Time Synchronization over Ethernet Passive Optical Networks

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ABSTRACT

Time synchronization is critical when using Ethernet passive optical networks as a mobile backhaul to support time-sensitive services. This article presents an overview of time synchronization methods over EPON. It outlines the requirements and challenges particular to the EPON link delay asymmetry, and presents the technical solution recently approved by IEEE. Performance analysis and prototype results demonstrate that this technical solution meets various time synchronization requirements. The article then reviews the major standard efforts on EPON time synchronization that employ this solution, IEEE Std 802.1AS™-2011 Clause 13. With this standard in place, EPON can play its part in time distribution networks.

INTRODUCTION

An Ethernet passive optical network (EPON) provides broadband access with a shared-fiber infrastructure and a maintenance-free optical distribution network (ODN). As shown in Fig. 1, a typical EPON system has an optical reach of about 20 km. The central office (CO) endpoint is the optical line terminal (OLT), and the subscriber endpoints are the optical network units (ONUs). The OLT is connected to a passive optical splitter by a single feeder fiber. The passive optical splitter fans out signals via multiple distribution fibers to the subscribers. Other than the OLT and ONUs, there are no active elements in the EPON system. This enables low capital and operational expenditures for high-speed full-service access.

The IEEE 802.3™-2008 standard [1] specifies the EPON physical layer, data link layer, and other related techniques. EPON features gigabit-level access rates (e.g., 1 Gb/s symmetrical rates). Time-division multiplexing (TDM) and time-division multiple access (TDMA) are employed in the downstream (i.e., from the OLT to the ONUs) and upstream (i.e., from the ONUs to the OLT), respectively [2, 3]. The EPON system uses a 1490 nm wavelength for the downstream transmission and the wavelength centered in 1310 nm for the upstream transmission.

Employing EPON as mobile backhaul is one of the emerging applications of fiber optical access. As exemplified in Fig. 1, ONUs can either connect to or collocate with base stations (BSs). The prime motivations of this application include cost saving on backhaul facilities, and extended reach and coverage of mobile access networks. The shared fiber infrastructure of EPON facilitates the aggregation of multiple BSs to the radio network controller (RNC) in the CO. When existing BSs are located in the areas served with an EPON system, it is highly efficient to share the same fiber optical access infrastructure with mobile backhaul networks. When there are remote BSs in a wireless network, the EPON systems are able to connect them to the CO by just extending some of the distribution fibers. This eliminates the requirement and effort of deploying a separate fiber network dedicated to mobile backhaul purposes.

Time synchronization (i.e., distribution of the absolute time, both frequency and phase) is a crucial issue of using EPON as mobile backhaul. Wireless technologies require precise time information to support various functions. Ordinary EPON cannot provide the time synchronization service. Therefore, a proper solution is highly desired to enable the provisioning of mobile services over EPON.

This article focuses on the issue of time synchronization over EPON. We review the time synchronization requirements of various wireless technologies, and present the key challenges of synchronizing time over EPON. We explore the technical solution and analyze its achieved performance. We demonstrate a prototype system and report its performance results. Relative standard trends and efforts are also presented to conclude this article.

EPON AS MOBILE BACKHAUL: REQUIREMENTS AND CHALLENGES

TIME SYNCHRONIZATION REQUIREMENTS OF MOBILE BACKHAUL

One of the most basic features of wireless is supporting mobility. This requires coordinated handoff when a user moves from one BS to the next. To make the handoff as smooth and loss-

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less as possible, precise time information is required to be distributed among a wireless network. Moreover, additional physical layer techniques such as geolocation require exact time synchronization to produce accurate results. From the service perspective, when a mobile user accesses the network while he/she is roaming among the areas covered by different BSs, the precise time information helps synchronize the services received by the mobile user [4].

The time synchronization requirements of several typical wireless technologies are listed in Table 1. Time accuracy in microseconds is required for the majority of these wireless networks. It should be noted that this is the endpoint requirement, and the access network would use only a fraction of this amount. Therefore, a useful time distribution system over EPON should target an inaccuracy of hundreds of nanoseconds.

