FIBER OPTIC TIME TRANSFER FOR UTC-TRACEABLE SYNCHRONIZATION FOR TELECOM NETWORKS

Łukasz Śliwczyński, Przemysław Krehlik, Jacek Kołodziej, Helmut Imlau, Horst Ender, Harald Schnatz, Dirk Piester, and Andreas Bauch

ABSTRACT

A robust and reliable synchronization network, able to distribute signals traceable to a recognized standard, is crucial for the operation of future 5G telecommunication networks. In this article we present the results of time transfer using optical fibers. The main goal is to test the long-term capability of ELSTAB technology (developed by AGH) to deliver time and frequency signals traceable at the sub-nanosecond level to UTC in a real telecommunication environment. In an ongoing cooperation between Deutsche Telekom (DTAG), the Physikalisch-Technische Bundesanstalt (PTB) and AGH University of Science and Technology, we deliver UTC — as realized by PTB in Braunschweig — to a test center of DTAG located in Bremen. For this purpose, a fiber optic link has been operated since July 2015. The results obtained show that the operator of a telecom network may use such a stabilized fiber optic link as a reliable source for synchronization signals with a precision and accuracy superior to those obtained using a state-of-the-art GNSS time receiver. Moreover, a fiber optic link delivering UTC traceable signals increases the robustness and reliability of the network's synchronization chain by making it less dependent on GNSS.

INTRODUCTION

Two prominent applications of high-accuracy time and frequency transfer can be identified: the operation of a global navigation satellite system (GNSS) and of telecommunication networks. Each of them has ambitious requirements regarding accuracy, availability, and security. Mobile telecommunication networks are operated according to the Long Term Evolution-Advanced (LTE-A) standard and are going to be prepared for future fifth generation (5G) standards. Mobile time-division duplex (TDD) operation, new features for increased spectrum efficiency like enhanced inter-cell interference cancellation (eICIC), future new mobile location-based services, and single-frequency network-based multi- and broadcast applications (MBSFN) services need not only frequency syntonization, but also time synchronization.

In order to reach the required network synchronization quality [1], dedicated synchronization chains are implemented, structured as a hierarchical and layered synchronization network. Each network equipment draws its synchronization signal from a superior hierarchy element located closer to the primary synchronization source(s). An example of such a network is shown in Fig. 1. It comprises the network production part, responsible for routine operation of the network, with the requirement of continuous 24/7 operation, and a primary clock supervision part. At the network core level, the highest accuracy synchronization equipment including a number of primary reference time clock (PRTC) functions [2] is used, which is responsible for passing down the network reference time along the hierarchy. In order to increase the network synchronization stability and minimize GNSS related risks, enhanced PRTCs (ePRTCs) [3] and coherent network PRTCs (cnPRTCs) [4] combine GNSS receivers with atomic (cesium) clocks. This approach has recently been proposed for standardization by the respective committees of the International Telecommunication Union — Telecommunication Sector (ITU-T). Over a few core locations, ePRTCs are going to be distributed geographically in the network.

The ITU-T specified maximum absolute time error (max|TE|) allowed for ordinary PRTC function is 100 ns [2], whereas the related value for ePRTC is more tightly set at 30 ns [3]. In addition, stability specifications for dynamic time error, expressed as maximum time interval error (MTIE) and time deviation (TDEV), apply. For 24/7 synchronization of the network production part, technologies such as synchronous Ethernet (SyncE) and Precision Time Protocol (PTP) with full timing support from the network (PTP-FTS) according to the ITU-T Recommendation G.826x series for frequency and G.827x for time synchronization, are able to ensure the required level of accuracy at the end application.

The ITU-T standards G.8272 (PRTC) [2] and G.8272.1 (ePRTC) [3] recommend that the network time reference has to be traceable to a recognized time standard, and ideally the underlying timescale should be coordinated universal time (UTC). At present, it is a common practice in the telecom industry to derive

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Łukasz Śliwczyński, Przemysław Krehlik, and Jacek Kołodziej are with AGH University of Science and Technology; Helmut Imlau and Horst Ender are with Deutsche Telekom Technik GmbH; Harald Schnatz, Dirk Piester, and Andreas Bauch are with Physikalisch-Technische Bundesanstalt.

