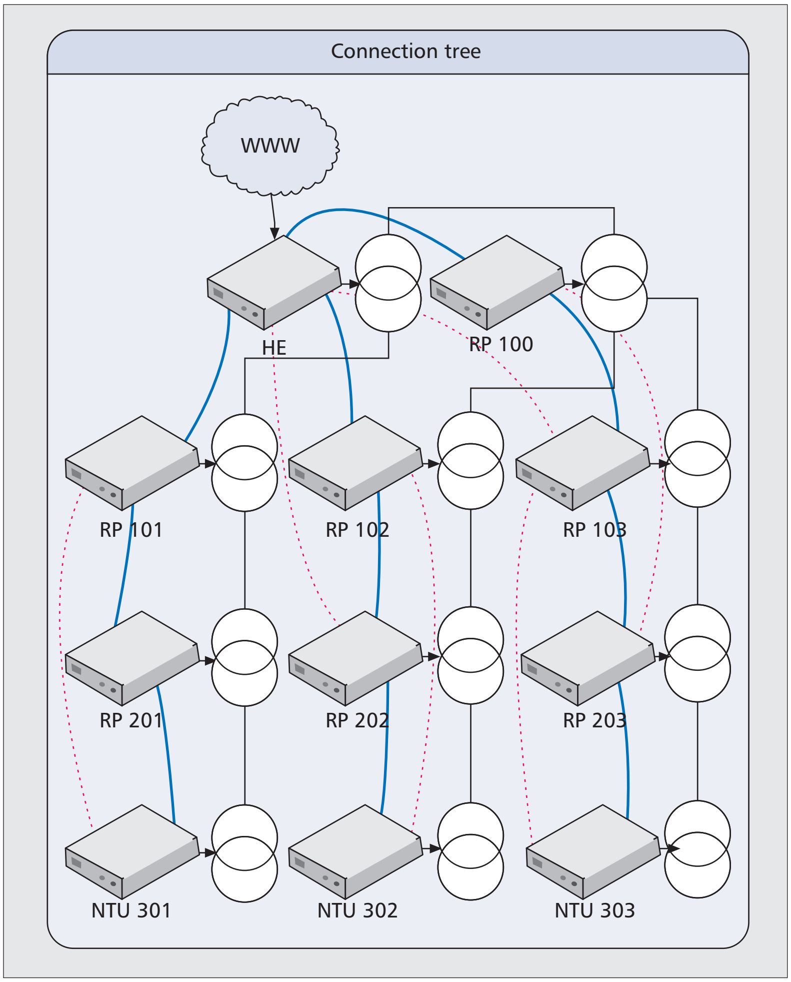

Figure 3. *1901 access cell physical installation topology example.*

BANDWIDTH ALLOCATION

CSMA AND TDMA

The default MAC protocol of access networks is carrier sense multiple access with collision avoidance (CSMA/CA) with prioritization. This MAC protocol is most suited for the broadband access topology that may contain hidden nodes. Moreover, CSMA/CA actually gives each station in the network the independent ability to compete with its neighbor stations for the right to use the medium without considering a master station, making it a good fit with the dynamic and multihop topology of the access network. Moreover, the dynamic nature of the access network and the unstable topology make it hard to set a local manager and define good master-slave relationship between the HE, the repeaters, and the edge stations throughout the network.

Nevertheless, CSMA/CA lacks a very important feature: it is not deterministic. This medium access algorithm is statistically based and does not guarantee bandwidth or minimum latency. Thus, it may not satisfy services and applications that require more deterministic QoS. Real-time applications such as telephony services (e.g., voice over IP) and videoconferencing are good examples of applications that require such determinism.

It is important that utility applications such as smart grid systems get access to the network in a deterministic way. TDMA can ensure bandwidth allocation as long as it is designed to function in the access cell multihop environment.

In order to support utility applications, a bandwidth allocation mechanism is required. The IEEE 1901 document introduced a concept of *TDMA over CSMA* in which the overall time resource is sliced into time regions. Each region defines the intervals for CSMA, for guaranteed TDMA allocations, and stay-out regions where TDMA allocations are granted to other stations

