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Medium Access Control for Power Line Communications: An Overview of the IEEE 1901 and ITU-T G.hn Standards

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ABSTRACT

Power lines are becoming increasingly popular for high-speed communications, while at the same time reliable communications over them poses several unique challenges. Recently, two standardization bodies, the Institute of Electrical and Electronics Engineers (IEEE) and the International Telecommunication Union (ITU), addressed in their IEEE 1901 and ITU-T G.hn standards, respectively, both the medium access control and the physical layer specifications of power line communications. In this article, we provide an overview of these standards from the media access control technology perspective, and the similarities and dissimilarities between the IEEE 1901 and ITU-T G.hn standards are discussed, as well as potential performance issues. We use a top-down approach to analyze the features and technologies of the standards.

INTRODUCTION

Home networking is a term that encompasses numerous important applications, such as indoor wired LAN services with broadband Internet access for both residential and commercial areas. These applications include smart home appliances and security, in-home audio/video streaming, and other applications such as traffic and street light controlling [1, 2].

Power line communication (PLC) is a good candidate for home networking because of the availability of power lines in almost every existing infrastructure. However, achieving good performance over the power lines poses unique challenges to modem designers [3]. Several technical problems are faced when using power line networks as the medium for high-speed data communication, because these networks were initially designed to distribute electric power at very low frequencies (50 Hz or 60 Hz) [1]. Power line cables are usually found to be unshielded and therefore generate and are subject to electromagnetic interference. However, recent developments in data-modulation and transmission techniques have made it possible to use power lines for high-speed communications, so that products are today available on the market for various PLC applications. In 2005, the IEEE Communications Society formed the 1901 working group (P1901 WG), which was tasked with creating an international technical standard for high-speed (>100 Mb/s at the physical layer) communication through AC electric power lines in order to bring PLC products into a common network framework.

The HomeGrid Forum [4], a global and nonprofit trade group, and its members have been supporting and contributing to G.hn specification of the International Telecommunication Union's Telecommunication standardization sector (ITU-T). The goal of G.hn is to unify connectivity of digital content and media devices by providing a wired home network over telephone, coaxial, and data-grade cable networks, as well as residential power line wiring to supply data at rates of up to 1 Gb/s. Thus, it addresses key concerns of service providers, electronic manufacturers, and consumers alike [2]. The goal of the ITU-T G.hn standard was to define the physical (PHY, layer 1) and link (layer 2) layers for home-wired networks; this work culminated in the ITU-T Recommendations G.9960 and G.9961 specifying the physical and data link layers of G.hn, respectively [5, 6]. The unified technology is desirable to reduce the cost and complexity of installation and to allow cross-device communication and functionalities. With the G.hn standard, ITU enables service providers to deploy new offerings, including Internet Protocol television (IPTV) more cost effectively. It also allows manufacturers in the consumer electronics market to provide powerful devices for connecting a variety of entertainment, home automation, and security products throughout the house, thus simplifying consumer purchasing and installation processes. In this article, the description of G.hn relates to power line operations only.

Both home networking standards discussed

0163-6804/11/$25.00

Feature and Technology	IEEE 1901		ITU–T G.hn
	FFT-PHY	Wavelet-PHY	
Channel Access			
Fundamental Technology	CSMA/CA	CSMA/CA	TDMA, CSMA/CA
Contention-based Scheme	CSMA/CA	CSMA/CA	CSMA/CA
RTS/CTS Reservation	Optional	Optional	Optional
Access Priorities	4	8	4
Virtual Carrier Sensing	Yes	Yes	Yes
Contention-free Scheme	TDMA	TDMA	TDMA
Persistent Access	Yes	Yes	Yes
Access Administration	Beacon Based	Beacon Based	MAP Based
Quality of Service	Supported	Supported	Supported
Security			
Security Framework	DSNA/RSNA	PSNA/RSNA	AKM
Encryption Protocol	CCMP	CCMP	CCMP
Burst Mode Operation	Uni-/bi-directional	Not supported	Bi-directional
Addressing Scheme			
Modes	Uni-, Multi-, and Broadcast	Uni-, Multi-, and Broadcast	Uni-, Multi-, and Broadcast
Space (per domain)	8-bit	8-bit	8-bit
Framing			
Aggregation Fragmentation and Reassembly	Supported	Supported	Supported

Table 1. *Features and technologies of the current PLC MAC standards at a glance.*

	ITU-T	IEEE
High-rate Broadband Access	No	1901
High-rate Broadband In-home	G.hn (50/100 MHz)	1901
Low-rate Broadband In-home	G.hn (25 MHz)	No
Low-rate, Low-frequency Narrowband	G.hnem (500 kHz)	1901 (500kHz)

Table 2. *Application areas of PLC MAC standards.*

above, although designed from different perspectives, share some common core technologies and functionalities, because their design goals are based on current market demand for standards to support several high-definition television (HDTV) and standard definition television (SDTV) streams, voice over IP (VoIP), and data traffic (i.e., Internet services, gaming etc.). To enable handling of such different types of traffic, both standards provide contention-free and contention-based channel access, Quality of Service (QoS) provisioning, and security, among other features. Some of the features offered are based on the same core technologies, while others use different technologies. The medium access control (MAC) features supported by IEEE 1901 and ITU-T G.hn are summarized in Table 1.

