Overview and Timing Performance of IEEE 802.1AS

Michael D. Johas Teener, *Member, IEEE*, Geoffrey M. Garner, *Member, IEEE*

***Abstract*— IEEE 802.1AS is being developed in the 802.1 working group as part of a set of standards for Audio/Video Bridging (AVB). AVB networks will carry time-sensitive, high-quality, audio/video traffic, and IEEE 802.1AS will provide synchronization for these networks and ensure that the jitter, wander, and synchronization requirements for the time-sensitive traffic can be met. IEEE 802.1AS includes an IEEE 802-specific layer 2 profile of IEEE Std 1588™–2008, plus additional requirements needed to ensure performance for both full-duplex 802.3 (Ethernet) and 802.11 (WiFi) networks. The standard provides for very few options, both to simplify the configuration and operation by the user and to result in low cost. At present, the major features and requirements of 802.1AS are decided, with planned completion by 1Q2009. This paper gives an overview of the 802.1AS standard, describing which features of IEEE Std 1588™–2008 it uses and what additional requirements it contains. The paper then describes performance testing that is in progress using early implementations of IEEE 802.1AS bridges and end stations.**

Index Terms—time synchronization, jitter, wander, Ethernet, WiFi

I. Introduction

THE IEEE 802.1 Audio/Video Bridging Task Group (AVB TG) is developing a set of standards to allow the transport of high-quality, time-sensitive audio/video (A/V) applications over IEEE 802 bridged local area networks (LANs). The initial focus is on full-duplex IEEE 802.3 (Ethernet) and 802.11 (WiFi) transport. The technology is expected to be used in both residential and business (e.g., small office, studio, theatre/concert hall, etc.) applications. Three of the standards will provide for precise network timing and synchronization, resource reservation, and traffic shaping, queueing, and forwarding mechanisms that allow latency requirements to be met. A fourth standard will specify the precise configurations and parameters for networks that will meet the requirements of time-sensitive A/V applications.

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G. M. Garner is a consultant, 196 Ambassador Drive, Red Bank, NJ 07701 USA (e-mail: gmgarner@alum.mit.edu)

M. D. Johas Teener is with Broadcom Corporation (e-mail: mikejt@broadcom.com)

B. Hur is with Broadcom Corporation (e-mail: bhur@broadcom.com)

D. Huang is with Broadcom Corporation (e-mail: daweyh@broadcom.com)

IEEE 802.1AS will specify the transport of timing and synchronization in a network of bridged full-duplex 802.3 and 802.11 LANs. The standard was developed with the intention of meeting jitter, wander, and time synchronization requirements for uncompressed (serial digital interface) video [1] and both consumer and professional grade audio applications [2]. The jitter and wander requirements are expressed in the form of maximum time interval error (MTIE) masks [3]. The time synchronization requirement of ±500 ns relative to the grandmaster (GM) clock was provided by industry participants in the AVB TG [4]. The standard will also allow requirements on maximum phase and frequency offset during transient events and on the duration of those events [4] to be met.

IEEE 802.1AS is based on, and includes a profile of, IEEE Std 1588™–2008 [5] (referred to as a precision time protocol (PTP) profile). Strictly speaking, an IEEE 802.1AS bridge acts as an IEEE 1588[1] boundary clock, and an IEEE 802.1AS end station acts as an ordinary clock. This is because both the bridge and end station are required to participate in best master selection, the bridge is required to transport synchronization, and both are required to provide synchronized time to applications via application service interfaces. However, the manner in which an IEEE 802.1AS bridge transports synchronization is very similar and, in fact, mathematically equivalent to the manner in which an IEEE 1588 peer-to-peer transparent clock (TC) transports synchronization. Each bridge measures frequency offset relative to its neighbors; the accumulated frequency offset relative to the GM and the time difference between the arrival of a Sync message on the slave port and the sending of a subsequent Sync message on a master port are used to construct the synchronized time placed in a Follow_Up message. In addition, propagation delays between neighboring bridges and/or end stations are measured using the peer delay mechanism. The bridge is not required to filter phase as part of transporting synchronization; all phase filtering occurs at endpoints (end stations or bridges that have service interfaces to applications). This ensures that the cost of filtering is borne by applications; those applications whose jitter, wander, or synchronization requirements are less stringent will not pay the cost of filtering needed by applications with more stringent requirements.

[1] Unless otherwise stated, all references to IEEE 1588 are to [5], which is often referred to as 'IEEE 1588 Version 2' (as opposed to the earlier 'IEEE 1588 Version 1').