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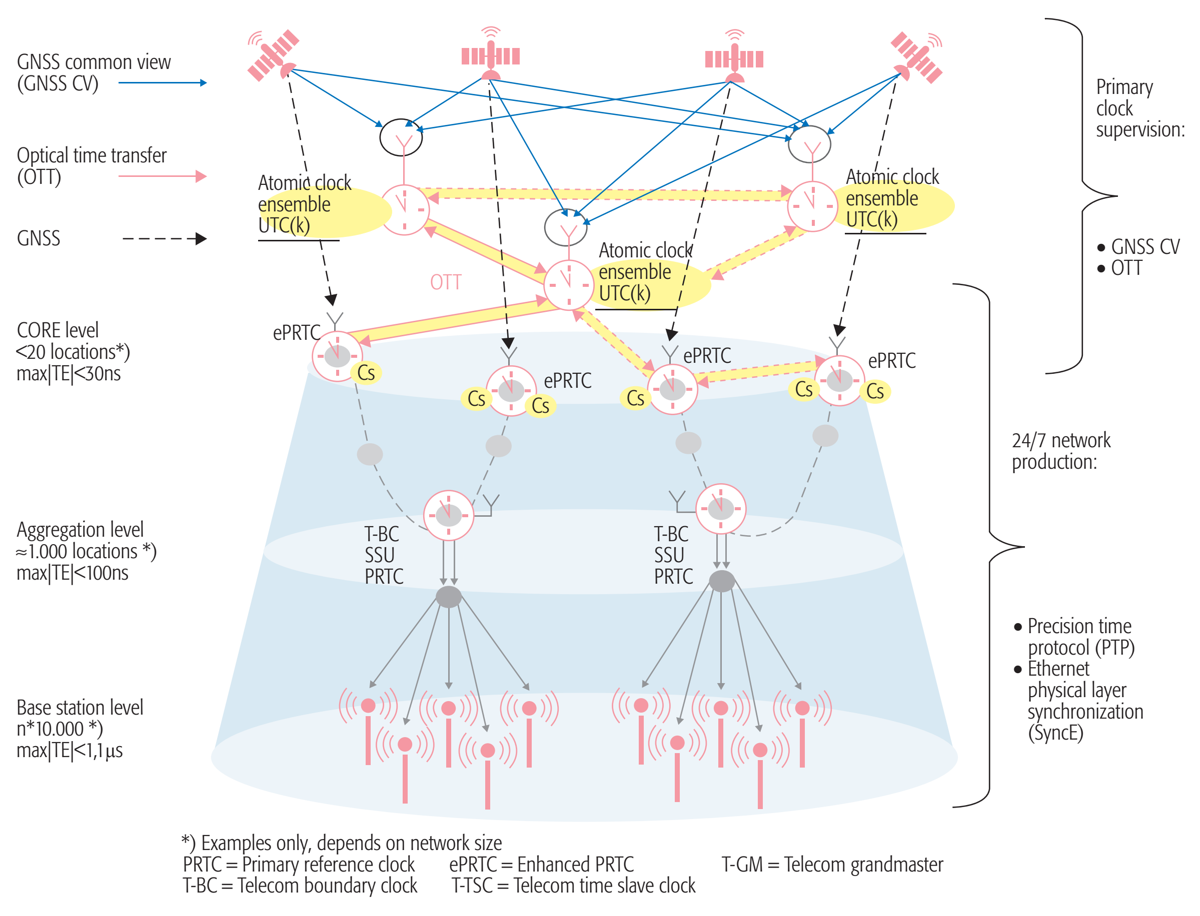

FIGURE 1. An example of a block diagram of a hirarchical telecommunication synchronization network.

the network time reference directly from GNSS signals as it is assumed that the underlying system time (e.g., GPS time) is kept in good agreement with UTC. In a more sophisticated approach, time transfer based on the reception of GNSS signals can be performed between the network operator's reference clock and an institution that operates atomic clock ensemble and realizes a representation of UTC — usually a national metrology institute (NMI). The realization of UTC is named UTC(k), and UTC(PTB) is an example thereof. This approach is discussed in more depth in the next section. It is also possible that both strategies may be used simultaneously on various nodes of the same network, depending on local needs and technical capabilities.

However, when UTC traceability of the network time is based on a local GNSS receiver only, a strategic risk arises for network operators as they have no control and influence on these satellite systems. In principle, the function of a GNSS requires dissemination of signals, including time-of-day information. Their reception allows the generation of standard frequency (e.g., 10 MHz or 2048 kHz) and one pulse-per-second (1 PPS) signals with the rising edge of each impulse corresponding to the respective epoch in UTC with low deviation. Currently, neither performance nor availability is guaranteed by the operators of such service. This situation may improve in the future as the European Commission plans to offer such service guarantees for its Galileo system. Even with such guarantees, the problem will not be fully solved because the GNSS signals may be jammed or spoofed relatively easily [5].

Thus, to ensure robust operation of a network with highest performance guarantees given to the customer, an additional level of synchronization hierarchy is desirable, providing the capability to monitor and supervise the real performance of the highest-level equipment. Monitoring of these key nodes with an accuracy much better than 30 ns, which is required to supervise the ePRTC, is currently a challenging task. The integration of fiber optic time transfer (OTT) techniques into the telecommunication infrastructure (at least at the operations supervision level) may circumvent many of the above-mentioned problems. It can be used to directly link the network equipment under supervision to an NMI, where usually an ensemble of atomic clocks is operated. In this way direct, GNSS-independent access to UTC is obtained.

Until now, only a few installations of this type were set up, oriented for either experimental or scientific purposes [6–9]. In this article we present a proof of concept (PoC) experiment, aimed at delivering UTC(PTB) (1 PPS and 10 MHz) to a test center of Deutsche Telekom in Bremen by optical fiber. Before presenting the results, we introduce and explain a few concepts related to time signals.