The fundamental difference between the two technologies is their application domains. Table 2 describes possible applications for ITU-T G.hn and IEEE 1901. ITU-T G.hn targets to high-rate broadband in-home, low-rate broadband in-home, and low-rate low-frequency narrowband. And IEEE targets high-rate broadband access and high-rate in-home applications. However, the New Standards Committee (NesCom) of the IEEE-SA Standards Board approved a revision to the scope of the Project Authorization Request (PAR) that clarifies the usability of the P1901 standard for Smart Grid applications, for transportation platforms (vehicle) applications, and for broadband over power line (BPL) devices operating on DC lines.

The low rate profiles of ITU-T G.hn enable scalable design supporting multiple bandwidths, and this technology supports seamless communications between low-end and high-end devices. A new project called "Home Networking Aspects of Energy Management" was started by ITU-T in association with the International Electrotechnical Commission (IEC) and Joint Coordination Activity on Home Networking (JCA-HN) to produce G.hnem in January 2010. The main goal of G.hnem is to define low complexity home networking devices for home automation, home control, electrical vehicles, and Smart Energy applications. The G.hnem standard was expected to be completed by February 2011.

The organization of standard documents in the two protocols is fundamentally different, as shown in Table 3. While ITU-T PLC targets coaxial cables, phone lines, and power lines as communications media, IEEE PLC only targets power lines.

Channel Access

In accessing channels, both IEEE 1901 and ITU-T G.hn provide non-prioritized and prioritized contention-based services for best effort and QoS-required traffic, while contention-free access is provided for QoS-guaranteed traffic as well. The fundamental access technology differs between the protocols; both IEEE 1901 (using CSMA/CA) and IUT-T G.hn (using CSMA/CA and TDMA) adopt synchronized access by beacon/MAP.

MAC Channel

PLC MAC protocols arrange access to the media by continuous MAC cycles. The MAC cycle is usually synchronized with the AC line cycle, but it can be synchronized with any external source. The MAC cycle in IEEE 1901 has three regions for three types of channel access, as shown in Fig. 1. The local administrator device (BSS Manager or BM) starts a new MAC cycle by transmitting beacon(s) during the beacon period. The beacons contain the start time of the other two periods in the cycle. In the contention period (CP), a station accesses the channel after a contention through CSMA/CA and backoff procedures. The TDMA-based contention-free access period starts after the CP. Multiple BSSs can be located in the same network. In that time, BSSs recognize each other and they share the medium. In this case, special periods called Reserved and Stayout are used to coordinate the access between multiple BSSs at the same location.

The management of MAC cycles in G.hn, however, is slightly different from that in IEEE 1901. First, there is no beaconing in the G.hn standard. Instead, a Medium Access Plan (MAP) is used to describe a MAC cycle. The local administrator, namely the Domain Manager or DM, transmits at least one MAP in a MAC cycle that defines the transmission opportunities (TXOP) of the following (one or several) MAC cycles. Second, the MAP in G.hn schedules TXOPs in a TDMA fashion, as shown in Fig. 1; however, it also enables CSMA/CA-driven contention-based access in one (or several) TXOP(s). The DM reserves TXOP(s) of the subsequent MAC cycles to broadcast the MAP for future cycles. Note here that ITU-T G.hn and IEEE 1901 differ in how they use information and which devices access the media. In G.hn, the beacon is used for the present cycle, while in MAP, it is used for the next cycle.

	ITU-T PLC	IEEE PLC
PHY Layer	Single (OFDM)	Dual (OFDM/ Wavelet)
MAC Layer	Single (OFDM)	Dual (OFDM/ Wavelet)
Target Medium	Coax, Phone line, Power line	Power line
Standard Docs.	G.hn (MAC-G.9961) G.hn (PHY-G.9960) G.cx (Coexistence-G.9972) G.hnem (Narrowband)	IEEE 1901 (MAC/PHY/Coexistence)