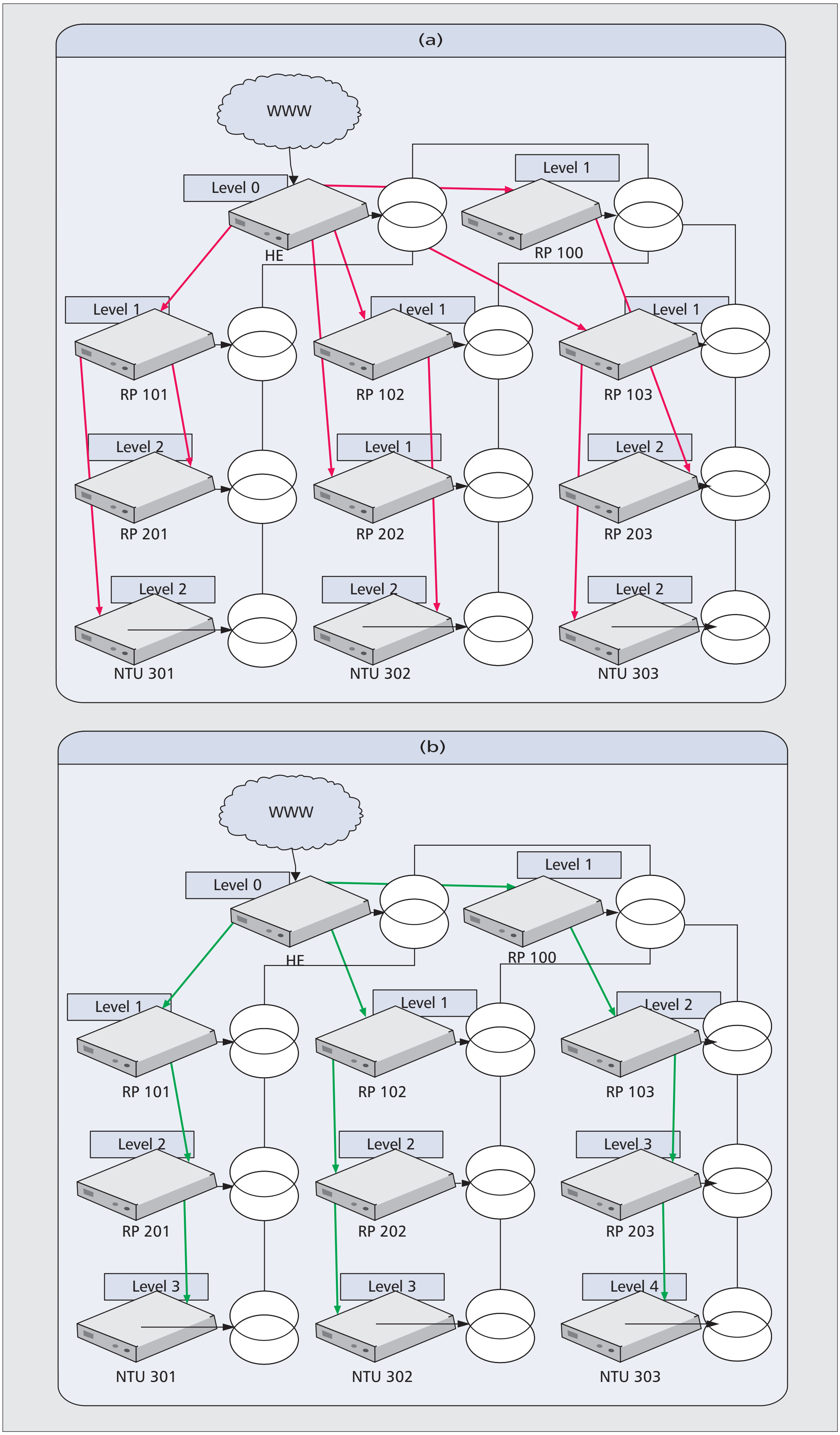

Figure 4. *a) Beacon tree example; b) repetition tree example.*

It is important that utility applications such as Smart Grid systems will get access to the network in a deterministic way. A TDMA can ensure bandwidth allocation as long as it is designed to function in the access cell multi-hop environment.

The IEEE 1901 document is a result of many years of work to include the presented access cluster functions that made it possible to apply it to large multi-hopping systems consisting of more than 1000 nodes.

in the station's neighborhood. Stations can contend for access in the CSMA region, and when allocated they get a persistent slot in the TDMA region. In the stay-out region the station will not transmit in order to avoid interfering with its neighbors' communication.

The HE is in charge of authorizing the opening of a TDMA channel within its cell. Each edge station that wants to use the TDMA service will request a channel based on the level of service required by the application. The HE will decide whether to authorize this request and start the allocation procedures according to the properties of the initiator of the TDMA channel and the available resources in the network.

The HE may use two methods to allocate the TDMA slots. It can schedule a slot per repetition hop on the way to and from a station as a central manager. Alternatively, it can initiate a remote and distributed procedure where the RPs allocate the slots, and each RP is responsible for its allocations according to its available time and bandwidth resources. The first method is referred to as *centralized TDMA* (since the HE manages everything itself). The second method is referred as *distributed TDMA* (since each station manages its own allocations independently after getting authorization from the HE).

The HE may use these two methods in parallel in order to have control of specific TDMA channels and simultaneously have other TDMA channels automatically adapted. This is also a method to achieve a level of prioritization and different service levels between TDMA channels.

Until a TDMA channel is established, traffic is sent using the CSMA default access method.