EPON TIME SYNCHRONIZATION CHALLENGES

A common approach to transporting time would be to use IEEE 1588™-2008 [6] over EPON. IEEE 1588™-2008 defines the precision time protocol (PTP) for synchronizing clocks connected via a packet network. When applying IEEE 1588™-2008 to an EPON system, the time information is encapsulated into EPON data packets (i.e., either Ethernet frames in EPON). The EPON system distributes those packets in the same way as user data.

Unfortunately, this mechanism cannot meet the mobile backhaul time synchronization requirements. A key assumption of IEEE 1588™-2008 is link delay symmetry between upstream and downstream channels. When calculating the one-way delay from a master clock to a slave clock, IEEE 1588™-2008 assumes such delay is equal to that of the reverse link, which is from the slave clock to the master clock. Without the link delay symmetry assumption, IEEE 1588™-2008 is unable to distribute precise time information.

Such assumption of link delay symmetry, however, does not hold in EPON. In EPON, TDM and TDMA are adopted in the downstream and upstream for data transmission, respectively. This implies that the upstream delay is different from that of the downstream. A typical upstream TDMA cycle is on the order of milliseconds; thus, an upstream IEEE 1588™-2008 packet can possibly be delayed by milliseconds when the upstream channel is loaded with user data. In contrast, the downstream channel exhibits much lower queuing delays (typically on the order of microseconds). Moreover, different wavelengths are used downstream and upstream, and the light propagation delays are asymmetric. Such delay asymmetries impair the time accuracy by introducing up to millisecond-scale delay differences. Even worse, the time errors would be dynamically affected by the EPON traffic load in the upstream.

As tabulated in Table 1, most wireless technologies require microsecond-level time accuracy. Therefore, employing IEEE 1588™-2008 over EPON in a transparent way is unable to meet the mobile backhaul requirements, and a solution with higher time accuracy is needed.

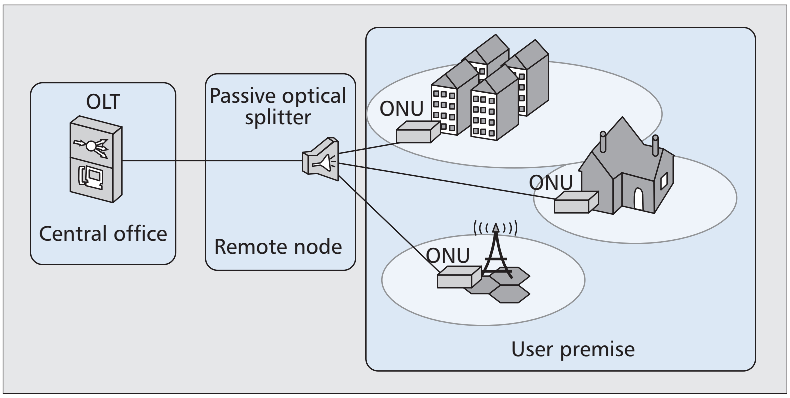

Figure 1. *Ethernet passive optical network (EPON).*

Wireless technology	Time requirement
CDMA2000	3 μs
TD-SCDMA	3 μs
WiMAX TDD	1 μs
WCDMA (UMTS) TDD	2.5 μs
LTE	From 1 μs to 50 μs

Table 1. *Time synchronization requirements of wireless technologies [5].*

TIME SYNCHRONIZATION OVER EPONS

LOCAL COUNTERS AND ROUND-TRIP TIME

While EPON has a special problem of delay asymmetry, it also has the special capability of very exact delay measurement. This comes from the use of TDMA in the upstream, which requires very accurately synchronized time.

In an EPON system, both the OLT and ONUs have a local counter. It is represented by 32 bits, and increases by 1 every 16 ns. The EPON Multipoint Control Protocol (MPCP) copies the local counter value into the timestamp field of MPCP messages when such messages are generated in the medium access control (MAC) control sublayer (Fig. 2a). The MPCP messages enable EPON control functionalities such as round-trip time (RTT) measurement, ONU registration, ranging, and ONU deregistration [1].

