Challenges to Realizing Next-Generation Synchronization Networks by Optical Clocks

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   - ✓ IOWN
2. Concept of All-Optical Synchronization Network
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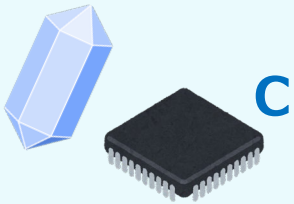
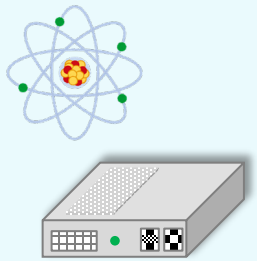
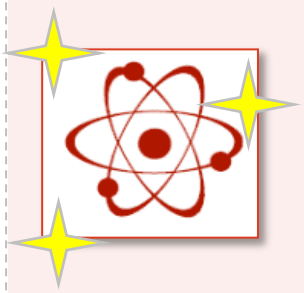
   - ✓ Fiber noise compensation
   - ✓ Frequency Conversion
4. Summary: Future Key Technologies

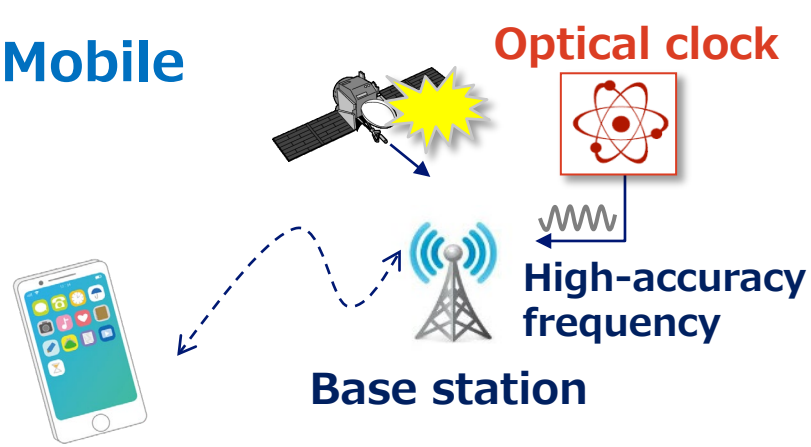
Background 1
Development of Optical Clocks

- We focus on optical clocks as a next-generation frequency source.
- Optical clocks have potential as a future frequency standard.

Frequency source	Accuracy	Domain	Deployment scene
 Crystal oscillator	10^{-6}	Microwave (e.g. 10MHz)	 Electric devices
 Atomic clock (Cesium, Rubidium)	10^{-11}–10^{-13}		 GNSS  Telecom networks
 Next-gen atomic clock (Optical clock)	10^{-15}–10^{-18}	Optical (e.g. 200THz)	Create new market