Table 3. *Organization of standard documents.*

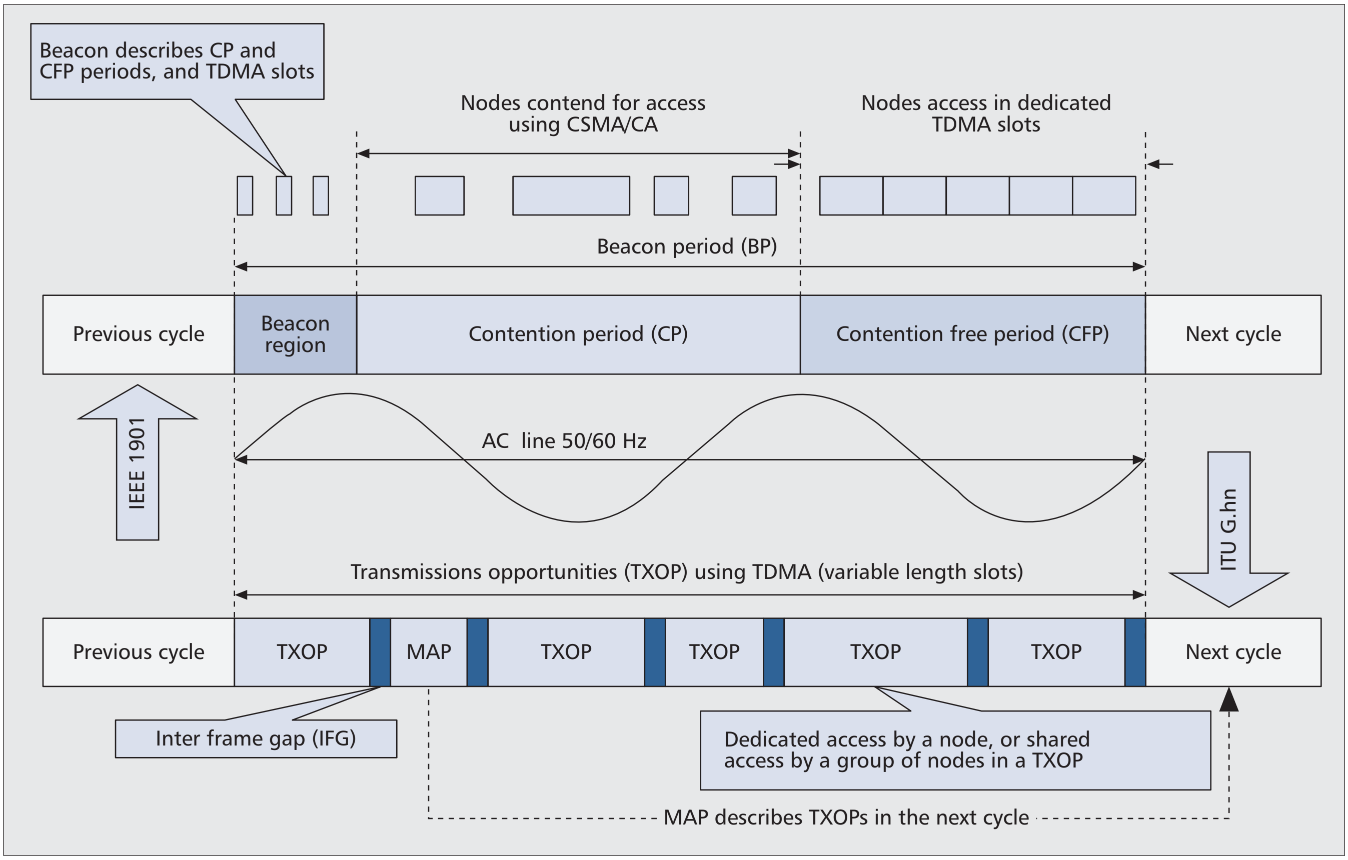

Figure 1. *The MAC cycle in IEEE 1901 and ITU-T G.hn.*

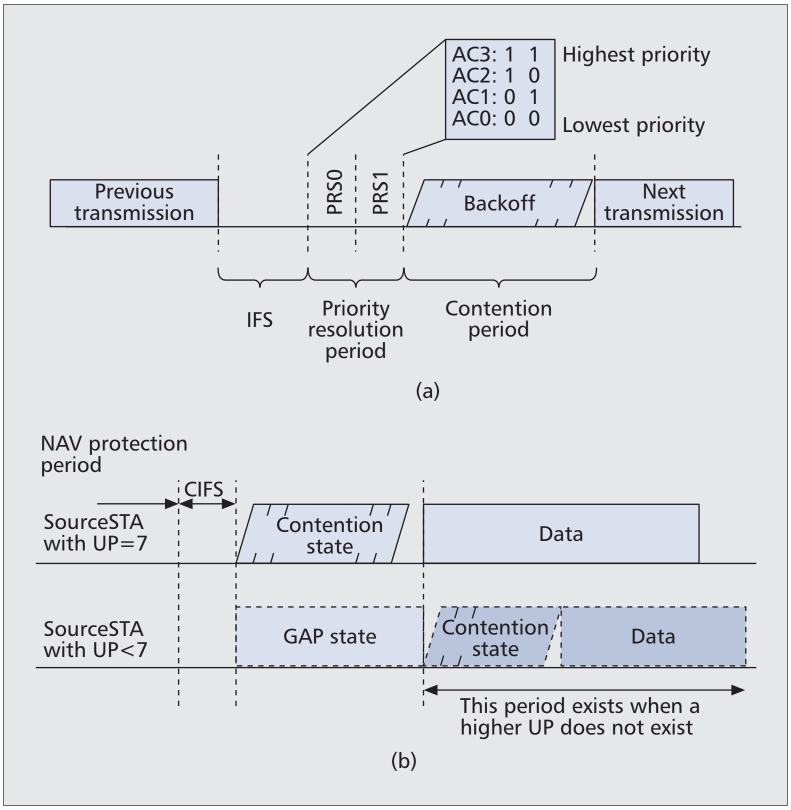

Figure 2. *Typical contention-based access in IEEE 1901: a) For FFT OFDM PHY; b) for wavelet OFDM PHY.*

