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Ultrastable Frequency Transfer in L-Band

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Abstract

Frequency dissemination in phase-stabilised optical fibre networks for metrological frequency comparisons and precision measurements are promising candidates to overcome the limitations imposed by satellite techniques. However, in an architecture shared with telecommunication data traffic, network constraints may restrict the availability of dedicated channels in the commonly used C-band. Here, SWITCH and its partners demonstrate the dissemination of an SI-traceable ultrastable optical frequency in the L-band over a 456 km fibre network with ring topology, in which data traffic occupies the full C-band.

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Executive Summary

Many scientific applications (for instance precision spectroscopy, remote clock comparisons in fundamental metrology, and relativistic geodesy or synchronisation in large-scale facilities) require dissemination of ultrastable frequency signals (10^{-18} relative frequency uncertainty). The two-way time and frequency transfer (TWTFT) or global navigation satellite systems (GNSS) achieve fractional frequency stabilities at the 10^{-16} level with measurement times of a few days.

To overcome this limitation, several optical fibre networks for the dissemination of ultrastable and accurate optical frequencies have been implemented, spanning thousands of kilometres and providing transfer stabilities of few 10^{-15} at 1s with ultimate accuracies beyond 10^{-19}. The majority of optical frequency dissemination networks [6] implemented their time and frequency services around International Telecommunication Union (ITU) channel 44 in the C-band (1530 nm to 1565 nm), where the optical loss is minimal and off-the-shelf telecommunication components are available. A spectrum-sharing solution as is implemented in France [2] is much more cost effective than using dark fibre. However, the network operators may have concerns placing such a fixed alien channel inside the C-band.

To solve these concerns, SWITCH - in collaboration with the National Metrology Institute (NMI) METAS, INRIM and CESNET - has designed a spectrum-sharing solution between the frequency signal and traditional data network by exploiting dense wavelength division multiplexing (DWDM). A stabilised frequency-metrology network in Switzerland, spanning over 456 km of optical fibres and operating in the L-band (1565nm to 1625nm) in ITU-T CH07 (λ=1572.06nm, f=190.7THz) was deployed between the METAS and two dedicated research institutes at the University of Basel and ETH Zurich.

This work demonstrated that a metrological signal can be implemented on L-band, sharing the same fibre with the data traffic in the C-band (SWITCH NREN users), without any measurable disturbance on the data transmission. The metrological signal reached the same performance as systems operating in the C-band. This however comes with the drawback of limited availability of L-band components, introducing longer lead times and higher manufacturing costs for early implementers.

This white paper summarises the work initially reported in the publication 'SI-traceable frequency dissemination at 1572.06 nm in a stabilized fibre network with ring topology' [1], which presents the scientific validation of this type of technology that the NRENs need to use to distribute ultrastable frequency signals to many scientific applications. This document focuses on the NREN perspective and is published as a part of the work of the Optical Time and Frequency Networks (OTFN) subtask of the GN4-3 Network Technologies and Services Development Work Package (WP6).

1 Introduction

Precise dissemination of accurate frequency signals traceable [2] to the International System of Units (SI) second definition is essential in many scientific fields, such as precision spectroscopy [7][8][9][10], remote clock comparisons [11][12][13] in fundamental metrology, relativistic geodesy [14][15][16], or synchronisation in large-scale facilities. In particular, a redefinition of the SI second, as is currently under evaluation, necessitates the comparison of state-of-the-art optical clocks with 10^{-18} relative frequency uncertainty. Most of these applications require a higher resolution than allowed by established satellite techniques based on two-way time and frequency transfer (TWTFT) or global navigation satellite systems (GNSS), which achieve fractional frequency stabilities at the 10^{-16} level with measurement times of a few days.

To overcome the limitations of satellite-based frequency comparison techniques, several phase-stabilised optical fibre networks for the dissemination of ultrastable and accurate optical frequencies have been implemented, spanning thousands of kilometres and providing transfer stabilities of few 10^{-15} at 1s with ultimate accuracies beyond 10^{-19}. The majority of these networks operate in dedicated fibres (dark fibres) and are spectrally situated in or around ITU channel 44 (λ=1542.14nm, f=194.4THz) in the C-band (1530 nm to 1565 nm), where the optical loss is minimal and off-the-shelf telecommunication components are available. However, the high recurring costs for dark fibre lease have hindered a wider development of such networks. Sharing the available spectrum of the fibre with other network users by exploiting the dense wavelength division multiplexing (DWDM) architecture can significantly reduce costs. A fixed 100 GHz dark channel in the C-band has been implemented in France [3] to integrate the bi-directional ultrastable frequency signal on one fibre of a unidirectional pair within the telecommunications data network. However, network operators may have concerns placing such a fixed alien channel inside the C-band. To alleviate many of these concerns, the same phase-stabilised frequency dissemination can be implemented with other wavelengths, within or even outside the C-band.