Use Cases of High-Accuracy Frequency

Mobile



Stable mobile communication due to long-term time holdover

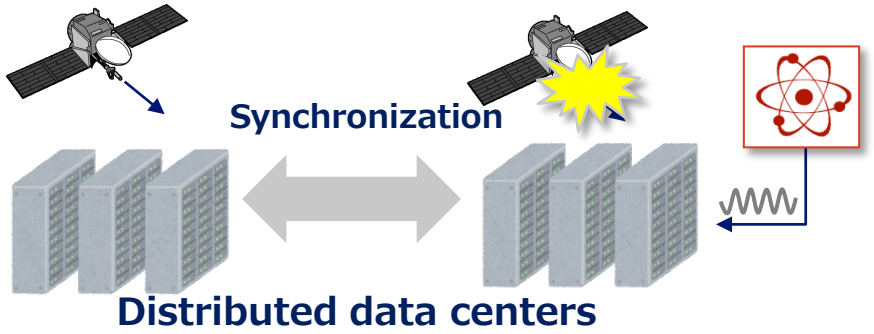
Frequency accuracy

10^{-14}

10^{-16}

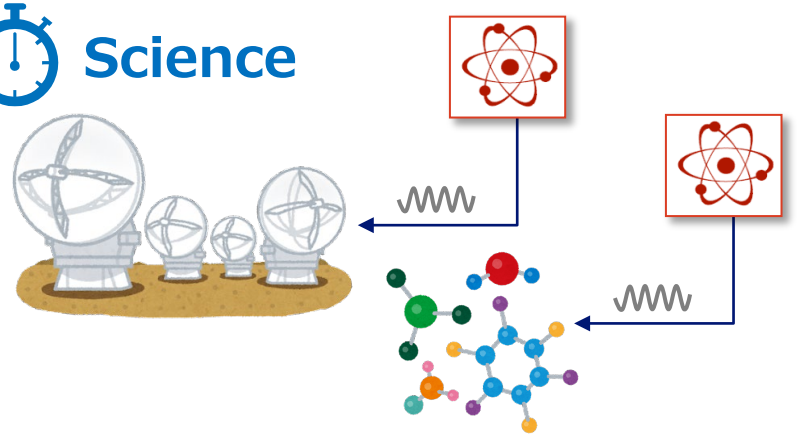
10^{-18}

Data Center



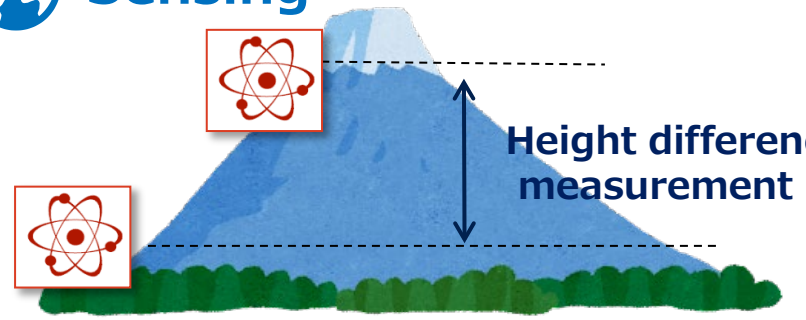
Stable calculation processing due to long-term time holdover

Science



Synchronization for measurement
(e.g. VLBI, Particle accelerator)

Sensing



Monitoring for disaster
(e.g. Earthquake, Volcanic eruption)

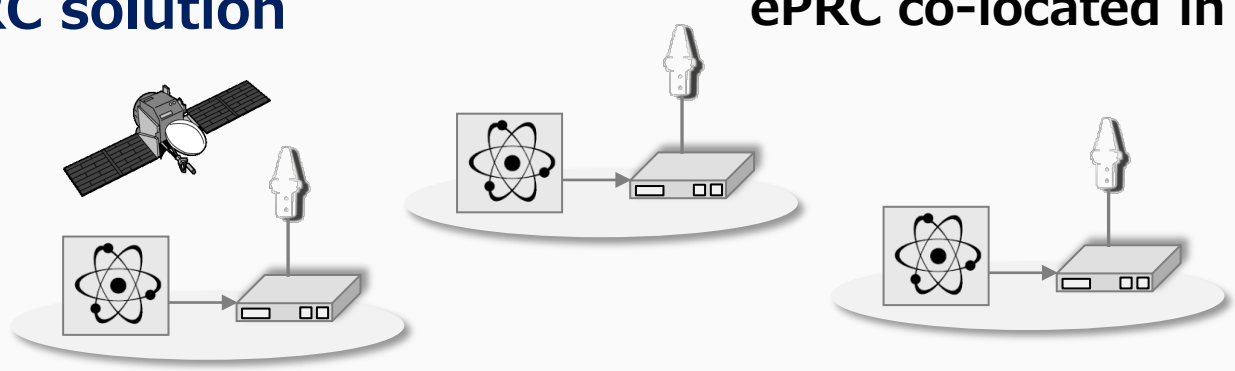
*Takano et al., "Geopotential measurements with synchronously linked optical lattice clocks", Nature Photon. 2016