CONTENTION-BASED ACCESS

Both standards provide contention-based access for best effort and QoS-required services with the help of CSMA/CA. However, because of the different cycle structures in the standards, the channel access procedures of the two protocols are fundamentally different from each other. In IEEE 1901, there is at least one CP in a MAC cycle after the beacon period. In G.hn, multiple contention-based time slots can exist in a single MAC cycle. The location and duration of these time slots are defined by DM. Between the contention-based time slots, contention free-time slots and MAP exist.

Contention Based Access in IEEE 1901 — In the contention-based access for this protocol, an IEEE 1901 station checks for a carrier in the channel before transmitting a data frame. A station transmits data immediately when it wins the priority contention. If the station fails to win the priority contention, then it follows a random backoff procedure. After deferral, or prior to attempting to transmit again immediately after a successful transmission, the station initiates a random backoff procedure to resolve medium contention conflicts. There is nevertheless still a probability of collision between contending stations when two or more stations defer for the same period and transmit simultaneously. A successful transmission is one in which an Ack frame is received from the receiving station. A station can make use of RTS/CTS handshaking prior to data frame transmission to further minimize collisions under various circumstances.

IEEE 1901 manages access to the medium differently for the two different PHY technologies. In FFT OFDM PHY-based MAC, stations that want to transmit send their own priority resolution period, as shown in Fig. 2a. Stations that do not have a higher priority than other stations join the random backoff procedure, and the winner station accesses the channel.

The MAC for Wavelet OFDM PHY, however, uses a gap state before the backoff procedure, as shown in Fig. 2, where the duration of the gap state is set according to the priority level of the transmission. The duration of the gap state for a station with the highest user priority traffic (UP = 7) is zero; hence, the station starts the backoff procedure immediately after the CIFS period (see the top sequence in Fig. 2b). The gap state duration of a station with lower priority traffic is greater than the backoff duration of the higher priority levels. Therefore, a station starts its backoff countdown only when it detects no high priority transmission in the channel, as shown in the bottom sequence in Fig. 2b.

Contention-Based Access in G.hn — In G.hn, contention-based access is offered within a TXOP, namely a shared TXOP (STXOP), as shown in Fig. 3. Unlike the contention in IEEE 1901, wherein every station can contend for channel access, the DM operating under the G.hn standard selects a single station or a group of stations to contend for channel access in a STXOP. Hence, the collision probability in G.hn is expected to be lower than that in IEEE 1901-based networks. An STXOP is divided into a grid of time slots (TS): a contention-free TS (CFTS), a contention-based TS (CBTS), and a registration CBTS (RCBTS), which is used for registration only. An STXOP can include only CFTS, only CBTS, or both. An STXOP that is composed only of CBTSs is denoted as CBTXOP. Nodes may also register in other CBTSs than RCBTS. The DM assigns a TS to one or a group of stations using a TS assignment rule. Stations sharing an STXOP track the passage of time slots on the line and transmit only within their assigned TS using carrier sensing. Because a DM may assign the same TS to a number of stations, a station performs a backoff procedure upon receiving a shared TS prior to channel access to avoid collisions. When a station obtains a TS designated for access, it transmits an INUSE signal in the TS and starts the priority resolution procedure. The G.hn adopts the PRS concept of the FFT type in IEEE 1901; i.e., a station resolves the priority level before the backoff state. Other stations that are not designated to access the slot stop TS counting as soon as they receive the INUSE signal. After the priority resolution, stations contend for medium access using the backoff procedure.

CONTENTION-FREE ACCESS

To provide QoS-guaranteed services such as high-resolution audio/video streams or VoIP, both standards offer TDMA-based contention-free channel access. IEEE 1901 uses a Beacon-based periodic channel access mechanism, whereas ITU-T G.hn uses MAP-based scheduling. IEEE 1901 stations (STAs) can use the power line communication