The example [1] presented in this white paper implements a stabilised frequency-metrology network in Switzerland, spanning over 456 km of optical fibres, and operating in the L-band (1565nm to 1625nm), in ITU-T CH07 (λ=1572.06nm, f=190.7THz). The metrological frequency channel allows the dissemination of an ultrastable SI-traceable frequency between the National Metrology Institute (NMI) METAS and two dedicated research institutes at the University of Basel and ETH Zurich. The metrological signal is hosted in the same fibre as the data traffic of the Swiss NREN, SWITCH, in the C-band, it must not have any measurable impact on data transmission and the metrological signal must have the same performance as systems operating in the C-band.

This white paper summarises the work initially reported in the publication 'SI-traceable frequency dissemination at 1572.06 nm in a stabilised fibre network with ring topology' [1][1], which presents the scientific validation of this type of technology that the NRENs need to use to distribute ultrastable frequency signals to many scientific applications. This document focuses on the NREN perspective and is published as a part of the work of the *Optical Time and Frequency Networks* (OTFN) subtask of the GN4-3 *Network Technologies and Services Development* Work Package (WP6).

[1] The original work presented in [1] was funded by: European Research Council (743121); National Center of Competence in Research Quantum Science and Technology; Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung (CRSII5_183579).

2 Frequency Dissemination

To disseminate a reference frequency in the optical domain, the wavelength of the laser itself is used as the disseminated variable, referenced to a primary frequency standard. However, since the fibres are subject to temperature changes, mechanical stress and vibrations, a transmission error is introduced leading to a phase error. Thus, Phase Noise Compensation (PNC) is required to maintain a proper frequency reference at the receiving station.

2.1 Master and Regeneration Lasers

The main components of the stabilised laser, the PNC systems, and the regeneration stations at the three laboratories are depicted in Figure 2.1. The regeneration stations and PNC systems presented here were designed and built by Istituto Nazionale di Ricerca Metrologica (INRIM). The stable frequency at METAS is generated by locking a laser (RIO Planex) to an ultra-low expansion (ULE) external cavity. This laser acts as the master and its frequency is continuously measured against an SI-referenced frequency comb (FC1500-250-ULN, Menlo Systems). Slow drifts in the laser frequency due to residual thermal relaxation of the cavity are compensated using a digital feedback loop acting on an acousto-optic modulator (AOM). The optical frequency comb is referenced by an active hydrogen maser [4], which contributes to the realisation of the Swiss timescale UTC(CH) and provides a short-term instability of $1.7\times10{-}13$ at 1 s. The phase of the maser is regularly compared to the International Atomic Time (TAI) via UTC(CH). This comparison makes it possible to determine the drift of the maser and thus to estimate its absolute frequency traceable to the SI definition of the second at all times. The stable and accurate optical frequency is then fed into a phase-stabilised link to the next terminal in Basel. The offset-locked regeneration lasers at the University of Basel and ETH Zurich are identical: a local external cavity laser (RIO Planex) with a free-running linewidth of around 2 kHz is phase locked to the incoming optical signal. A small part of the regeneration laser output is split out for local use (e.g. locking an optical frequency comb), while the bulk of the signal is injected into the subsequent PNC system and sent to the following section. In both regeneration stations, a Global Positioning System Disciplined (GPSD) Rb clock (SRS FS725 Rb standard) is used as a local oscillator.

In this setup, a third link was added to send the stabilised frequency from Zurich back to its origin in Bern. While not technically required for the labs in Basel and Zurich, this setup makes it possible to evaluate the overall system quality by comparing the full round trip signal back to the original reference.