Whenever an ONU receives an MPCP message from the OLT, the ONU resets its local counter by using the timestamp value in the received MPCP message. In this way, the ONU local counter is locked to the OLT local counter. The EPON local counter mechanism provides a time granularity of 16 ns. It rolls over approximately every 68.72 seconds (i.e., $2^{32} \cdot 16$ ns). Figure 2b shows the RTT measurement in the ranging process. The OLT sends an MPCP message with timestamp A. When an ONU receives this message, the ONU sets its local counter according to the value in the timestamp field in the received message (i.e., A). After a certain wait time (e.g., when the ONU local counter reaches B), the ONU sends an MPCP message back to the OLT. This MPCP message contains timestamp B. The OLT receives this massage when its local counter reaches C. The RTT between the OLT and the ONU is measured as $RTT = t_{downstream} + t_{upstream} = t_{response} - t_{wait} = (C - A) - (B - A) = C - B$. Outside the ranging process, the OLT is able to measure the RTT drift by comparing its local counter value to the timestamp of the received MPCP message [1].

Therefore, EPON provides an accurate local distributed time-base. This can be leveraged to provide synchronized time transport in the following way. First, the OLT obtains an accurate network time reference, which will be used as the reference of the system. Second, the OLT figures out the difference between its local clock value and the synchronized network time. The downstream propagation delay is also factored into the clock difference. Third, the adjusted clock difference is transmitted to the ONUs via a control or management message. Fourth, the ONU then applies the difference to its local clock to produce the precise network time.

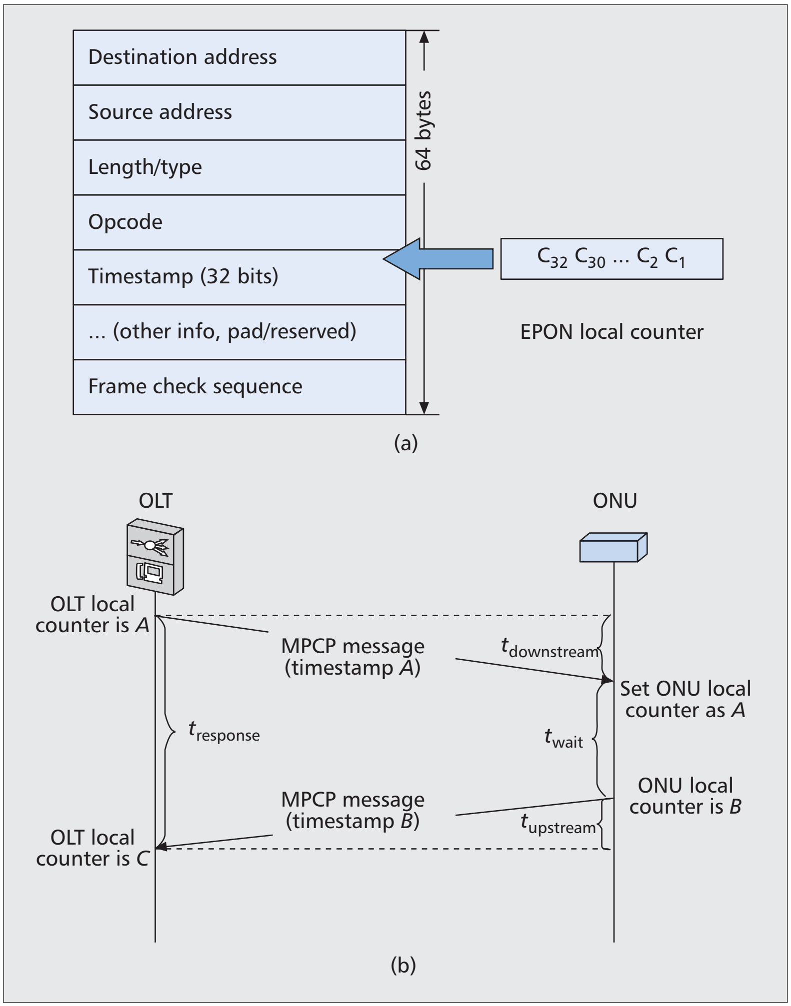

Figure 2. *EPON time measurement: a) 32-bit local counter; b) RTT measurement.*

TIME SYNCHRONIZATION MECHANISM

The aforementioned discussion of time synchronization challenges and EPON local counter functionalities motivate the following time synchronization solution. The major steps of this solution are illustrated in Fig. 3. The rest of this subsection describes each step.