CENTRALIZED TDMA

When the HE uses the centralized TDMA scheme, the HE becomes the sole manager of the channel between it and the relevant edge station. It is responsible for allocating a TDMA slot for each repeater in the route toward and from the edge station. The HE senda a message toward each relevant repeater and assigns the slot according to its knowledge of vacant bandwidth in the cell. Using this centralized method can ensure good synchronization between the time allocations of slots through the entire path. The HE can allocate the slots in order to optimize their timing to minimize latency for the whole channel. The HE can also take into consideration several channels being aggregated into one slot according to the topology of the channels.

DYNAMIC TDMA POLLING

Another flavor of the centralized TDMA method is TDMA polling. In this method the master, usually the HE, will fix the slot schedule at the time of initiation. Because the channel condition and network resources change dynamically, the schedule table will be modified simultaneously after considering the polling results and channel conditions.

Master polling can be useful for managing numerous automatic meter readers (AMRs) by avoiding collisions due to CSMA. The signaling is designed to allocate time slots in a semi-persistent manner. Indeed, one allocation is signaled in beacons, and beacons are expected to have a periodicity around one or two seconds. It means that the same allocation is repeated during these one or two seconds.

This type of semi-persistent allocations is typically useful for data flows such as voice or video, with a rather constant bit rate over a long period. It is not applicable for AMR polling, were the typical flow profile is a single short data packet (a few hundred kilobits) every several minutes. In fact, if the TDMA schedule scheme defined in the previous sections is not carefully used for AMR devices, much bandwidth may be wasted.

DISTRIBUTED TDMA

If the HE uses the distributed TDMA method, it controls only the first hop toward the destination edge station. Each repeater in the route is in charge of allocating a time slot according to its local time allocation map built from the information it gathers from its neighbor's beacons and from its already assigned slots. The time slots are being allocated in serial fashion per each hop until the channel is built from the HE toward the edge station and vice versa.

The main advantage of distributed TDMA is that due to its local management nature, each station can set the time slot according to its local constraints and is able to perform fast recovery in cases of allocation collision between neighbor stations, hidden nodes, and neighbor cells. The distributed method is also much easier to manage in cases where the route path has changed, causing the need for fast teardown and recreation of whole or parts of the TDMA channel path.

CONCLUSIONS

This article has covered the main challenges in the broadband power line access network environment, and has given a glimpse of concepts introduced by the IEEE P1901 Working Group. A short description was given for access's most unique mechanisms such as the network concept of an access cell, smart repetition, data forwarding, QoS requirements, and power saving sleep mode.

The access network related mechanisms share some common functions with the IH network such as the physical layer and basic channel access. The main difference between the access and IH environments is the large number and variety of dynamic network topologies the access network needs to support.

The most challenging aspect of access oriented systems is the fact that they are designed for a multihop environment, while a typical IH network only has one or two hops.

The IEEE 1901 document is the result of many years of work to include the presented access cluster functions that made it possible to apply it to large multihopping systems consisting of more than 1000 nodes. The QoS mechanism based on master-slave topology is ideal for optimizing the multihop access environment.

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BIOGRAPHIES

SHMUEL GOLDFISHER (shmulikg@mainnet-plc.com) received his B.Sc. degree in computer science and mathematics from Bar-Ilan University of Ramat-Gan, Israel. He started his career as a software engineer in 3Com in the ATM networking field. In 2000 he joined MainNet Communication Ltd. and has been involved in design and development of the MainNet main product line in the Access over Broadband Power Line Communication segment. Since 2005 he is a software manager involved in MainNet's system architecture. As a member of the HomePlug Broadband Power-Line Communication Specification Working Group, he was one of the contributors of the HomePlug access specification. Since 2007 he has been an active participant in and contributor to the IEEE P1901 Working Group. His interest is in access communication in general and power line communication specifically. He holds several patents in power line communication and smart grid technologies.

SHINJI TANABE [SM] (Tanabe.Shinji@dh.MitsubishiElectric.co.jp) is a chief engineer in the Advanced Technology R&D Center of Mitsubishi Electric Corporation. He is a member of IEEE SA. He received his B.Sc. in physics from Tohoku University, Sendai, Japan, in 1980 and his Ph.D. in electromagnetic field analysis and high-speed communications from Tohoku University in 2003. He joined Mitsubishi Electric in 1980 and developed magnetic heads for hard disk drives and VCRs, and electromagnetic numerical simulation methods for EMC analysis. He was a visiting researcher at Tohoku University from 1982 to 1983 and a visiting researcher at the University of Minnesota from 1989 to 1990. He has been involved with IEC and IEEE standardization activities since 1995 as a member of IEC TC106, and IEEE P1528, P1675, P1775, and P1901. He published 12 papers and eight conference papers in the field of magnetic recording, magnetic materials, electromagnetic field simulations, EMC, and high-speed communications, and one book about electromagnetics.