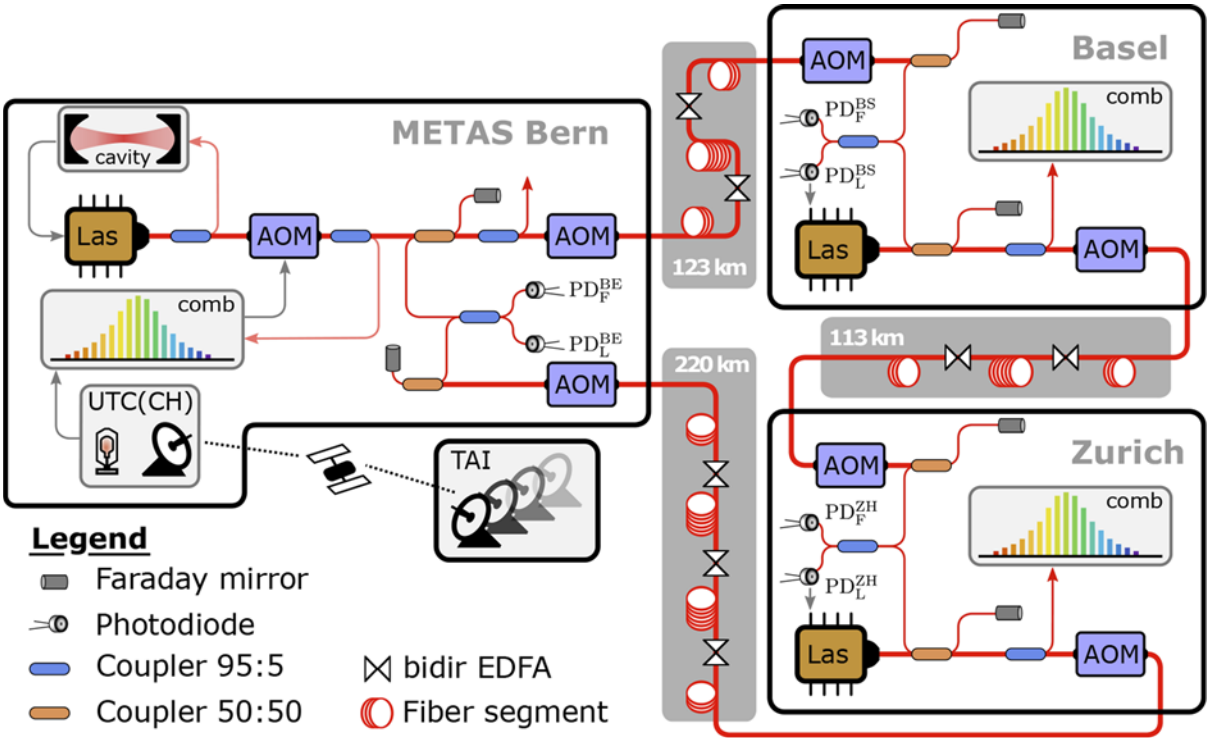

Figure 2.1: Detailed schematic of the optical layout [1]

2.2 Phase-Noise Compensation

Each of the three stations have a PNC system that stabilises the subsequent fibre link between the local and a remote station. The PNC system consists of a first AOM (35 MHz) at the local end that applies a frequency correction to the outgoing signal. At the remote end, a second AOM shifts the incoming signal by a fixed frequency of 45 MHz. A coupler with a Faraday mirror reflects part of the signal back to the local end. The second AOM makes it possible to distinguish the full two-way round-trip signal from detrimental reflections. The AOM frequencies are chosen to be incommensurate with the PNC full round-trip beat note to prevent amplitude modulation from spurious reflections in the fibre link.

The round-trip signal of each of the PNC arms is overlapped with a local copy of the original signal in an all-fibre Michelson-type interferometer, and the beat signal is detected with the photodiodes PDBEF, PDBSF and PDZHF, with typical Signal-to-Noise Ratio (SNR) of the beat note of 35 dB at a resolution bandwidth of 100 kHz. Two tracking voltage-controlled oscillators (VCO) at each station are locked to this beat signal by phase-locked loops (PLL), allowing noise rejection outside the locking bandwidth, and, thus, cleaning of the signal. A proportional-integral (PI) feedback circuit applies a proper frequency correction to the optical signal via the local AOM that stabilises its frequency against the detected perturbations. The PI parameters are matched to the fibre length. The second auxiliary VCO is used as a redundant counter that makes it possible to spot cycle slips (CS) in the PNC.

2.3 Application by End Users

The majority of experiments that require a precise frequency reference operate at a radio or optical frequency that is very specific to the experiment itself, and is typically a different frequency to the reference itself. Therefore, the reference frequency must be translated to the frequency required for the experiment.

For example, the frequency dissemination described here was used to reference a near-infrared spectroscopy laser at a wavelength of 729 nm. As there is no frequency reference available at that wavelength, a frequency comb is used to reference the 729 nm laser to a stable source. Using the optical reference disseminated over the fibre, the spectroscopy measurements were improved by at least two orders of magnitude in accuracy compared to the GPSD Rb standard reference used before.