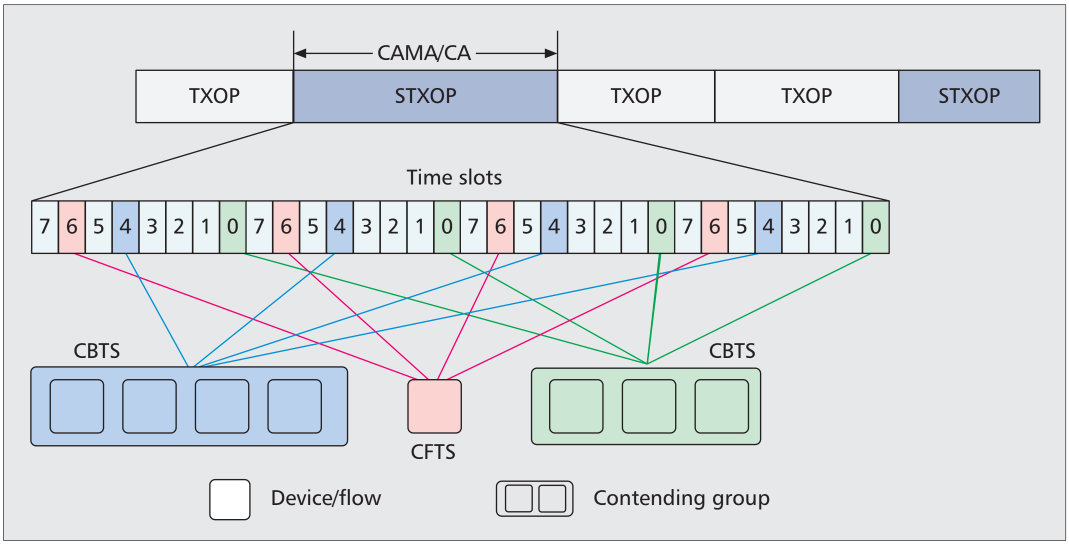

Figure 3. *Contention-based access in a STXOP in the G.hn standard.*

Persistent access is useful when the channel conditions of a power line are poor and a beacon/MAP is lost in one or more consecutive cycles. In this situation, persistent access is able to prevent an interruption in transmission.

medium exclusively by implementing a TDMA mechanism during the contention-free period (CFP). The BM assigns a bandwidth for each link, but not for the STA. STAs can guarantee the time for frame transmission for each link to use the TDMA mechanism, thus the TDMA is usually used for audio/video streams and VoIP streams.

The admission-control procedure plays a critical role in TDMA. Admission control deals with long-term allocation of network resources. All contention-free sessions go through an admission-control procedure during the session establishment. The scheduling procedure deals with the short-term (on a Beacon-period basis) allocation of network resources.

In *persistent access*, a flow gets channel access at the given reserved TDMA unit (or CFTXOP in G.hn) in subsequent MAC cycles. Persistent access is useful when the channel conditions of a power line are poor and a beacon/MAP is lost in one or more consecutive cycles. In this situation, persistent access is able to prevent an interruption in transmission.

QOS SUPPORT

PLC MAC schemes provide QoS traffic scheduling for the intra-BSS QoS frame transfers used by delay constraint services by assigning timeslots for transmissions using either CSMA-based or TDMA-based access protocols. A possible implementation is as follows. In contention-based channel access, user priority (UP) affects the AC/MA/gap state duration. In contention-free channel access, traffic specification (TSpec) affects bandwidth management.

IEEE 1901 provides two basic mechanisms to support applications with QoS requirements. The first mechanism delivers traffic based on differentiated UPs. This differentiation is achieved by varying the following for different UP values:

- Amount of time a station senses the channel to be idle before backoff or transmission.
- The length of the contention window to be used for the backoff.
- The duration during which a STA may transmit after it acquires the channel.

The second mechanism allows for the reservation of transmission slots (TXOPs) in the CFP. A non-BM station, based on the requirements placed by the upper layer, requests TXOPs, both for its own transmissions as well as for transmissions from the BM to itself. The BM either accepts or rejects the request, based on an admission control policy. When the request is accepted, the BM schedules TXOPs for both the BM and the non-BM station.

The QoS prioritization facility in IEEE 1901 supports eight UP levels with values identical to the IEEE 802.1D priority tags listed in Table 4. A station with low-delay/low-jitter traffic requirements is tagged as UP > 3 and is allowed exclusive use of the medium during the CFP. All streams requiring transmission in the CFP are managed by a QoS controller. A station with these priority levels can also gain access during a CP. The priority resolution during a CP in the IEEE 1901 Wavelet MAC provides direct support for the eight UP levels for both contention-based and contention-free access. The FFT-MAC in IEEE 1901 and G.hn, however, offer four priority levels in the CP because of the 2-bit priority resolving slot (PRS). These standards follow the access category levels used in IEEE 802.11 (listed in Table 5). However, some related works show that the priority based mechanism may not work well, and its contention window size value may be optimized based on the traffic load and the delay requirements [7].

SECURITY

According to the inherent characteristics of power lines, power line channels are considered to be shared media for communication. Thus, a PLC network may be affected by both external and internal attacks. An external threat implies an attacker capable of eavesdropping on transmissions and sending frames within the network, but with out-of-network access credentials. Internal threats refer to those from legitimate users

User Priority	Application Class
7	Network Control — to maintain the network infrastructure.
6	"Voice" — less than 10 ms delay, and hence maximum jitter
5	"Video" or "Audio" — less than 100 ms delay.
4	Controlled Load —for bandwidth reservation per flow
3	Excellent Effort — important best effort
0	Best Effort — LAN traffic as we know it today
1,2	Background — bulk transfers and other activities that are permitted on the network, but that should not impact the use of the network by other users and applications.