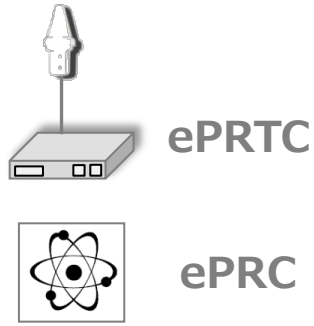
Use Case for Mobile: Backup of enhanced PRTC

- We propose a remote PRC solution.
- The configuration was agreed in ITU-T SG15 and G.8272.1 will be revised.

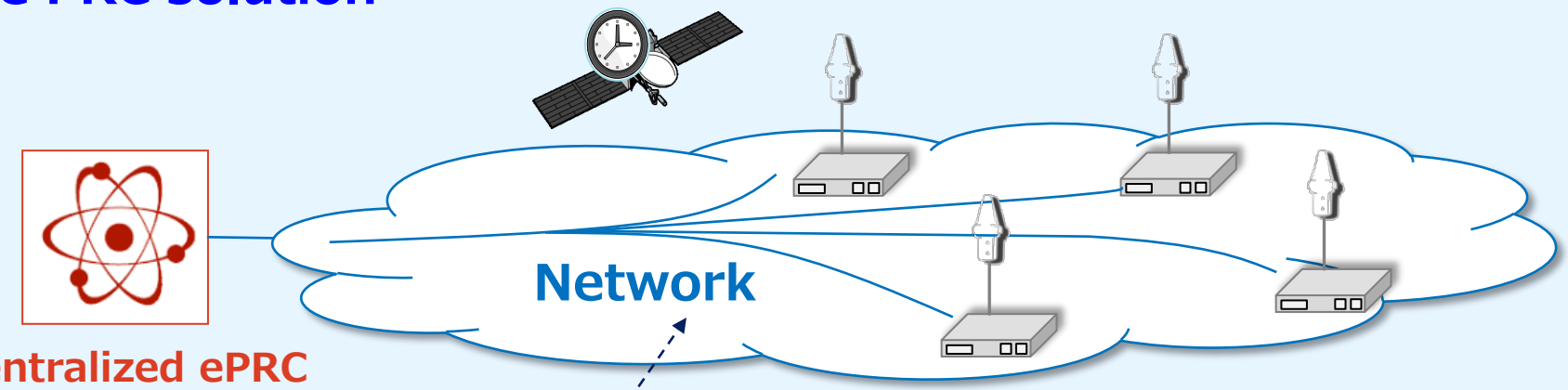
Local PRC solution

ePRC co-located in each ePRTC site





Remote PRC solution

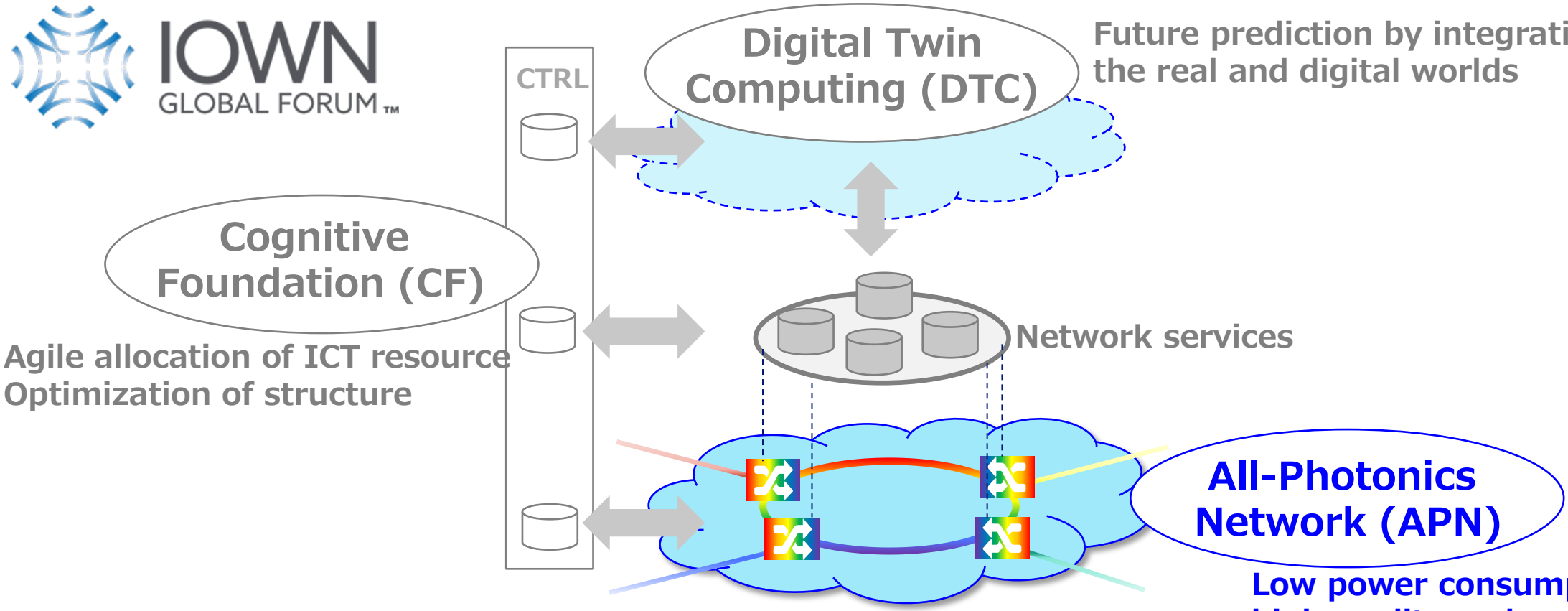


Centralized ePRC
(e.g. Optical clock)

Distribute the frequency for time holdover

Background 2
What is IOWN?

- NTT announced the IOWN (Innovative Optical and Wireless Network) concept.