Another advantage of the disseminated frequency is its direct reference to a primary frequency standard. All its calibration and comparison to the international SI definition of the second is maintained by the NMI. The end user is given the final exact frequency of the signal they received at each point in time.

3 Spectrum Sharing

The leasing cost of long distance fibres can be very expensive, depending on geographic location and availability. For the project described here, it would have been prohibitive. However, considering that the frequency dissemination signal is essentially an unmodulated carrier occupying very little spectrum, sharing a fibre with other users is desirable.

The predominant application on these types of fibres are telecom data transmissions. They often already use wavelength multiplexing (e.g. DWDM in the C-band) to combine a high number of data channels on (typically) a pair of fibres and using EDFAs and possibly RAMAN amplification to cover longer distances. The frequency signal in contrast uses only a single fibre, but it requires bidirectional amplification for the PNC system. This can be realised using special bidirectional EDFAs as well as RAMAN or a Semiconductor Optical Amplifier (SOA) if necessary.

The network described here combines the frequency signal on the long distance fibre (105km and 97km) between Bern, Basel and Zurich, with the existing DWDM system, while using dedicated fibres in the local loop where the existing data network does not include a fibre link. The DWDM system uses a traditional two-fibre setup with EDFAs (but no RAMAN amplifiers), while the reference frequency signal is transmitted in both directions on a single fibre of the pair. As described earlier, the second fibre is used to transmit the frequency back to its origin for quality assurance. In the local loop fibres, the same spectrum sharing scheme is employed to also extend the management network towards the laboratories for remote management of the regeneration stations.