Step 1: The OLT local clock is compared to a precise network time. There are different methods to deliver the network time to the OLT. Typical options include GPS and IEEE 1588™-2008. After synchronization, the OLT controls the time synchronization over EPON as a clock master, and the ONUs work as clock slaves.

Step 2: The OLT selects a local counter value, X, as the timing reference, compensates the link asymmetry by using the one-way downstream transmission delay, and calculates the corresponding network time at ONU$_i$ as

$$T_{x,i} = T_{x,o} + RTT_i \frac{n_{down}}{n_{down} + n_{up}}. \tag{1}$$

$T_{X,o}$ is the OLT sending time of a hypothetical MPCP message with the identification of X. X is the timestamp field value of this hypothetical MPCP message. $T_{X,i}$ is the ONU$_i$ receiving time of the hypothetic MPCP message. RTT$_i$ is the RTT measured between the OLT and ONU$_i$, n_{down} is the index of refraction for the downstream wavelength, and n_{up} is the index of refraction for the upstream wavelength. RTT$_i$ consists of two parts: the downstream transmission time of

$$RTT_i \frac{n_{down}}{n_{down} + n_{uup}}$$

and the upstream transmission time of

$$RTT_i \frac{n_{down}}{n_{down} + n_{uup}}.$$

In Eq. 1, the downstream transmission time is used to compensate for the fiber propagation asymmetry.

Step 3: The OLT informs ONUi of the association between the local counter value and network time as (X, $T_{X,i}$). The pair of values of (X, $T_{X,i}$) can be transmitted to ONU$_i$ via a Slow Protocol message in EPON [1].

Step 4: When ONUi receives the value pair, its local clock is adjusted as

$$T = T_{X,i} + (Y - X) * T_{granularity}. \tag{2}$$

Y is the ONUi local counter value when the clock slave adjustment is performed. $T_{granularity}$ is the local counter time granularity, which is equal to 16 ns.

The timing reference X selected in step 2 is a virtual reference point. The corresponding MPCP message may or may not actually be used to carry the timing message to the ONUs. In other words, X is picked by the OLT only for timing reference purposes. Any value of X can be chosen, as long as it is relative to the current epoch of the OLT local counter. Since the EPON local counter rolls over about every 68.72 s, a good practice of selecting X is to set it in the near future. This could facilitate an easy implementation of time synchronization by avoiding counter rollover confusion.

After receiving the pair of values of $(X, T_{X,i})$, an ONU could adjust its local time immediately or afterward. Essentially, Y in Eq. 2 can be either the exact local counter value when ONU$_i$ receives the pair of values, or a later-on local counter value when ONU$_i$ decides to perform the adjustment a certain while after the value pair has been received. Again, for the same reason as local counter rollover, the adjustment time should be set in the near future.

PERFORMANCE ANALYSIS

Performance metrics of time synchronization include local counter inaccuracy, RTT drift, and fiber propagation delay difference.

The EPON local counter granularity is 16 ns, implying an offset of up to 8 ns. Such an offset would impact the accuracy of values X and Y in Eq. 2. The EPON TDMA drift tolerance is specified to be 12 Time_quanta. Each Time_quantum is defined by the EPON standard as 16 ns. Such a drift is equivalent to an RTT drift tolerance of up to 192 ns, which corresponds to a one-way delay error of about 96 ns. It should be noted that the standard tolerance is the worst case value, and that most implementations actually achieve far better jitter performance than this.