During the development of IEEE 802.1AS it was planned that bridges would not participate in best master selection and, therefore, would essentially be IEEE 1588 peer-to-peer TCs. However, recent discussions in the AVB TG indicated that the requirements of high-quality audio applications for phase and frequency offset during transient events (e.g., switching to a new GM and change of time base of the existing GM) and for the duration of those events could not be easily met in larger networks of TCs. In addition, it was realized that various timeouts (e.g., announce receipt timeout) would need to be made larger for larger networks, i.e., the networks would not be scalable. Finally, it was realized that having the bridges participate in best master selection would also allow them to determine the spanning tree for synchronization, rather than requiring the synchronization transport to use the data spanning tree determined by IEEE 802.1 Rapid Spanning Tree Protocol (RSTP). This latter point is significant, because the spanning tree determined by RSTP may not be the optimal, or even a good, spanning tree for synchronization. It was therefore decided to require the bridges to participate in best master selection. However, the specification of synchronization transport was done in a way that is mathematically equivalent to the way in which it is done for peer-to-peer TCs, to retain the low-cost aspects of TCs.

It was demonstrated via simulation [6], [7] that the synchronization transport in 802.1AS can meet the jitter, wander, and synchronization requirements given in [3] and [4]. Subsequently, test results for initial prototype systems were reported in [8], which indicated that the synchronization requirement of ±500 ns relative to the GM clock is easily met in a 5-hop network with 1 Gbit/s links. The test results also indicated that wander requirements [3] for observation intervals greater than approximately 10 s can be met for this network. However, the tests did not use any endpoint filtering, so shorter-term wander and jitter requirements were not met. Since the work of [8], additional testing has been performed, involving (1) a wider variety of network traffic scenarios, (2) a 7-hop network (the hypothetical reference model (HRM) assumed in [4]), (3) both 100 Mbit/s and 1 Gbit/s Ethernet links, and (4) endpoint filtering. The results of this testing are reported here.

The paper is organized as follows. Section II summarizes the IEEE 1588 features used in the IEEE 1588 profile contained in IEEE 802.1AS, and then provides an overview of IEEE 802.1AS. Section III describes the hardware used in the tests, emphasizing those aspects that are different from [8]. Section IV describes the test cases. Section V presents conclusions.

As of the preparation of this paper, the latest draft of IEEE 802.1AS is contained in [9]. Note that IEEE 802.1AS is under development and, while the major features and requirements are decided, details can change as the standard is completed.

II. OVERVIEW OF IEEE 802.1AS

A. *Summary of IEEE 1588 Features Used in PTP Profile*

Subclause 19.3.1.2 of [5] indicates that a PTP profile should define the following:

a) Best master clock algorithm (BMCA) option: An alternate best master clock algorithm (BMCA) is used, though one that is very similar to the BMCA of Clause 9 of [5].
b) Management mechanism: This is still to be decided.
c) Path delay mechanism: The peer delay mechanism will be used.
d) Range and default values of all PTP configurable attributes and data set members: The precise values are still to be decided. Ranges for sync interval, announce interval, Pdelay_Req interval, and announce receipt timeout of 0.01 – 1 s, 1 to several s, 0.1 – 1 s, and 3 announce intervals, respectively, have been discussed. It is likely that 802.1AS will specify ranges, and the fourth AVB standard referred to in the introduction will specify precise values for AVB.
e) Transport mechanism: The PTP profile contained in IEEE 802.1AS will allow full-duplex IEEE 802.3 (Ethernet) as the transport mechanism. IEEE 802.1AS will also allow transport over IEEE 802.11 (WiFi); however, this is not considered to be part of the PTP profile because [5] does not address synchronization transport over wireless networks. In fact, synchronization transport over IEEE 802.11 networks will use synchronization-related features being specified in IEEE 802.11v for location determination in WiFi networks [10]. In addition, it is still to be decided whether IEEE 802.1AS will support synchronization transport over a coordinated shared network (CSN) and over an IEEE 802.3 passive optical network (EPON) in the version being developed, or whether such support will be deferred to a future version.
f) Node types: An IEEE 802.1AS network may include ordinary clocks (OCs) and boundary clocks (BCs). As described in II.C, the synchronization transport by the BC is mathematically equivalent to that in a peer-to-peer TC. This simplified approach is used to achieve low-cost bridges.
g) Optional features: IEEE 802.1AS bridges and end stations will not be required to physically syntonize their frequency to the GM frequency, in the sense of adjusting the oscillator frequency (though they will be allowed to do this). They will, however, be required to measure their frequency offset relative to each of their neighbors using the peer delay messages. These measured frequency offsets will be (i) used to correct the measured propagation time relative to the nearest neighbor, and (ii) accumulated to obtain measured frequency offset relative to the GM, which will be used in transporting the synchronized time. IEEE 802.1AS will not use any of the optional features of Clauses 16 and 17 of [5], with the possible exception of the path trace feature (this is still to be decided). IEEE 802.1AS will not use the experimental security protocol of Annex K of [5]. IEEE 802.1AS will not use the cumulative frequency scale factor offset TLV of Annex L of [5]; however, it will transport the cumulative frequency offset (a different quantity from that defined in Annex L), along with information on transient behavior during network reconfiguration or GM change, in a standard organization TLV in the Follow_Up message.