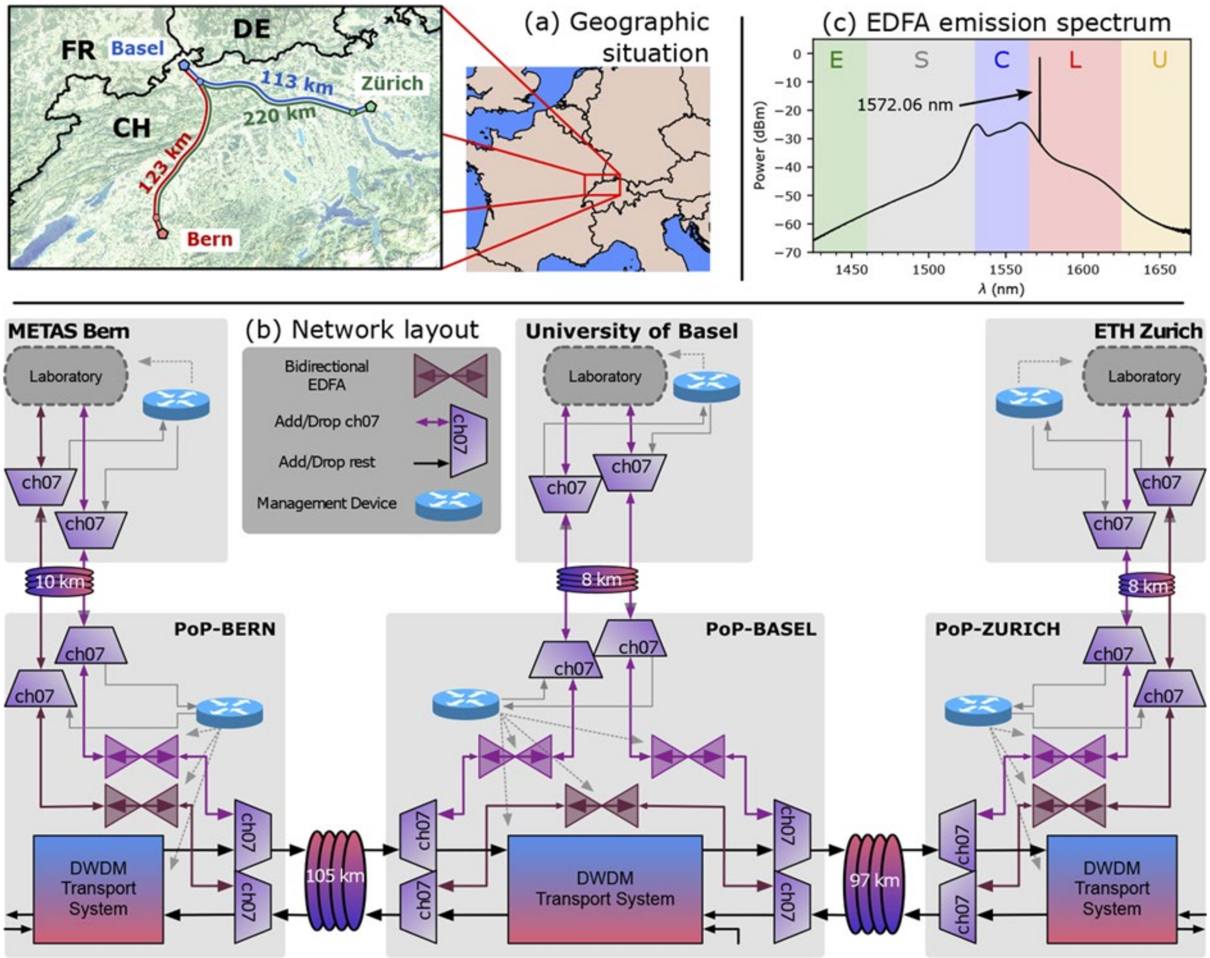

Figure 3.1: Geographical situation and network layout [1]

3.1 Wavelength/Frequency Selection

Combining a frequency signal with a DWDM system requires careful selection of the wavelength. The phase noise cancellation system uses relatively few components that are specific to the selected wavelength, i.e. the lasers themselves, a bidirectional EDFA that can work in the required range, and wavelength filters (typically 100GHz wide add/drop multiplexers) that block unwanted Amplified Spontaneous Emissions (ASEs) and prevent self-lasing. The latter also double as multiplexers to combine the frequency- and DWDM-signals in this case. Once implemented, however, the chosen wavelength is extremely hard to change since it has to be consistent across the network, and replacing all the components can be expensive. Therefore, the frequency signal is considered fixed.

From a technical standpoint, any wavelength for which the optical fibres are permeable and for which the optical amplification technology is available could be used. Limits are mainly set by the availability of the parts. Most vendors claim normal availability for any parts in the C-band, whereas parts in (or optimised for) the L-band, despite working with the same principles, are much less common and, therefore, often require long delivery lead times and sometimes up-front manufacturing costs.

The other limiting factor is which wavelength a network operator is willing to accept under those circumstances. A classical DWDM system using static add/drop multiplexers is quite easy to integrate. More advanced systems that use a colourless architecture [5], where the wavelength of each channel can be changed through software configuration and the spectrum management is handled by the network management application, can pose an issue. With upcoming modulation techniques where not only the wavelength itself but also the baud rate (and thus the spectral width) can change dynamically, even more so. Some DWDM system vendors are already exploring the use of super-channels [17] that might require hundreds of GHz of continuous spectrum. With these developments, a fixed channel in the middle of the C-band might increasingly become an issue. In the example presented here, the ITU-T CH07 (λ=1572.06nm, f=190.7THz) was chosen to remain outside the C-band and avoid future conflicts with flexible spectrum allocations. Even in case of future C+L systems, this bandwidth gap between C and L-band is typically unused by data traffic, because of EDFA amplifiers implementation.

Further limiting factors (which were not relevant in this case) could be encountered with very long fibre spans where the operator may not accept additional attenuation by add/drop multiplexers. In such cases, there might still be options to operate such a link without adding attenuation if using RAMAN amplifiers that are fully modular (where multiplexers can be added between the RAMAN preamp and the successive EDFA booster amplifier) or provide an L-band extension port (sometimes also used for OTDR applications).

3.2 Selection of Components

As previously stated, the main challenge when choosing a wavelength outside the C-band is the availability of parts. A prominent product used in optical frequency dissemination is RIO's PLANEX lasers, which they were able to supply in the L-band. The specific wavelength chosen was one where RIO was most confident of achieving the required quality. However, this required quite a long lead time of over 6 months and a considerable up-front payment to start production. This should not be the case in the future if L-band use becomes more popular.

The bidirectional amplifiers by Czechlight could be tailored to get optimal performance at the required wavelength. Also, the single-channel add/drop multiplexers at ITU-T CH7 could be sourced by local supplier Deltanet with whom SWITCH has a long-standing relationship, but which were also offered by multiple other suppliers claiming availability of any wavelength in C- and L-band.

3.3 Performance

Thanks to the full-loop setup, the performance could be evaluated versus the original source frequency. The results show a link instability of 4.7×10^{-16} at 1 s measurement time. The overlapping Allan deviation (ADEV) of the stabilised link shows a $1/\tau$ dependence, which is a typical behaviour for fibre links affected by phase noise in the acoustic range, and reaches a noise floor of $3.8\times10{-}19$ at 2000 s. Further a decrease of the ADEV below $1\times10{-}19$ is observed for integration times of around 1 day, indicating averaging out of diurnal fluctuations. These results show comparable performance to similar setups operating in the C-band, with the link stability exceeding the stability of Cs primary frequency standards by at least two orders of magnitude.