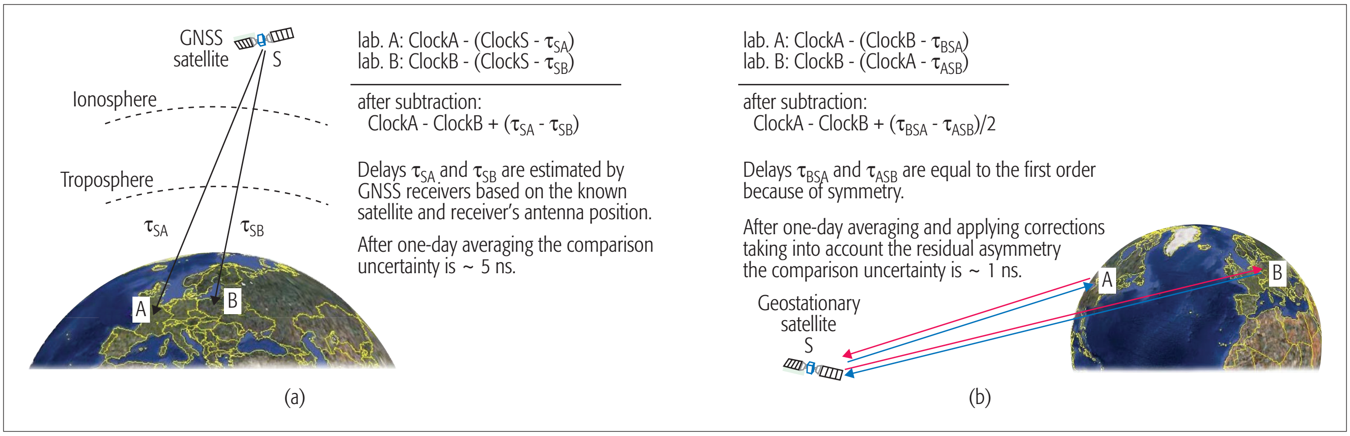

Figure 2. Principle of time transfer using standard satellite techniques: a) GNSS common view; b) TWSTFT.

UTC, Traceability, and Time Transfer

A timescale is defined by a sequence of 1-s marks, and starts from a defined beginning. International Atomic Time, or Temps Atomique International (TAI), and especially UTC, allow events in science and technology to be dated. At the same time, UTC provides the basis of the "time" that is used in everyday life. For its calculation, a task of the Bureau International des Poids et Mesures (BIPM) Time Department, approximately 400 clocks from some 70 time-keeping institutes, distributed all over the world, are averaged, as explained in [11]. The clock ensemble mean is called Echelle Atomique Libre (EAL, free atomic timescale). In a second step, TAI is obtained, whose scale unit is kept in agreement with the base unit second of the international system of units SI by comparison with so-called primary frequency standards operated in a few NMIs. The beginning of TAI was defined in such a way that the 1st of January 1958, 0 o'clock TAI, agreed with the respective moment in (astronomical) Universal Time UT1. From TAI one obtains UTC, which is the basis of today's world time system with 24 time zones. UTC and TAI have the same scale unit. The difference between UTC and UT1 is limited to less than 0.9 s by inserting leap seconds in UTC [12]. In consequence, today TAI differs from UT1 by 37 s. UTC is published by BIPM in the form of a document known as Circular T, which includes calculated time differences with reference to the timescales UTC(k) realized in the individual time-keeping institutes k. The UTC(k) scales shall agree as well as possible with UTC, and thus also among each other.

UTC can be obtained from a time laboratory collaborating with the BIPM. Most NMIs provide access to their UTC(k) — or to the legal time of the country derived thereof — by various means, and such services are documented inter alia in the BIPM Annual Report [13]. For applications that do not require such high-level accuracy, standard frequency and time signals may be obtained from radio broadcast, which is available in Europe from services like DCF77 (Germany), MSF (United Kingdom), and France Inter (France). For widespread applications of time-of-day information, NMIs operate Internet-based services, which are documented in [13]. Several NMIs document the reception of GNSS signals with calibrated receivers, and users of such signals are invited to consult the NMI documentation to get assurance about the performance of the GNSS signals. In all the above mentioned cases the NMIs control or supervise the time signals and provide documentation of the performance, including uncertainty data. Thus, an unbroken chain of comparisons to the national standard exists, which in metrology is referred to as traceability.

The delay of the signal received from the satellite is not constant and fluctuates over time in a random way. In order to suppress such effects, for the most demanding applications interested parties may perform time comparisons with the NMI. The most common method is GNSS time transfer, where both parties operate dedicated GNSS timing receivers that provide, in a first step, the measurement of the time delay between the local timescale and the space clock of the individual GNSS satellites. Combined with the GNSS navigation message, all measurements are referred to the underlying GNSS system time and corrected for the propagation delay caused by the geometrical distance, ionosphere, and troposphere delay (all are time-dependent). If higher accuracy is needed, post-processing of the data includes information from external sources, including precise satellite orbits, ionosphere observation, and so on, provided by the International GNSS Service (IGS). This is in principle a comparison of the user's local clock with the NMI's timescale and typically uses the GNSS onboard atomic clocks as an intermediate. In the so-called GNSS Common View (CV) comparison (Fig. 2a), data from observations of the same satellite during the identical period of time are differenced. In this case, thanks to a great degree of symmetry and the differential nature of the comparison, the characteristics of the space clock and to some extent of the satellite orbit do not affect the obtained results. The other, more accurate and advanced option is a two-way satellite time and frequency transfer (TWSTFT — Fig. 2b) where interested parties interchange signals via a link involving a broadcast geostationary satellite as an intermediate. In this case the propagation conditions in both counter-propagating directions may be assumed to be almost the same, so the unknown and time varying propagation delay between the laboratories operating their clocks can be effectively ruled out by proper processing of comparison data.

Time transfer via GNSS signals is a standard procedure for all NMIs in their involvement in UTC realization via collaboration with BIPM. It requires in addition a calibration of the signal delays in the timing receivers and involves data exchange in agreed formats. It is rather rarely performed by the telecom industry. It is a German peculiarity that Deutsche Telekom operates its timing center in Frankfurt/Main and obtains traceability of UTC(DTAG) to UTC directly through the BIPM Circular T, just as NMIs and research institutes do.