The fiber propagation delay difference is generated as a result of the disparity between the downstream and upstream wavelengths. For a typical SMF-28 fiber, the indices of reflection are $n_{down} = n_{1490} = 1.4682$ and $n_{up} = n_{1310} = 1.4677$, respectively [7]. The difference between the downstream and upstream wavelengths impacts on the index correction factor

$$\frac{n_{down}}{n_{down}+n_{up}}$$

in Eq. 1. Assume $N = (n_{up} - n_{down})/n_{down}$; the impact of the index correction factor can be analyzed by expanding it into a Taylor series [8] as follows.\:

$$\frac{n_{down}}{n_{down}+n_{up}} = \frac{n_{down}}{2n_{down}+\left(n_{up}-n_{down}\right)}$$
$$= \frac{1}{2+\left(\dfrac{n_{up}-n_{down}}{n_{down}}\right)} = \frac{1}{2+N} = \frac{1}{2} - \frac{N}{4} + \frac{N^2}{8} + \ldots \quad (3)$$

The zero order analysis essentially assumes the index is constant over wavelength. This results in the index correction factor of 0.5. The first order analysis employs nominal fiber but at the fixed central wavelengths. This gives an index correction factor of 0.500085. As compared to the zero order result, it implies a fiber propagation error of 170 ppm in a typical EPON system with 20 km distance, which is equivalent to 17 ns. The second order analysis considers the variation of both fibers and wavelengths, and reveals the fiber dispersion impact. The index correction factor in the second order analysis varies from 0.500041 to 0.500090. This introduces an error of up to 5 ns [7]. Therefore, the error of the first order analysis dominates the fiber propagation error.

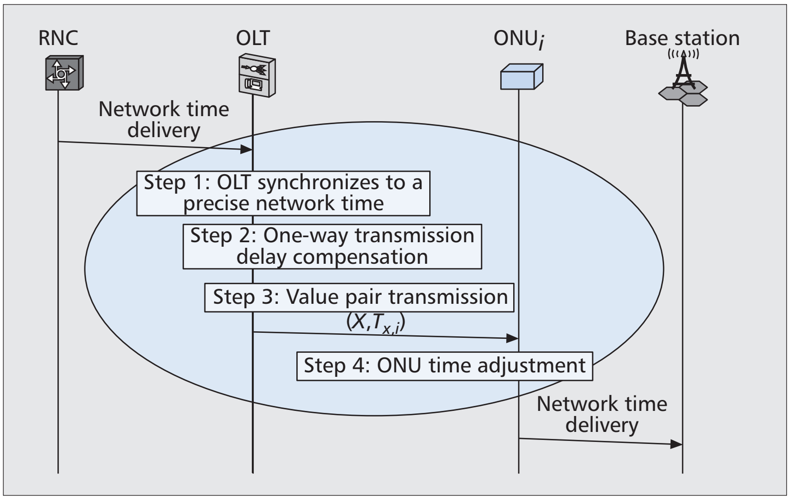

Figure 3. *Time synchronization over EPON.*

The maximum errors introduced by local counter, RTT drift, and fiber propagation are 8 ns, 96 ns, and 17 ns, respectively. Adding all of the three factors together, the maximum error introduced to EPON by the time synchronization mechanism is in the order of 100 nanoseconds. This is in a much smaller order than the wireless technology time accuracy requirements listed in Table 1.

PROTOTYPE SYSTEM AND RESULTS

Figure 4 shows the prototype system design of EPON time synchronization for performance evaluation. The RNC node is configured to distribute two types of time information to the wireless network: IEEE 1588v2 network time and local time with 1 pulse/s (PPS). The IEEE 1588v2 time input emulates the network time source. The local time input emulates other time sources such as GPS. The prototype system is designed to work with either type of the time information. The time source selection logic on the control card of the OLT chassis selects one of the time information to feed into the EPON OLT card. The selection of time source is for the purpose of prototype testing. Two EPON ONUs with BSs are connected to the network via fibers with certain length and a splitter. Mobile users transmit services to and receive services from BSs via the wireless channel. The other ONU is designed for wired service access. Time synchronization in EPON follows the mechanism described earlier.