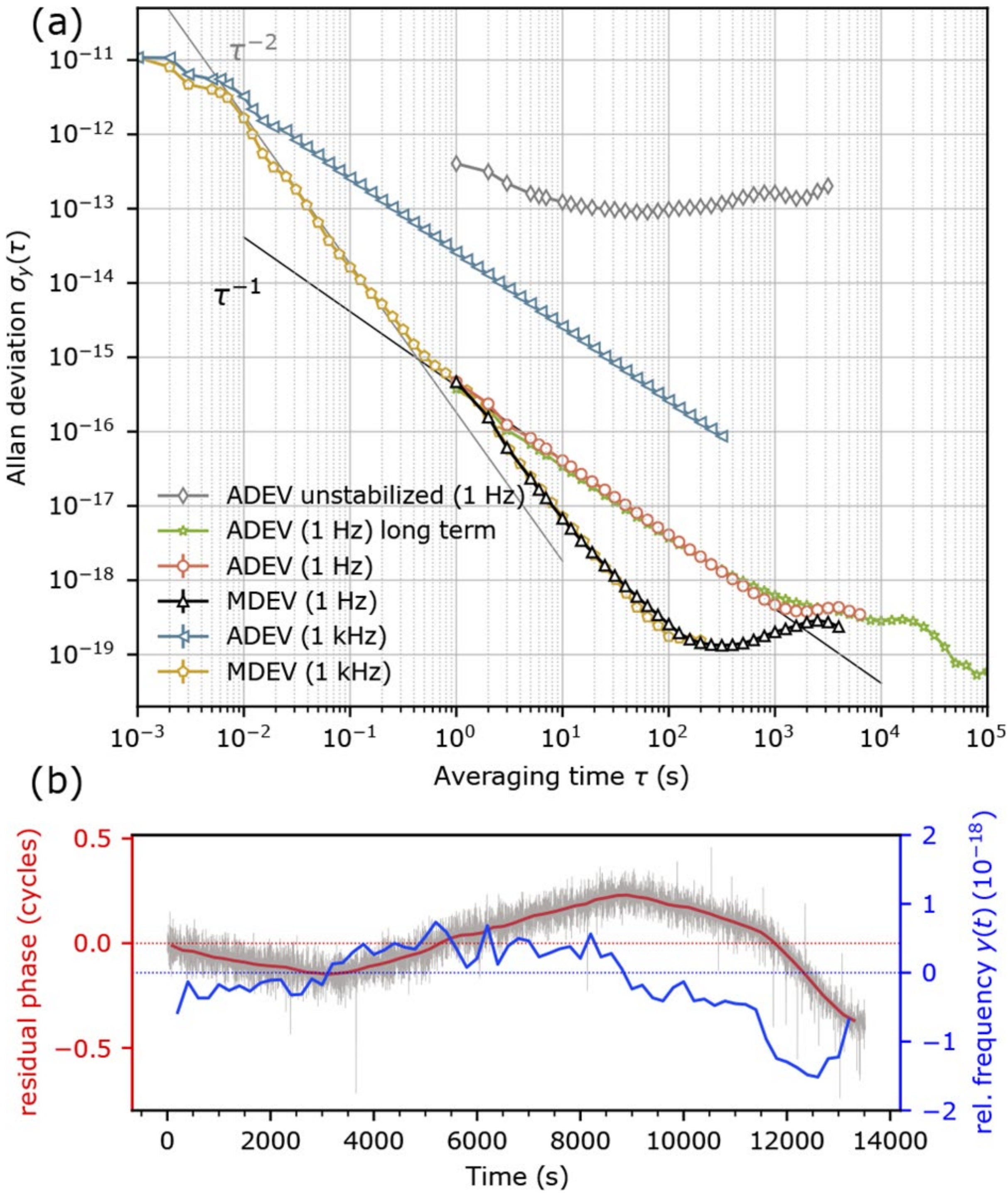

Figure 3.2: Noise cancellation performance [1]

In terms of the optical signal, the fibre attenuation at the chosen wavelength of 1572.06nm is virtually identical to the C-band. Also, the amplifiers show comparable performance in terms of achievable signal gain and ASE emissions, provided they are placed between narrow single-channel filters.