Time transfer based on satellite technologies is an offline service, requiring substantial data processing. Optical time transfer (OTT), discussed next, is a further step in the direction of enhancing performance and becoming independent of GNSS signals. It differs from the ordinary GNSS time transfer as it is an online service, able to deliver stable frequency and accurate time to a remote location without need for the operation of an atomic clock at the remote site.

Optical time transfer is a further step in the direction of enhancing performance and becoming independent from GNSS signals. It differs from the ordinary GNSS time transfer, as it is an online service, able to deliver stable frequency and accurate time to a remote location without need for the operation of an atomic clock at the remote site.

Fiber Optic Time Transfer

An optical fiber is a very convenient means to transport information as it offers high bandwidth and high immunity to external electromagnetic interference. Inherent low attenuation of up-to-date fibers (typically below 0.2 dB/km at 1550 nm) in connection with an efficient way of optical regeneration using erbium doped fiber amplifiers (EDFAs) allows to transmit signals over distances spanning hundreds or even thousands of kilometers. For decades this has been the basis of telecommunications, making it possible to exchange the accrued amount of data at high speed regardless of the distance separating communicating parties.

For the transfer of time signals, an important fact is that the propagation of light in an optical fiber is affected by external temperature, resulting in a change of the propagation delay with a typical thermal coefficient of 40 ps/(km · K) that is only weakly dependent on the wavelength and the fiber type. This value is small, unnoticeable in usual telecom applications, but for typical seasonal temperature variations of 25° K the delay in a 100 km long fiber cable will change accordingly by about 100 ns (and thus increases the TE budget). For highly accurate time transfer applications, this value is unacceptably high and limits the so-called unidirectional fiber transfer to either very short distances or less demanding applications.

However, an optical fiber can easily guide two signals in counter-propagating directions (a feature not much exploited in telecom, but very attractive here), and thus the symmetry of the propagation conditions in both forward and backward directions is guaranteed to a high degree. In this way a time transfer system based on a similar principle as used in TWSTFT can be arranged to compare two atomic clocks via an optical fiber [7]. The operational distance of the system can be made as large as necessary by implementing special fiber optic amplifiers along the line [10]. These amplifiers, required to regenerate the optical signals without violating the fiber link symmetry, are operated bidirectionally and are based on a single span of Er-doped fiber.

The idea of using an optical fiber for time transfer has been further developed in systems that offer not only comparison of clocks, but also deliveriy of a time signal with stabilized and accurately known delay to a remote location that does not need to operate its own atomic clock. To achieve this, measures are required to compensate the variations of the propagation delay of the fiber, in either the optical or electrical domain. In addition, a feedback loop must be implemented that keeps the overall propagation delay constant. Systems that operate in the optical domain may use either mechanical variable delay lines or heated fiber spools, but suffer from either a small compensation range or large size and high power consumption. Systems operating in the electrical domain based on variable electronic delay lines are compact and low-power-consuming, and allow compensation of seasonal fluctuations of the fiber propagation delay in links spanning hundreds of kilometers. This is the way the AGH-developed electronically stabilized (ELSTAB) system (Fig. 3a) works [10].

The system is designed to send 10 MHz and 1 PPS signals to a distant location. In the local module the 10 MHz frequency signal is first phase-modulated at each occurrence of the 1 PPS pulse in a PPS embedder. The signal bearing both the frequency and time information is passed through a forward variable delay line and subsequently modulates the intensity of the laser light that is sent to the fiber in the forward direction via an optical circulator. After having reached the remote end, the signal is converted back into the electrical domain and used to modulate another laser (with a slightly different wavelength to avoid interference caused by Rayleigh backscattering occurring in the fiber), whose signal is sent in the backward direction to the local module. In the remote module the time (1 PPS) and frequency (10 MHz) signals are also separated in the PPS de-embedder and directed into the output of the system. The signal returned to the local module is converted to the electrical domain, passed through the backward variable delay line, and separated into 10 MHz and 1 PPS signals. Next, the phase difference between input and returned 10 MHz frequency signals is sensed and used to control both forward and backward delay lines. Phase measurement plus delay control form a feedback system known as a delay locked loop (DLL). The feedback keeps the phase difference at zero, which means the round-trip propagation delay is stabilized at a constant value.

In the described system great care is taken to make the tuning characteristics of both forward and backward delay lines the same. This is ensured by their careful design and manufacturing as an application-specific integrated circuit (ASIC). If the propagation delay of the fiber is subject to changes, these are actively compensated in the feedback loop. Thus, the propagation delay from the input of the system to its output (equal to the sum of the delay introduced by the forward delay line and by the fiber) stays constant as well (Fig. 3b).