B. Additional Network and Equipment Assumptions for IEEE 802.1AS

A bridge or end-station that meets the requirements of IEEE 802.1AS is referred to as a "time-aware system." IEEE 802.1AS requires that all bridges and end-stations in the 802.1AS network be time-aware-systems, i.e., the protocol will not transfer timing over "ordinary bridges" that meet the requirements of [11] and [12] but not the requirements of IEEE 802.1AS, nor over end-to-end TCs. A time-aware system uses the peer delay mechanism on each port to determine if an "ordinary bridge" or end-to-end TC is at the other end of the link or in between itself and the Pdelay responder. If, on sending Pdelay_Req (i) no response is received, (ii) multiple responses are received, or (iii) the measured propagation delay exceeds a specified threshold, the protocol concludes that an "ordinary bridge" or end-to-end TC is present. In this case, the link attached to the port is deemed not capable of running 802.1AS. The port is not considered when the BMCA is invoked; Sync, Follow_Up, and Announce messages are not sent on the port; any such messages received on the port are ignored; and 802.11v time synchronization information is neither sent nor paid attention to on the port. However, the port continues to attempt the measurement of propagation delay using either the peer delay mechanism (for full-duplex, 802.3 links) or 802.11v messages (for 802.11 links), and periodically checks whether the link is or is not capable of running 802.1AS.

A time-aware system is assumed to contain, at minimum, an oscillator with free-run frequency accuracy of ±100 ppm and frequency of at least 25 MHz (i.e., 40 ns or smaller phase measurement granularity), to be used for time stamping. This is consistent with the requirements for full-duplex 802.3 and 802.11 links. The full-duplex 802.3 links are assumed to have rates of either 100 Mbit/s or 1 Gbit/s. The 802.11 links are assumed to have a rate of at least 100 Mbit/s (i.e., the links meet the requirements of IEEE 802.11n).

All time-aware systems are two-step clocks, i.e., a Follow_Up message corresponding to each Sync message and a Pdelay_Resp_Follow_Up message corresponding to each Pdelay_Resp message are sent.

An 802.1AS network consists of a single PTP domain, with domain number 0. The timescale is the PTP timescale.

C. Synchronization in IEEE 802.1AS

Each port of each time-aware system measures propagation delay to its neighboring time-aware system using the peer delay mechanism with individual requestReceiptTimestamp and responseOriginTimestamp values (see 11.4.3, item (8) of item (c), of [5]). In addition, the responseOriginTimestamp values in successive Pdelay_Resp_Follow_Up messages and the <pdelayRespEventIngressTimestamp> values of successive Pdelay_Resp messages are used by the requestor to measure frequency offset of the responder relative to the requestor.

This measured frequency offset is used for two purposes. First, it is used to correct the propagation time measurement for inaccuracy due to differences in the rates of the requestor and responder timestamp clocks. The correction is equal to the fractional frequency offset multiplied by the difference between the responseOriginTimestamp and requestReceiptTimestamp (see 6.5.5 of [5]). Second, it is accumulated in a standard organization TLV, attached to each Follow_Up, so that each time-aware system can know its frequency offset relative to the GM. This method of measuring frequency offset relative to the GM was chosen, rather than using the received Sync and Follow_Up messages directly, to allow faster convergence to a new steady-state after a change in GM or topology. With this method, the frequency offset relative to the new GM is known on receipt of the first Follow_Up message that originates at that GM, compared to having to receive multiple Sync and Follow_Up messages if they are used for the frequency offset measurement. The method used in 802.1AS takes advantage of the fact that the nearest-neighbor frequency offsets are continually measured and known, even on links that are not currently part of the synchronization spanning tree.