Tests have been conducted in scenarios with different fiber distance. The received time at the user side is compared with the reference time from the OLT chassis control card. For illustration purposes, both reference time and received time are converted into 1 PPS with 50 ms width

The presented solution forms the basis of the relevant standards. The standardization effort and status in the IEEE have been reviewed. Given its time accuracy performance, this solution is able to tackle the time synchronization issue over the 10GE-PON system with minor updates. The standard trends have also been highlighted as a preview of this area.

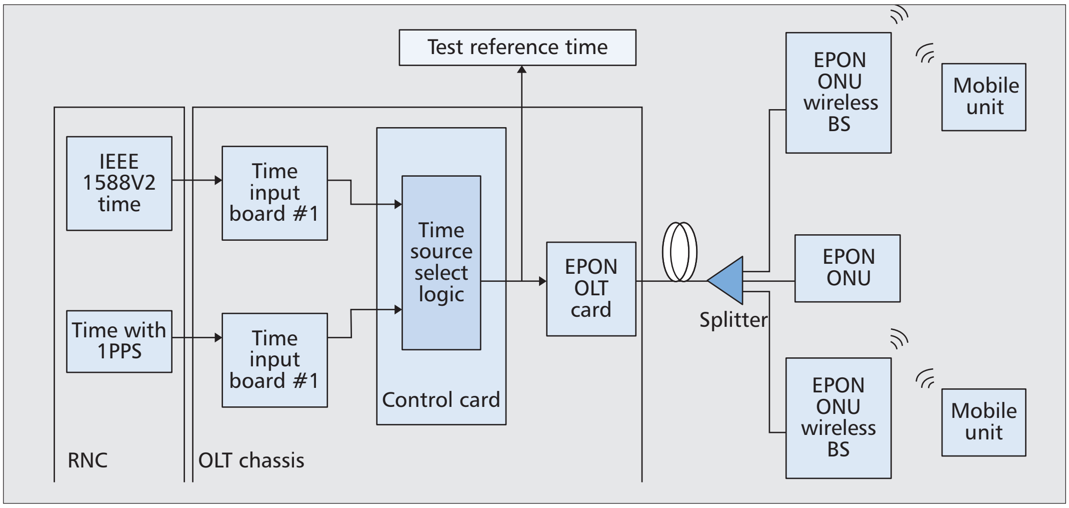

Figure 4. *A prototype system of time synchronization over EPON.*

to measure the disparity. The reference time is represented by a falling-edge 1 PPS signal. The received time is represented by a rising-edge 1 PPS signal.

Figure 5 shows the worst case results of various fiber distances with different time sources. When the fiber distance between the OLT and an ONU in the prototype system is 5 km, the received time shows a maximum disparity of 60 ns. The maximum time disparity increases to 65 ns when the fiber distance is 10 km. When the fiber distance reaches 15 km, the maximum time disparity is 70 ns. The maximum time disparity is measured as 90 ns when the fiber distance is 20 km. All of the maximum time disparities measured in the prototype system are less than 100 ns. Therefore, various wireless services can be delivered to the mobile users.

In addition to the above measurement, wireless voice, data, and video services have been tested in the prototype. Because the network time is precisely synchronized from the RNC node to mobile users via EPON, these services have been provided to the mobile users with satisfied quality. Wired services of voice, data, and video have also been tested. There was no interference between wired and wireless services.

STANDARD STATUS AND TRENDS

The IEEE 802.1AS standard was published on March 30, 2011 [9]. It specifies the protocol and procedures for time synchronization across bridged and virtual bridged networks. The issue of EPON time synchronization is addressed by Clause 13. In particular, the clock master role of the OLT and the slave role of the ONUs are enforced by properly configuring the acceptable master table feature, which determines the clock priorities and best master selection in an IEEE 802.1AS network. An Organization-Specific Slow Protocol (OSSP) message (i.e., TIMESYNC) is employed to transmit the pair of values of $(X, T_{X,i})$ from the OLT to ONU$_i$. The relevant service primitives, interfaces, and station machines are also defined by Clause 13 in this standard.