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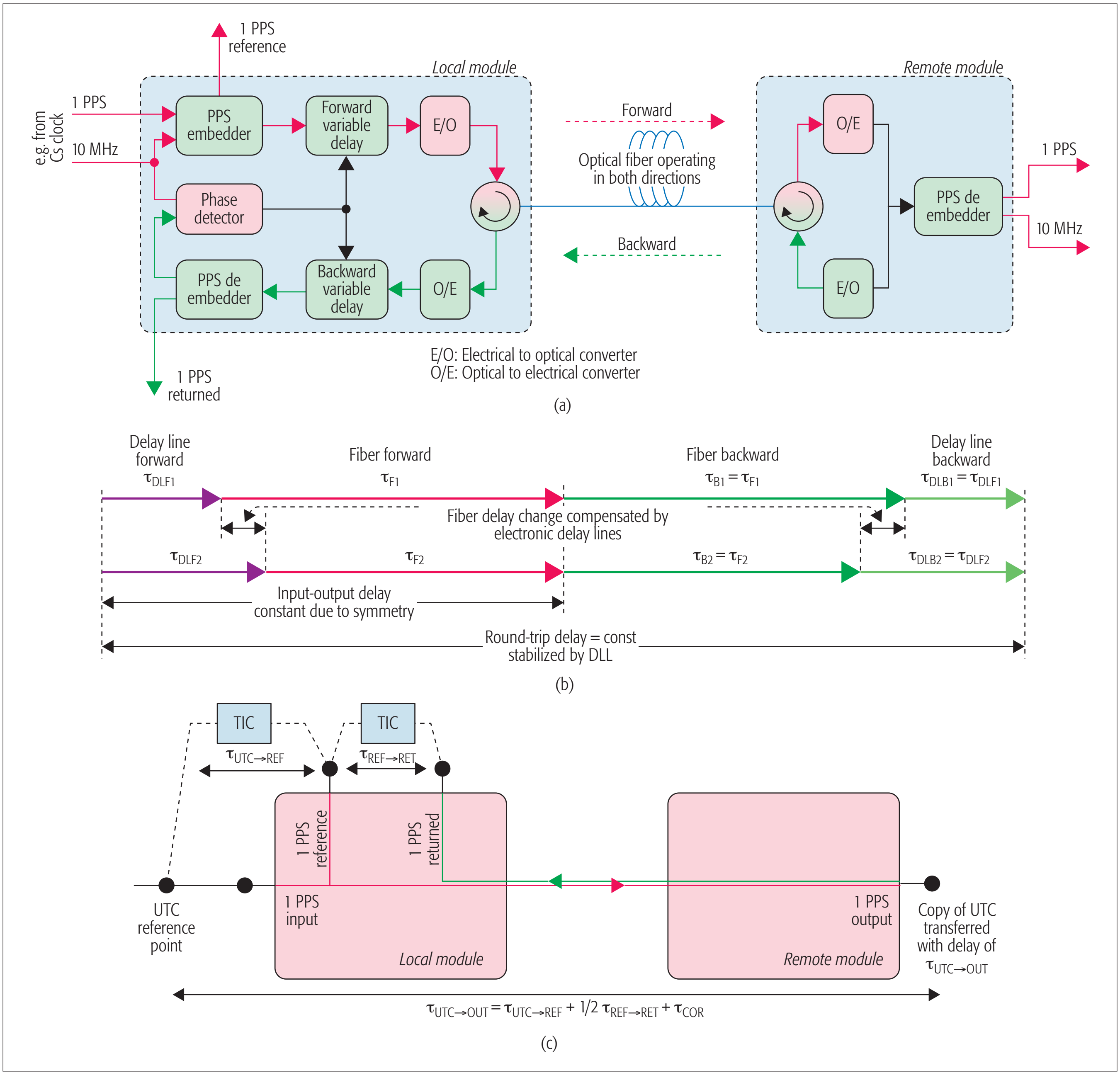


FIGURE 3. Principles of the ELSTAB system: a) simplified block diagram; b) illustration of the delay stabilization; c) illustration of time transfer calibration.

of the delay between the UTC(k) reference point and the output of the system has to be initially calibrated. In our system this calibration is done based on two time interval measurements using a time interval counter (TIC) at the local side (Fig. 3c). The propagation delay ($\tau_{UTC\to OUT}$) is the sum of the delay between the UTC reference point and the reference point of the transmission system ($\tau_{UTC\to REF}$), one half of the round-trip delay ($\tau_{REF\to RET}$), and τ_{COR}. This latter term comprises the fiber chromatic dispersion, the Sagnac effect, and an initial calibration value of the internal hardware delays. All the constituents required to determine the value of $\tau_{UTC\to OUT}$ are known with an uncertainty in the picosecond range, resulting in a total uncertainty (defining a potential time error introduced by the transfer system) in the range of tens of picoseconds, depending on the length and type of the fiber connecting local and remote modules [10].

The single fiber operation and bidirectional amplification may be avoided in principle by using a pair of fibers running in the same cable, as their temperature fluctuations are closely correlated. In this case, however, the lengths of the forward and backward paths are not exactly the same (due to, e.g., different patchcord lengths, different length of the fibers inside unidirectional EDFAs), and the difference is difficult to predict. Such asymmetry will result in a constant time error equal to about 5 ns per each meter difference of fiber length, which may further change in an unpredictable manner (e.g., due to link maintenance after fiber breaks). This means that for precise time transfer, required for telecom applications, the bidirectional single-fiber approach is the right option to follow.