Each time-aware bridge sends Sync and Follow_Up on its master ports. Under normal conditions, Sync and Follow_Up are sent when Sync and Follow_Up are received on the Slave port. However, Sync is not sent until at least one-half Sync interval has elapsed since the last Sync was sent, to prevent any bunching of successive messages. In addition, Sync is sent after a Sync interval has elapsed, even if Sync and Follow_Up have not been received.

Each Sync is time stamped when sent, and the corresponding network-synchronized time is computed at the receiver as the sum of (i) the preciseOriginTimestamp of the most recently received Follow_Up, (ii) the correctionField of the most recently received Follow_Up, (iii) the path delay on the upstream link, and (iv) the difference between the time stamp of the transmitted and most recently received Sync messages, relative to the local free-running oscillator, multiplied by the accumulated fractional frequency offset relative to the GM. The contribution (iv) is equivalent to the residence time in a TC. However, the summation is also the operation that would be done, functionally, to compute the preciseOriginTimestamp for a Sync message transmitted by a BC. The main difference between synchronization transport by a TC and a BC is in how the timestamp value is distributed between the preciseOriginTimestamp and the correctionField. This is the basis for the earlier statement that synchronization transport in a BC and TC can be made mathematically equivalent.

D. Best Master Clock Selection in IEEE 802.1AS

All time-aware systems are required to invoke the BMCA and forward best master selection information via Announce messages. However, as will be described shortly, a time-aware system is not required to be GM-capable. This is a generalization of the default BMCA of [5], where only OCs can be slave-only; here, a BC need not be GM-capable but still invokes the BMCA and sends Announce messages.

IEEE 802.1AS uses the default BMCA of [5], with the following modifications: (i) all Announce messages received on a Slave port that are not sent by the same time-aware system are used immediately, i.e., there is no notion of qualification of messages from foreign masters, and (ii) when the BMCA determines that a port should be a master port, it enters the Master state immediately, i.e., there is no pre-master state.

The BMCA is expressed in 802.1AS using a subset of the formalism for RSTP in [11]. This is possible because both the default BMCA of [5] and RSTP create spanning trees. The root of the spanning tree created by the BMCA is the GM, unless no time-aware system in the network is GM-capable. The attributes priority1, clockClass, clockAccuracy, offsetScaledLogVariance, priority2, and clockIdentity are concatenated, as unsigned integers in that order, into the overall attribute systemIdentity. The first part of the dataset comparison algorithm (Figure 27 of [5]) is expressed in terms of a comparison of systemIdentity attributes: the time-aware system with the numerically smaller systemIdentity is better if the clockIdentity attributes are not the same (the case where the clockIdentity attributes are the same is handled separately in the second part of the dataset comparison algorithm). The most significant bit of priority1 is used to indicate whether a time-aware system is GM-capable; the value ‘0’ indicates it is GM-capable, and the value ‘1’ indicates it is not. This ensures that the spanning tree root will be GM-capable unless no time-aware system in the network is GM-capable. A spanning tree priority vector is defined, consisting of rootSystemIdentity (systemIdentity of the root of the spanning tree, i.e., the GM unless no time-aware system is GM-capable), rootPathCost (number of hops from the root, i.e., stepsRemoved [5]), sourcePortIdentity (portIdentity of the time-aware system that transmitted the Announce message), and portNumber of the receiving port. Following [11], the spanning tree priority vector is used to define six different, but related, priority vectors. These priority vectors are set and compared in four interacting state machines; these machines also set each port to Master, Slave, or Passive.[2] The operation of these state machines is equivalent to the dataset comparison and state decision algorithms of [5]. Details are given in [11], [13], and [14]; [14] contains an example that shows the same spanning tree is obtained using the BMCA formalisms of [5] and [11].

The spanning tree determined by the BMCA may or may not be the same as the spanning tree for ordinary data traffic determined by RSTP. As indicated in the introduction, one reason for requiring all time-aware systems to participate in best master clock selection was to allow 802.1AS to create a spanning tree for synchronization, because the best spanning trees for synchronization and data transport may not be the same. A time-aware system that is not GM-capable will become the root of the BMCA-determined spanning tree only if no time-aware systems in the network are GM-capable. Every time-aware system can determine whether the current root is GM-capable by examining the most significant bit of priority1. The time-aware systems will send Sync messages only if the root is GM-capable.