Table 4. *Application classes for user class mappings.*

Priority Resolution		FFT MAC	G.hn	Description
PRS0	PRS1			
0	0	AC0	MA0	Lower Priority
0	1	AC1	MA1	↕
1	0	AC2	MA2	↕
1	1	AC3	MA3	Higher Priority

Table 5. *Channel access priority in 1901 FFT MAC and ITU-T G.hn.*

of the network who have an illegitimate interest in the communications of another user or access to a specific network client. In the case of hidden stations, communications between two particular stations may pass through a relay station, causing a man-in-the-middle threat [1].

The PLC MAC standards do not provide any specialized security protocol for access control. The IEEE 1901 standard uses the security framework in IEEE 802.1X, along with the Cipher-block chaining Message authentication code Protocol (CCMP; counter mode with cipher-block chaining MAC). The IEEE 1901 WG was basically inspired by the 802.11i standard for security in wireless networks, which is based on the robust security network association (RSNA) concept found in 802.1X and CCMP. The RSNA defines a number of security features:

- Enhanced authentication mechanisms for stations.
- A set of key management algorithms.
- Cryptographic key establishment.
- An enhanced data cryptographic encapsulation mechanism called Counter mode with CCMP.

Security services in IEEE 1901 are provided by the authentication service and the CCMP mechanism. The scope of the security services provided is limited to station-to-station data exchanges. The data confidentiality service offered by an IEEE 1901 CCMP implementation is protection of the MSDU. CCMP combines counter mode (CTR) for data confidentiality, Cipher Block Chaining Message Authentication Code (CBC-MAC) for data integrity, and it also provides message integrity code (MIC) protection for both the frame body and almost the entire header in a MAC frame. The security services provided by CCMP in IEEE 1901 are as follows:

- Data Confidentiality.
- Authentication.
- Access control in conjunction with layer management.

For the purposes of the standard, CCMP is viewed as a logical service located within the MAC sublayer, as shown in the reference model in Fig. 4. The security mechanisms span the MAC layer through the station management services.

During the authentication exchange, both parties exchange authentication information. The MAC sublayer security services provided by CCMP rely on information from nonlayer-2 management or system entities. Management entities communicate information to CCMP through a set of MAC sublayer management entity (MLME) interfaces and management information base (MIB) attributes.

To deal with external threats, G.hn defines an authentication procedure based on the Diffie-Hellman algorithm and the Counter with Cipher Block Chaining-Message Authentication Code algorithm (CCM), which uses Advanced Encryption Standard (AES) –128 [8]. G.hn defines pairwise security against internal threats: a unique encryption key is assigned to each pair of communicating nodes and is unknown to all other nodes. Pairwise security maintains confidentiality between users within the network and builds another layer of protection against an intruder who has broken through the network admission control. The expected grade of security in G.hn is the same as or stronger than that defined in the most recent specification for WLAN IEEE 802.11n.

Burst Mode Operation

To operate effectively in an environment with periodic impulse noise, the power line MAC protocols allow a station to transmit multiple packets of the same priority level one after another in a single access. This feature is usually referred to as the burst transmission mode, and both IEEE 1901 and ITU-T G.hn support burst mode transmission in both CFP and CP. Figure 5 shows typical bursting modes that are supported by IEEE 1901. In general, the MAC header of each frame contains an indication whether it is the final frame of the burst transmission or not, and the receiver tunes itself based on the indication. Further, the first frame may also indicate the ACK policy for the bursting: immediate ACK or selective ACK (SACK). In the immediate ACK policy, the receiver replies with an ACK frame upon receiving every frame. However, in the SACK policy, when the destination station receives any frame that is not the final one, the receiver does not reply with an ACK frame and stores the corresponding ACK information. This process continues until the last frame is received. Upon receiving the last frame in the burst, the receiver transmits an ACK frame, acknowledging all frames belonging to that burst.

In case of burst transmission in a CFP, the bursting is allowed only until the end of the current contention-free allocation (or TXOP). In G.hn, contention-based access occurs within a STXOP, and hence, a station can use bursting until the end of STXOP. However, in the case of bursting during a CP in IEEE 1901, the standard assigns a maximum duration of a burst (for example, 5 ms for FFT MAC).

Bi-directional Bursting — Both IEEE 1901 (using FFT-PHY) and G.hn offer bi-directional bursting between two communicating stations of a flow. Using this mechanism, the destination may request a bi-directional flow in the burst through the ACK frame header to the source station. The source station may accept or reject the request. When accepted, the source station sends the grant information through the header in the immediate next frame and the receiver transmits in the reverse direction after transmitting the ACK frame. The source station adjusts the burst interframe space to accommodate the reverse flow.