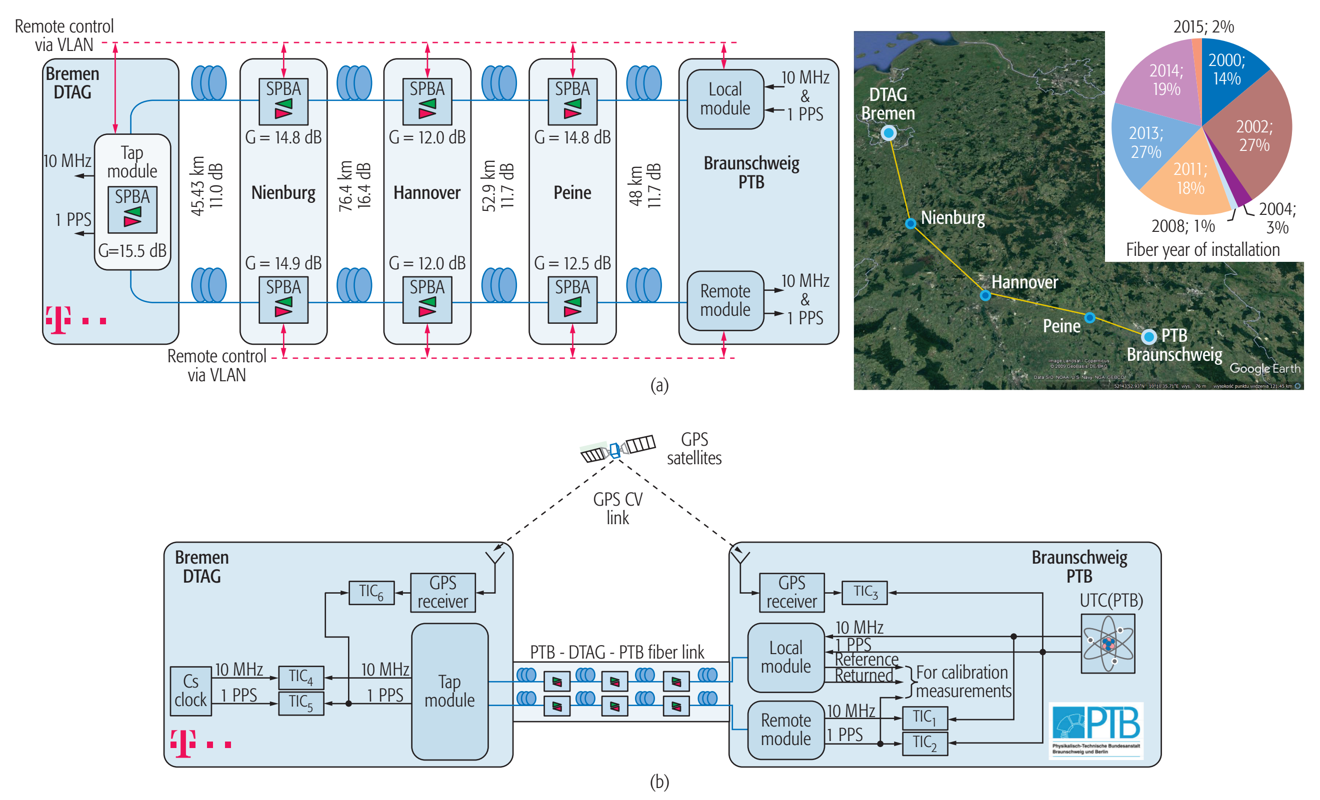


Figure 4. PoC time and frequency fiber optic transfer link: a) block diagram showing equipment installed and the details of the link; b) simplified measurement setup used to assess parameters of the link.

PROOF OF CONCEPT EXPERIMENT

The experiment started in July 2015, and is a joint initiative of PTB, Germany's NMI, by law entrusted to disseminate legal time for the country; DTAG, a user of the synchronization signals; and AGH, developer of the OTT ELSTAB technology [14]. The main goal of the PoC experiment was to demonstrate the UTC(PTB) traceable time dissemination at the sub-nanosecond level, and assess its long-term performance and reliability when exploiting typical single-mode fibers (G.652) installed by Deutsche Telekom between 2000 and 2015. To do this, a fiber optic link was set up between the PTB site in Braunschweig and the test center of DTAG, located in Bremen. In order to monitor and evaluate the performance of the signals, we decided to arrange a loop configuration (using a pair of fibers) with the local and remote modules of the ELSTAB system located at PTB. The signals have been made available in Bremen using a so-called tapping module able to extract the stabilized signals from the fiber link [15].

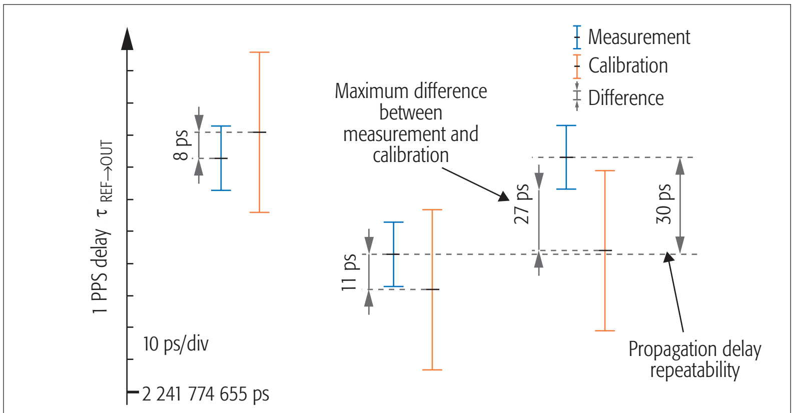
The schematic of the link is presented in Fig. 4a, together with the map and a chart providing information about the time of installation of the fibers. The total length of the fiber is almost 446 km round-trip (Braunschweig-Bremen-Braunschweig) and half of this length, from Braunschweig to Bremen. The total attenuation of the link exceeds 100 dB. To compensate this loss, seven single-path bidirectional amplifiers (SPBA) are used along the fiber route (two in each location in Peine, Hannover, and Nienburg, respectively, plus one more in Bremen). Each piece of equipment installed along the line is equipped with a 10/100 Mb/s Ethernet port for remote management and status monitoring, accessible via a virtual LAN (VLAN).