Looking forward, the rate enhanced system of EPON is 10GE-PON [10]. 10GE-PON features the downstream rate of 10 Gb/s, and the upstream rate of 1 Gb/s or 10 Gb/s. Time synchronization would be updated to align to the transmission rate improvement and system specification enhancement.

When migrating from EPON to 10GE-PON, the mechanisms of TDM, TDMA, local counter, and RTT management are well maintained. The major changes are the adopted wavelengths. This means that the EPON time synchronization mechanism described earlier can be applied to the 10GE-PON system with the proper update of the indices of refraction. The aforementioned update has been accommodated in IEEE 802.1AS Clause 13.

SUMMARY

This article has examined the solution of time synchronization over EPON. The primary objective is to facilitate the EPON implementation of mobile backhaul and to support time-sensitive broadband access services. Time accuracy requirements of various wireless technologies and challenges of link delay difference have been investigated.

Based on EPON link asymmetry analysis, the accepted time synchronization solution in standards bodies has been introduced. In the solution, the existing local timing mechanism of EPON is employed to provide timing reference. The OLT plays a master role in distributing time to individual ONUs. After conducting link asymmetry compensation and value pair calculation, the OLT informs an ONU the association between the accurate time and the ONU local counter value. An ONU is able to adjust its local time after receiving the value pair via a control or management message.

With such procedures defined, the performance evaluation has been conducted by analyzing local counter inaccuracy, RTT drift, as well as fiber propagation difference. Analysis has shown that the maximum error is restricted in the 100-nanosecond level. The analysis has been verified in a prototype system, which demonstrated nanosecond order accuracy. This