To measure the performance of the data channels, mainly in terms of introduced bit errors (or lack thereof), the internal forward error correction (FEC) data from the transponders can be used. At speeds of 100G and beyond there are always some bit errors to be corrected by FEC. Based on FEC counters, it is possible to compare the rate of corrected errors per second (measured over 2-3 days) in the presence and absence (link on/ link off) of the metrological signal. This comparison will provide a good indication of any influence. While there are clear day-to-day fluctuations, the data show no significant impact of the 1572 nm signal on the number of corrected errors in the measured data channels. Figure 3.3 shows some exemplary data of 10Gbit/s (CH50.5), 100Gbit/s (CH27.5) and 200 Gbit/s (CH17) links.

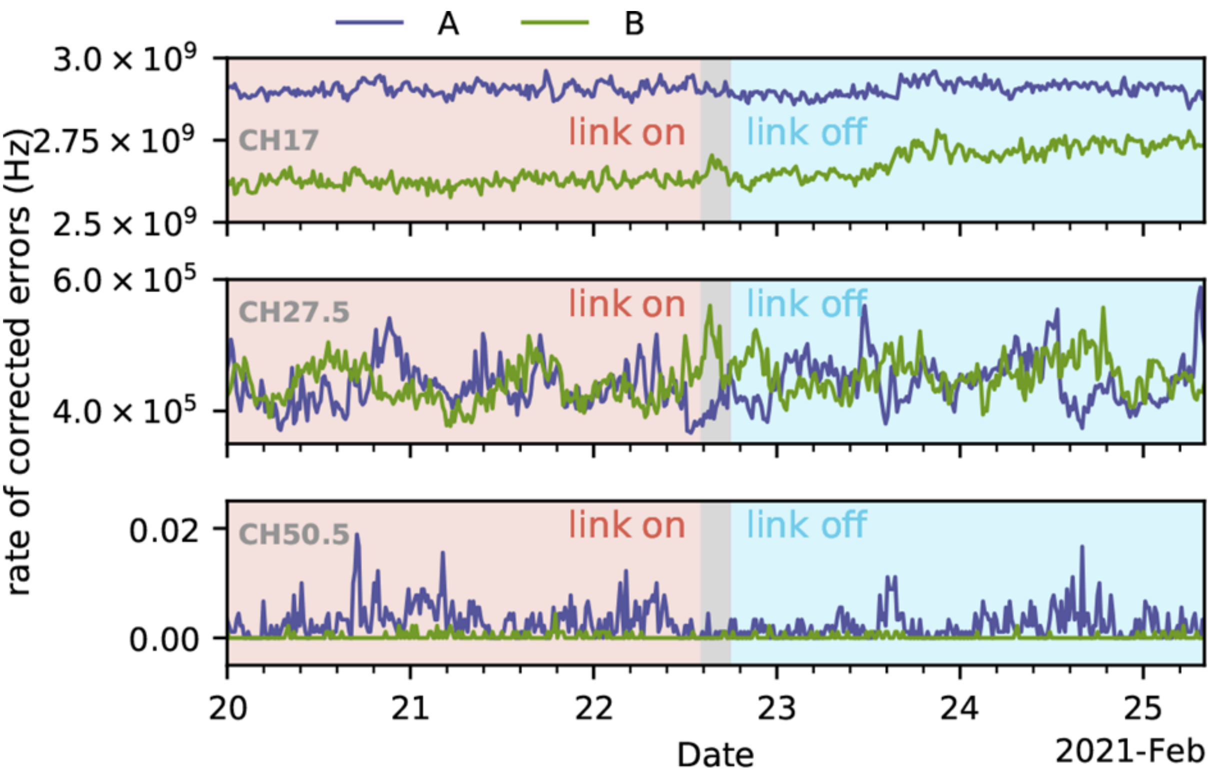

Figure 3.3: BER measurement [1]

4 Combined Operations

Sharing a common infrastructure often also mandates a shared approach to management and operations. While network operators are versed in remote operations of optical and other networking devices and have the required systems already in place, they tend to lack the specific knowledge to operate and fine-tune specialised systems such as this frequency transfer, especially while it is at an early, rather experimental, stage. The researchers of NMIs or other similar institutions can provide this very detailed knowledge and experience, but they themselves lack the required infrastructure.

4.1 Remote Management

The frequency dissemination technology represents a distributed solution, consisting of different components such as amplifiers and specialised electronics that need to be configured and monitored. Part of the locations where these components are deployed belong to the network operator and are already equipped with a management network. The end stations, in contrast, are the laboratories belonging to the respective universities. While the laboratories have internet access provided by the universities, setting up remote access can be quite complex due to the different policies employed by these organisations. However, since the frequency dissemination already requires optical fibres between the network operator's location and the laboratories, these can also be used to extend the operator's management network to the labs, using the same multiplexing techniques as on the long-distance links. Still, such a setup must be coordinated with the local university to ensure their local network remains separated, and avoid the creation of back doors.