COEXISTENCE OF IEEE 1901 AND ITU-T G.HN PRODUCTS

IEEE 1901 and ITU-T G.cx (or G.9972) specify the same coexistence mechanism — ISP (Inter System Protocol) — to accommodate up to four power line systems: IEEE 1901 in-home OFDM, IEEE 1901 in-home Wavelet, ITU-T G.hn, and the one access system [9]. In G.cx, ISP is a self-contained independent coexistence recommendation, whereas in IEEE 1901 ISP is contained mostly (not entirely) in one chapter [10]. The first coexistence mechanism developed was Inter-PHY Protocol (IPP) in IEEE 1901. This was necessary because 1901 lacks interoperability as it specifies two non-interoperable PHY/MACs. Recognizing the importance of coexisting with G.hn, IPP was modified to allow interoperability with G.hn, and IPP became ISP in IEEE 1901. To transfer the ISP to ITU, a new project called G.cx was created. G.cx gained consent in October 2009 and became recommendation G.9972. G.9972 is currently in the Last Call Comment (LCC) resolution period, and is expected to be approved by June 2010.

G.9972 will cover resource allocation for Frequency Domain Multiplex (FDM) and Time Domain Multiplex (TDM), start-up and re-synchronization procedures, power control, and management functionalities. Because G.9972 and IEEE 1901 have gone through two different comment resolution schemes, the two specifications are now diverging and may no longer be compatible. Now both G.cx and 1901 working groups are actively working on aligning the specifications during the comment resolution phase.

ITU-T G.hn supports not only power lines but also pre-existing wire lines such as coaxial cables and phone lines, and it extends its domain into the in-home Smart Grid area by enabling G.hnem. Thus, G.hn is designed for high/low-rate broadband/narrowband in-home services. IEEE 1901 is designed to support broadband access and high-rate broadband in-home services. Nevertheless, there is still no single standard to cover all application areas, and a single co-existence standard technology is a key focus in communications research. Several co-existence scenarios can be expected, such as between ITU-T G.hn and IEEE 1901 in the same in-home area, between IEEE 1901 broadband access and ITU-T G.hn broadband in-home, and between ITU-T G.hnem and IEEE 1901 broadband access in-home.

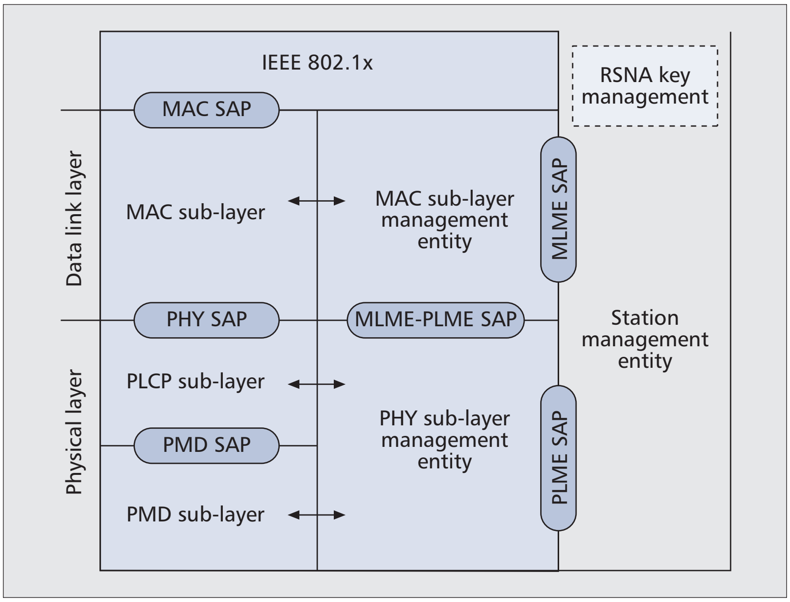

Figure 4. *Security reference model of IEEE 1901.*

SUMMARY

In this article, we tried to point out the available features and technologies in the PLC standards IEEE 1901 and ITU-T G.hn. As both of these standards are still in the development stage, it is difficult to make direct comparisons and comment on the compatibility issues. The IEEE 1901 working group has decided to make a standard based on the already existing technologies with additional improvement, while ITU-T G.hn decided to make a new standard in a clean-state approach. However, based on an analysis of the current stage and defined targets, it is clear that both of these standards offer similar features such as the master-slave architecture, contention-based and contention-free medium access schemes, transmission modes, QoS, and security services, among others. Therefore, many commonalities of the two standards will help facilitate dual mode implementation, which can help solve non-interoperability issues. However, an eventual solution to the problem is for the two standards bodies to agree on recommending a single coexistence standard. Thus, a single coexistence standard will solve non-interoperability issues between multiple technologies such as

An eventual solution to the problem is for the two standards bodies to agree on recommending a single coexistence standard. Thus, a single coexistence standard will solve non-interoperability issues between multiple technologies such as ITU-T G.hn, IEEE 1901, other forthcoming and legacy technologies.