[2] As described earlier, the pre-master state is not used in 802.1AS. The uncalibrated state is not needed because, as indicated in the Introduction, the time-aware systems do not themselves do filtering; all filtering is done at endpoints. The initializing, faulty, disabled, and listening states are modeled using the portEnabled global variable of [11]. Finally, note that the term ‘port state’ in [5] is equivalent to the term ‘port role’ in [9] and [11].

III. TEST CONFIGURATION AND EQUIPMENT

The tests will be done using upgraded versions of the hardware described in [8] configured as shown in Figure 1. Differences between the hardware used in [8] and the new hardware include: (a) the end stations will perform endpoint filtering (endpoint filtering was not implemented in [8]), (b) both 100 Mbit/s and 1 Gbit/s Ethernet tests will be performed ([8] was limited to 100 Mbit/s), (c) for 1 Gbit/s Ethernet, the timestamping is done with a 125 MHz rather than a 25 MHz clock, resulting in 8 ns measurement granularity rather than 40 ns, and (d) the end stations have clock signal outputs, enabling phase error measurements to be made using an oscilloscope or a time interval analyzer.

The previous tests also used much earlier versions of the 802.1AS protocols that did not include any rate ratio compensation, nor did they include any BMCA capabilities.

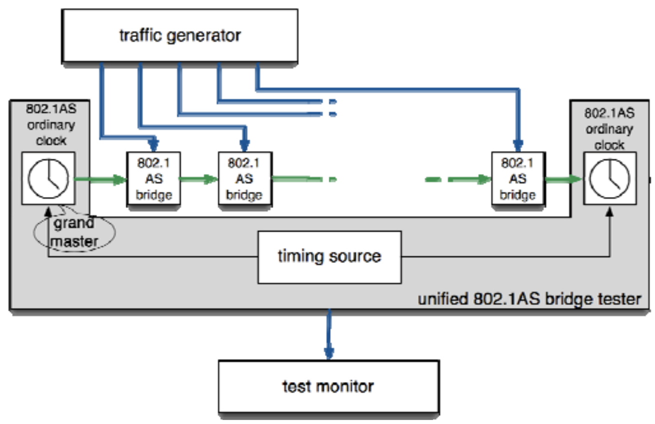

Figure 1 - Test configuration

IV. TEST CASES AND RESULTS

Reference [8] contained initial test results for a limited number of cases. More extensive testing is planned for the current paper. Each test will have 7 hops (6 bridges) between the master and slave end stations. In each test, the specified random arrival traffic will be inserted at the first bridge after the GM and each successive bridge, traverse 1 hop, and be removed at the next bridge or slave OC. The specified constant arrival traffic will similarly be inserted and removed. The random traffic is intended to represent best effort traffic; the constant arrival traffic is intended to represent time-sensitive, AVB traffic. Each test will be run for both 100 Mbit/s and 1 Gbit/s links. The endpoint filter bandwidth will be chosen in the range 0.01 – 10 Hz (the exact values are not yet decided, and will depend on the obtained performance; tests with several different bandwidths may be run). Cases will be run with the following four traffic mixes (load refers to the link utilization due to that stream):

a) No traffic.
b) Constant arrival stream consisting of 1088-byte frames sent at an 8 kHz rate (roughly 75% load at 100 Mbit/sec). For 1 Gbit/sec link tests, the stream will consist of 1088-

byte frames sent at an 80 kHz rate. This emulates a fully-saturated AVB network (time-sensitive traffic in an AVB network will be limited to 75% of the load).

c) Random traffic sent at an average rate of 75 Mbit/sec for 100 Mbit/sec links and 750 Mbit/sec for 1 Gbit/sec rates (roughly 75% load).

d) Same as (b), but with random traffic increased so that the total load is as close to 100% as the tester will allow.

Selected phase error and MTIE results will be presented for each case, and compared to the requirements.

V. CONCLUSION

This paper has provided an overview of IEEE 802.1AS, and described performance testing that is in progress. IEEE 802.1AS is compatible with IEEE Std 1588™-2008, in that it includes a PTP profile. The specifics of the PTP profile were chosen to provide for lower-cost systems that would still allow the respective application performance requirements to be met. It allows very few user-configurable options, and therefore provides for plug-and-play interoperability. It adds support for shared media such as IEEE 802.11. It uses an alternate BMCA that is very similar to the default IEEE 1588 BMCA, but simplified to provide for faster convergence.

Unfortunately, the final test results are unavailable at this writing. An amendment to this paper will be available by late September, 2008.

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