Connecting the devices to the network operator's management network is easily done, with the disadvantage that they are not separated from the other devices belonging to the network operator. This approach to remote access is a bit more elaborate, because the systems typically used would provide access to all the devices in the management network. To that end, an ssh 'jump' or 'bastion' host is used to grant selective access for remote users outside the network operator's realm. User accounts on that jump host are restricted to ssh-key only authentication, and deny shell login (using the `nologin` shell). To restrict access to the managed devices with fine granularity, local outbound firewall rules are used on the jump host which identify the user-id as part of the matching rule. The listing below shows a simplified example using nftables.

```
#!/usr/sbin/nft -f

table inet filter {
  chain output {
    type filter hook output priority 0;
    ct state new log group 4 prefix "bastion new:" continue
    ip addr <device-address> skuid <userid> accept
    ...
    log log group 4 prefix "bastion denied:" reject with icmpx
type admin-prohibited
  }
}
```

In addition to granting access to specific devices, all connection attempts are logged to detect malicious use.

For the end users, ssh access to the devices can then either be done using ssh jump (`ssh -J`) or by using the jump host as a SOCKS5 proxy for all other protocols (`ssh -ND`).

4.2 Operations

The day-to-day operations are mostly done by the NMI researchers. The end stations currently use lab equipment, controlled by a local computer running MATLAB. The amplifiers, on the other hand, are mostly in line with other service provider equipment. Besides direct access to those devices, the monitoring, alarming, and statistics infrastructure of the network operator can be used. In this case, these utilities were already set up to allow access for third parties.

To remain on the cautious side, from the beginning of the design and during operations, optical power limits for the frequency signal were agreed on an absolute limit of +10dBm and a soft limit of +5dBm that should be targeted in order to avoid issues with Brillouin scattering, etc. Within these limits the researchers are allowed to fine-tune the amplifiers themselves. However, the network operator is always able to take control and shut down the amplifiers if any issues should arise, or if required for fibre maintenance. Operating on a network using RAMAN amplifiers would require close coordination as the RAMAN amplification will also affect the frequency signal, and possibly vice-versa, which was not the case in this example.

Finally, the frequency signal should be integrated as a spectrum service to the usual service management to provide advanced maintenance notice and incident handling.

5 Conclusions

SWITCH in collaboration with the National Metrology Institute (NMI), METAS, INRIM, and CESNET have designed a spectrum sharing solution with other network users by exploiting the properties of dense wavelength division multiplexing (DWDM) to facilitate the spectrum sharing of frequency and data services.

A stabilised frequency-metrology network in Switzerland, spanning over 456 km of optical fibres, and operating in the L-band (1565nm to 1625nm), in ITU-T CH07 (λ=1572.06nm, f=190.7THz) was deployed between the METAS and two dedicated research institutes at University of Basel and ETH Zurich. Avoiding the use of dedicated dark fibre allows significant cost savings.

This work demonstrated that a metrological signal can be implemented on L-band (1572.06 nm) sharing the same fibre with the data traffic in the C-band (SWITCH NREN users), without any measurable impact on the data transmission. The metrological signal reached the same performance as systems operating in the C-band in this condition. This comes with the drawback of limited availability of L-band components, introducing longer lead-times and higher manufacturing costs for early implementers.

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Glossary

ADEV	Allan deviation
AOM	Acousto-Optic Modulator
ASE	Amplified Spontaneous Emissions
CS	Cycle Slips
dB	Decibel
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fibre Amplifier
FEC	Forward Error Correction
GHz	Gigahertz
GNSS	Global Navigation Satellite Systems
GPSD	Global Positioning System Disciplined
INRIM	Istituto Nazionale di Ricerca Metrologica
ITU	International Telecommunication Union
kHz	Kilohertz
MHz	Megahertz
nm	Nanometre
NMI	National Metrology Institute
OTFN	Optical Time and Frequency Networks
PI	Proportional-Integral
PLL	Phase-Locked Loops
PNC	Phase Noise Compensation
Rb	Rubidium atomic clock
SI	Système International - International System of Units
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SSH	Secure Shell
TAI	International Atomic Time
TWTFT	Two-Way Time and Frequency Transfer
ULE	Ultra-Low Expansion
UTC(CH)	Universal Time (Switzerland)
VCO	Voltage-Controlled Oscillators