The characterization of the link performance was the key objective of the PoC. Most of the measurements were made at PTB. Because of the loop configuration, we have been able to compare the signals transferred via the ELSTAB link directly against UTC(PTB) with the highest possible accuracy. For this purpose, a measurement setup (Fig. 4b) has been employed for measuring the stability of 1 PPS and 10 MHz signals (using TIC$_2$ and TIC$_1$, respectively) and for checking the link calibration locally at PTB. The main measurement goal at the remote location at Bremen was verification of the long-term reliability of the transfer system. Hence, the signals received from the tapping module were compared against a local cesium clock and logged (using TIC4 and TIC5). In addition, a GNSS CV link has been used to perform time transfer between UTC(PTB) and a cesium clock operated in Bremen to compare the OTT with the time transfer technique that is currently used most often.

EXPERIMENTAL RESULTS

Experimental data obtained from the PoC link can be divided into two categories. The first one is related to the evaluation of accuracy and repeatability of 1 PPS delay calibration, and the second one to the stability of the 1 PPS and 10 MHz signals received at the output of the remote module.

The measurements of 1 PPS delay were performed three times at an interval of about half of a year to check the long-term performance of the



Date	10.07.2015	11.12.2015	21.06.2016
Measurement [ps]	2 241 774 726±10	2 241 774 696±10	2 241 774 724±10
Calibration [ps]	2 241 774 734±25	2 241 774 685±25	2 241 774 697±25

FIGURE 5. Propagation delay introduced by the PoC link.

link. The results are collected in Fig. 5 and compared to the calibration values of $\tau_{UTC\rightarrow OUT}$ (cf. Fig. 3c and associated discussion in the section Fiber Optic Time Transfer). It may be noted that during the experiment, the repeatability of the propagation delay, understood as the maximum dispersion of measured values, stayed within the range of 30 ps. The difference between the measured and predicted delays did not exceed 27 ps and in general are covered by the measurement uncertainty.

The stability of 1 PPS and 10 MHz signals at the output of the remote module, referred to UTC(PTB) at 1/s rate (without any averaging), is illustrated in Fig. 6a. It is worth mentioning here that when measuring timing signals at the picosecond level, the noise of the measuring instruments can be a limiting factor. For 10 MHz phase measurements, a special high-precision measurement technique developed at PTB was used, whereas for 1 PPS signals a Stanford Research SR620 TIC was used that shows much higher intrinsic noise.

The comparison of MTIE and TDEV curves calculated from the raw data with the masks defined by ITU-T G.827x [1–3] Recommendations is presented in Figs. 6b and 6c, respectively. The values obtained are below even the most rigorous mask proposed for ePRTC function by more than one order of magnitude, making OTT suitable for online monitoring of its parameters.

The lower curve in Fig. 6a shows the comparison of UTC(PTB) with the 1 PPS signals at the output of the tapping module installed in the DTAG laboratory in Bremen obtained using the GPS CV technique. In this case the noise is much higher compared to OTT, although the signal was averaged over one hour (note the change of the vertical scale) but quite normal for the GPS CV method. As another distinction, we recall that any GNSS time transfer technique requires data post-processing and averaging, whereas OTT is an online, real-time service.

The two gaps noticeable in the raw data plots were due to temporary failure of the OTT link, caused by a problem with the system stabilizing the wavelength of the laser in the local module (first gap) and by a power supply failure in one of the regenerating stations (second gap). In both cases, however, it was possible to diagnose the link remotely using VLAN access. It was even possible to fix the laser wavelength stabilization system remotely. It is also important to note that after restoring the normal operation of the link, no phase jump was observed between UTC(PTB) and link output signals. The lengths of the gaps did not correspond to the time required to fix the problems but results from the low priority level given to the PoC link.

SUMMARY

In this article we present an idea of extending the synchronization network of future 5G mobile telecom systems by implementing OTT links to obtain traceability to a UTC(k) timescale operated by NMIs and allow real-time monitoring of parameters of PRTC functions in key locations at the network core level. Such an additional supervision level will increase the robustness and reliability of the network's synchronization chain, making it less dependent on ubiquitous GNSS systems. In some cases it can be considered as an alternative source of synchronization signals of a quality superior to GNSS.

The PoC experiment was performed by sending UTC(PTB) traceable signals via the OTT link from PTB in Braunschweig to the DTAG test center in Bremen using the AGH-developed ELSTAB system. Its results clearly show that the OTT technology fulfills the needs of the telecom operator