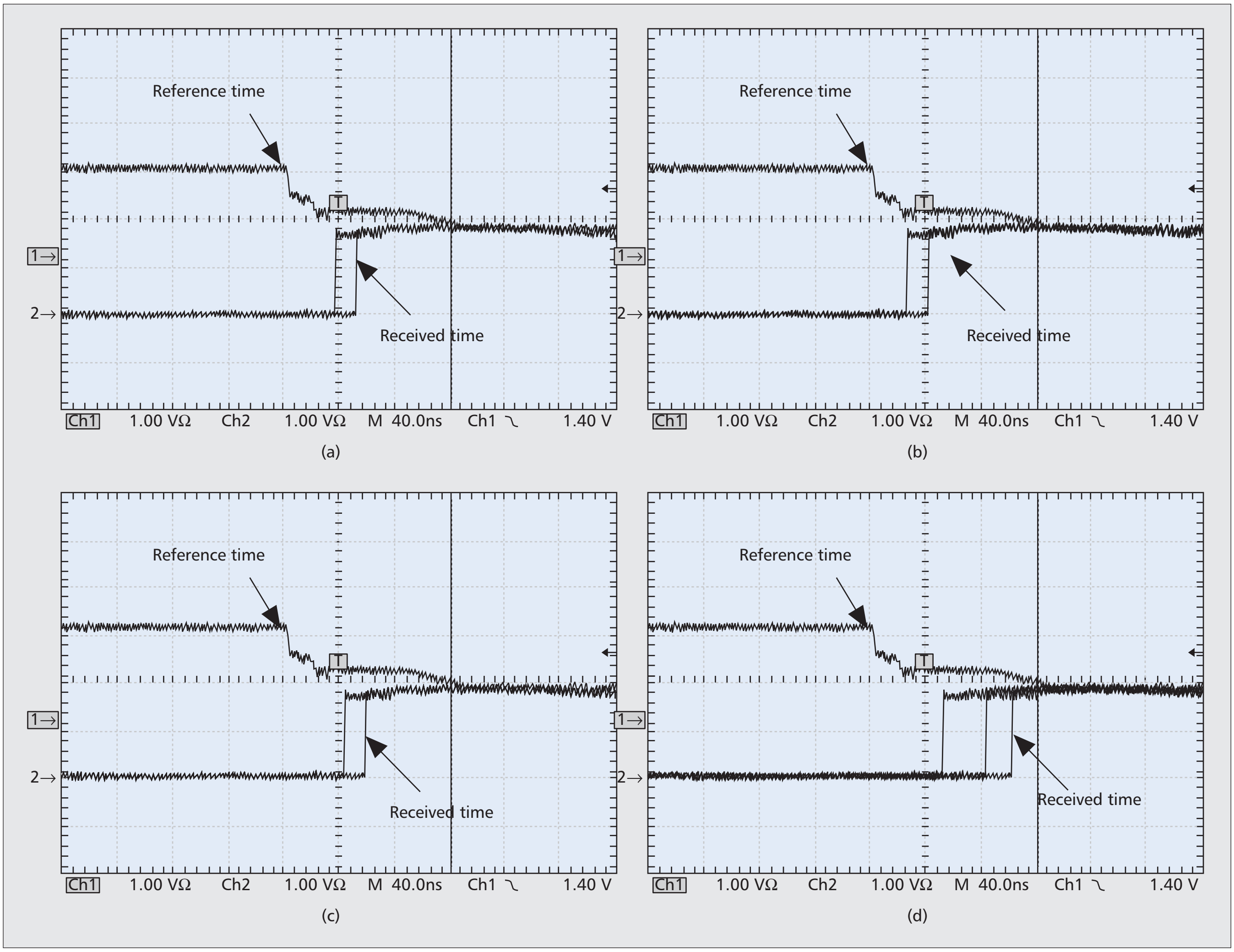

Figure 5. *Test results (time granularity: 40 ns; Ch1: reference time; Ch2: received time): a) 5 km fiber; b) 10 km fiber; c) 15 km fiber; d) 20 km fiber.*

is an order of magnitude better than the mobile backhaul time synchronization requirements.

The presented solution forms the basis of the relevant standards. The standardization effort and status in the IEEE have been reviewed. Given its time accuracy performance, this solution is able to tackle the time synchronization issue over the 10GE-PON system with minor updates. The standard trends have also been highlighted as a preview of this area.

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BIOGRAPHIES

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FRANK J. EFFENBERGER completed his doctoral work in 1995. He then took a position with Bellcore (now Telcordia) where he analyzed all types of access network technologies, focusing on those that employed passive optical networks. He witnessed the early development of the FSAN initiative and the development of the APON standard. In 2000 he moved to Quantum Bridge Communications (now a part of Motorola), where he managed system engineering in their PON division. This work supported the development and standardization of advanced optical access systems based on B-PON and G-PON technologies. In 2006 he became director of FTTx in the Advanced Technology Department of Huawei Technologies USA. He remains heavily involved in standards work, and has been the leading contributor and editor of the major PON standards in the ITU. In 2008 he became chairman of ITU-T Q2/15 — the group that creates standards for optical access systems. He and his team work on forward-looking fiber access technologies, including the 802.3av 10G EPON and ITU XG-PON topics. Notably, his team supported the world's first field trial of XG-PON. In 2011 he was named a Huawei Fellow.

NIRWAN ANSARI [S'78, M'83, SM'94, F'09] received his B.S.E.E. (summa cum laude with a perfect GPA) from the New Jersey Institute of Technology (NJIT), Newark, in 1982, his M.S.E.E. degree from the University of Michigan, Ann Arbor, in 1983, and his Ph.D. degree from Purdue University, West Lafayette, Indiana, in 1988. He joined NJIT's Department of Electrical and Computer Engineering as an assistant professor in 1988, and has been a full professor since 1997. He has also assumed various administrative positions at NJIT. He authored *Computational Intelligence for Optimization* (Springer, 1997) with E.S.H. Hou, and edited *Neural Networks in Telecommunications* (Springer, 1994) with B. Yuhas. His research focuses on various aspects of broadband networks and multimedia communications. He has also contributed over 400 technical papers, over one third of which were published in widely cited refereed journals/magazines. He has also guest edited a number of special issues, covering various emerging topics in communications and networking. He was/is serving on the Advisory Boards and Editorial Boards of eight journals, including as a Senior Technical Editor of *IEEE Communications Magazine* (2006–2009). He has served or is serving the IEEE in various capacities.