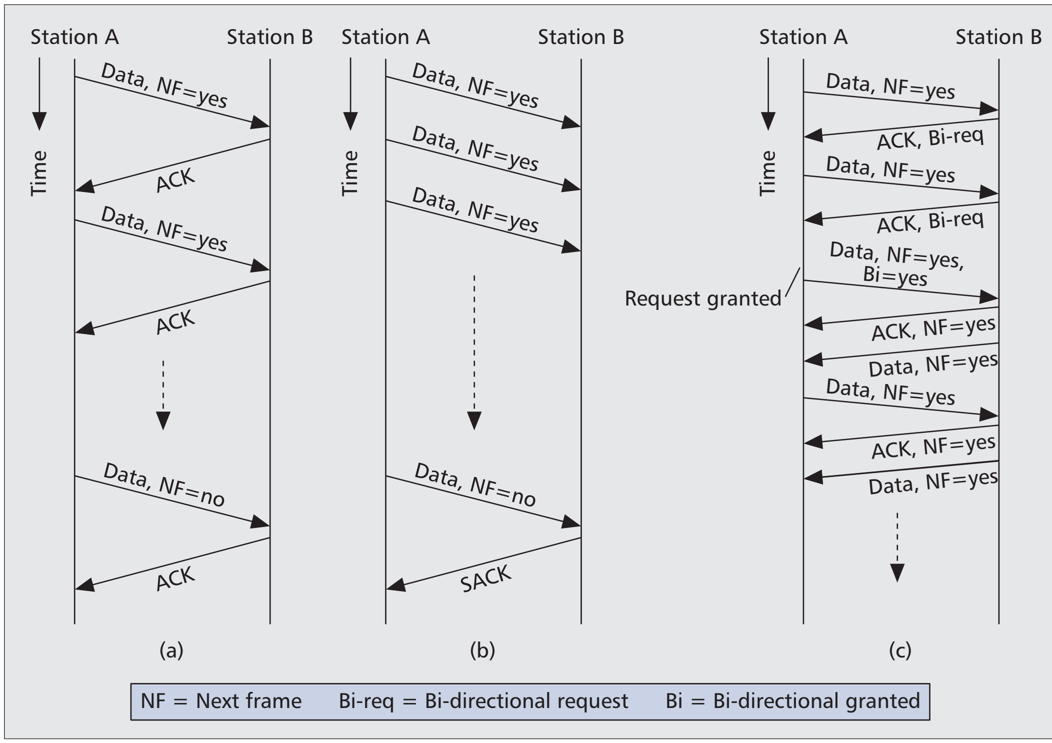

Figure 5. *Typical Burst Mode scenarios for IEEE 1901 devices: a) uni-directional bursting with an immediate ACK policy; b) uni-directional bursting with a selective ACK policy; and c) bi-directional bursting.*

ITU-T G.hn, IEEE 1901, other forthcoming and legacy technologies.

ACKNOWLEDGMENTS

This work was supported by a grant from the Kyung Hee University in 2010 (KHU-2010372). Dr. C. S. Hong is the corresponding author.

REFERENCES

[1] S. Galli and O. Logvinov, "Recent Developments in the Standardization of Power Line Communications within the IEEE," *IEEE Commun. Mag.*, vol. 46, no. 7, July 2008, pp. 64–71.

[2] V. Oksman and S. Galli, "G.hn: The New ITU-T Home Networking Standard," *IEEE Commun. Mag.*, vol. 47, no. 10, Oct. 2009, pp. 138–45.

[3] E. Biglieri, "Coding and Modulation for an Horrible Channel," *IEEE Commun. Mag.*, vol. 41, no. 5, May 2003, pp. 92–98.

[4] The HomeGrid Forum; http://www.homegridforum.org.

[5] ITU-T Recommendation G.9960, "Unified High-Speed Wire-Line based Home Networking Transceivers — Foundation," Jan. 2010.

[6] ITU-T Recommendation G.9961, "Data Link Layer (DLL) for Unified High-Speed Wire-Line based Home Networking Transceivers," Jan. 2010.

[7] M. Y. Chung *et al.*, "Performance Analysis of HomePlug 1.0 MAC With CSMA/CA," *IEEE JSAC*, vol. 24, no. 7, July 2006, pp. 1411–20.

[8] IEEE P1901/D2.01, "IEEE Draft Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications," Jan. 2010.

[9] S. Galli, A. Kurobe, and M. Ohura, "The Inter-PHY Protocol (IPP): A simple Co-existence Protocol," *IEEE ISPLC*, Dresden, Germany, Mar. 29–Apr. 1, 2009.

[10] ITU-T Recommendation G.9972, "Coexistence Mechanism for Wireline Home Networking Transceivers, " Jan. 2010.

BIOGRAPHIES

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