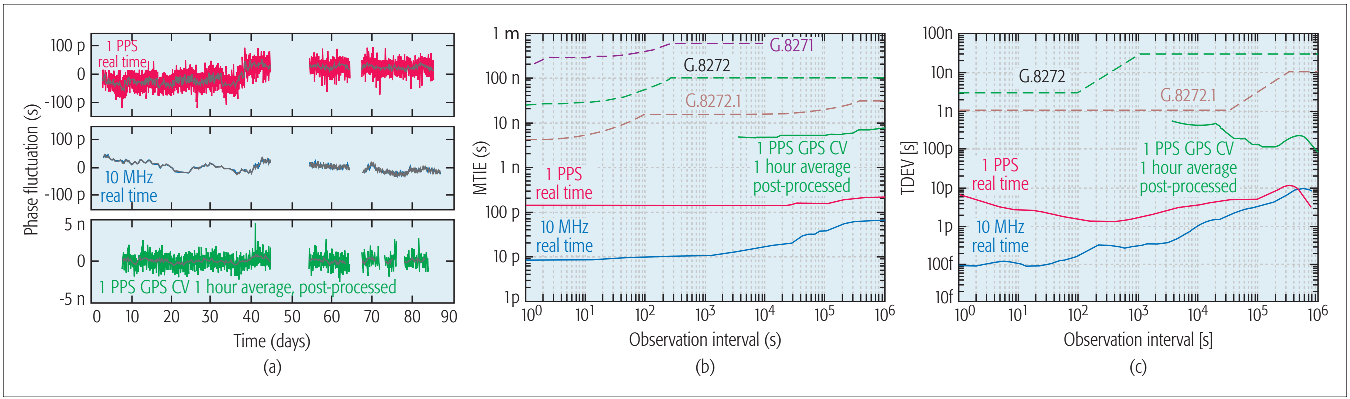


FIGURE 6. a) Plots of raw data collected over almost three months (started at 16.12.2015) of the operation of the PoC link; a moving average is shown with the blue line and an arbitrary constant is subtracted; b) MTIE curves; c) TDEV curves. ITU-T G.827x masks are shown with dashed lines.

concerning quality of delivered signals, long-term reliability, scalability, and operation on typical single-mode fibers. Currently, the ITU-T Study Group 15 Question 13 is investigating inclusion of OTT in future ITU-T standards as a means of having the time error under control in a live network.

The operation of the OTT link between PTB and DTAG continues, and the future plans are to change its status from experimental to operational. It is also under consideration to use the same technology to link PTB with the other DTAG timing centers in Germany, in particular with the facility in Frankfurt/Main, where the company's main timing center is located and UTC(DTAG) is realized today.

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BIOGRAPHIES

ŁUKASZ ŚLIWCZYŃSKI [M] (sliwczyn@agh.edu.pl) received M.Sc. and Ph.D. degrees from AGH University of Science and Technology, Kraków, Poland, in 1993 and 2001, respectively. He worked on various high-speed transmitters and receivers for digital fiber optic transmission systems. For about 10 years he has been working on precise time and frequency transfer systems exploiting optical fibers. He has authored and co-authored more than 60 papers in journals and conference proceedings.

PRZEMYSŁAW KREHLIK (krehlik@agh.edu.pl) received his M.Sc. and Ph.D. degrees in electronics from AGH University of Science and Technology in 1988 and 1998, respectively. Since 1988 he has worked in the Fiber Optic Transmission Group of the Department of Electronics, AGH. His R&D activities include electronic circuits, direct modulation of semiconductor lasers, and application-specific fiber optic systems. He has authored and co-authored more than 60 papers in journals and conference proceedings.

JACEK KOŁODZIEJ [M] (jacek.kolodziej@agh.edu.pl) received his M.Sc. and Ph.D. degrees in electronics in 1999 and 2007, respectively, both from AGH University of Science and Technology. His scientific interests include advanced electronic circuits for telecommunication, wireless sensor networks, analog-digital converters, sigma-delta modulators, adaptive non-uniform sampling delta modulators, software engineering, testing, and reliability.

HELMUT IMLAU (helmut.imlau@telekom.de) is with Deutsche Telekom Technik GmbH, and since 2002 he has been responsible for synchronization systems. His current focus is on synchronization strategy including phase synchronization for mobile base stations. He has worked in ITU-T Study Group 15 Question 13 on synchronization since 2005. His involvement is focused on Ethernet physical layer synchronization, phase synchronization, and primary reference time clocks. He is a member of the ITSF Steering Group.

HORST ENDER (horst.ender@telekom.de) joined Deutsche Telekom Technik GmbH in 1980. He studied computer science between 1991 and 1996 at Fernuniversität Hagen and after that worked as a software developer until 2010. Currently he is working at Deutsche Telekom in the time and synchronization group.

HARALD SCHNATZ (harald.schnatz@ptb.de) joined PTB at the end of 1989 and succeeded in the first phase-coherent frequency measurement of visible radiation using a conventional frequency chain in 1996. His current work includes stabilization of lasers, nonlinear optics, wavelength standards and optical frequency measurements, and frequency dissemination. Since 2011 he is head of PTB's Quantum Optics and Unit of Length Department He is a member of the Deutsche Physikalische Gesellschaft.

DIRK PIESTER (dirk.piester@ptb.de) received his diploma degree in physics and Dr.-Ing. degree from the Technical University of Braunschweig. Since 2002, he has been with the Time Dissemination Group of PTB, where he is in charge of PTB's time services, among them the low-frequency transmitter DCF77. His research activities are focused on improvements of time and frequency transfer technologies and calibration techniques via telecommunication and navigation satellites as well as via optical fibers.

ANDREAS BAUCH (andreas.bauch@ptb.de) joined PTB in 1983 and has been involved in time and frequency metrology since then. Today he is head of PTB's Time Dissemination Working Group. He has served as delegate to the Comité Consultatif du Temps et Fréquences and to Study Group 7 of ITU. Between 2009 and 2013 he chaired the EURAMET Technical Committee for Time and Frequency. Since 2009 he has been a member of ESA's GNSS Science Advisory Committee.

The experiment's results clearly show that the OTT technology fulfills the needs of the telecom operator concerning quality of delivered signals, long-term reliability, scalability and operation on typical single-mode fibers. Currently the ITU-T Study Group 15 Question 13 is investigating inclusion of OTT in future ITU-T standards as a means of having the time error under control in a live network.