- APN is a fully meshed-optical network to reach high performance.



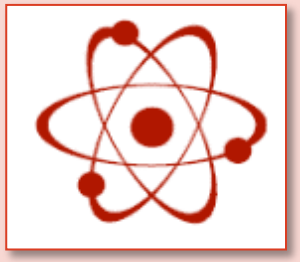
https://www.rd.ntt/e/iown/

Optical Clock x IOWN

- **Optical clocks and IOWN APN have high affinity.**
- **We consider an all-optical synchronization network based on two technologies.**

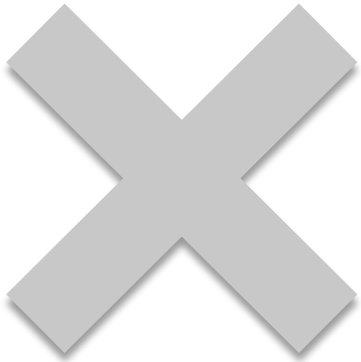
Frequency source

Optical Clock



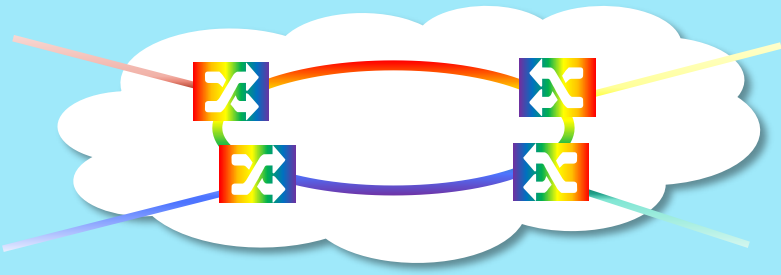
High-Accuracy Frequency in Optical Region

High affinity



Network

IOWN



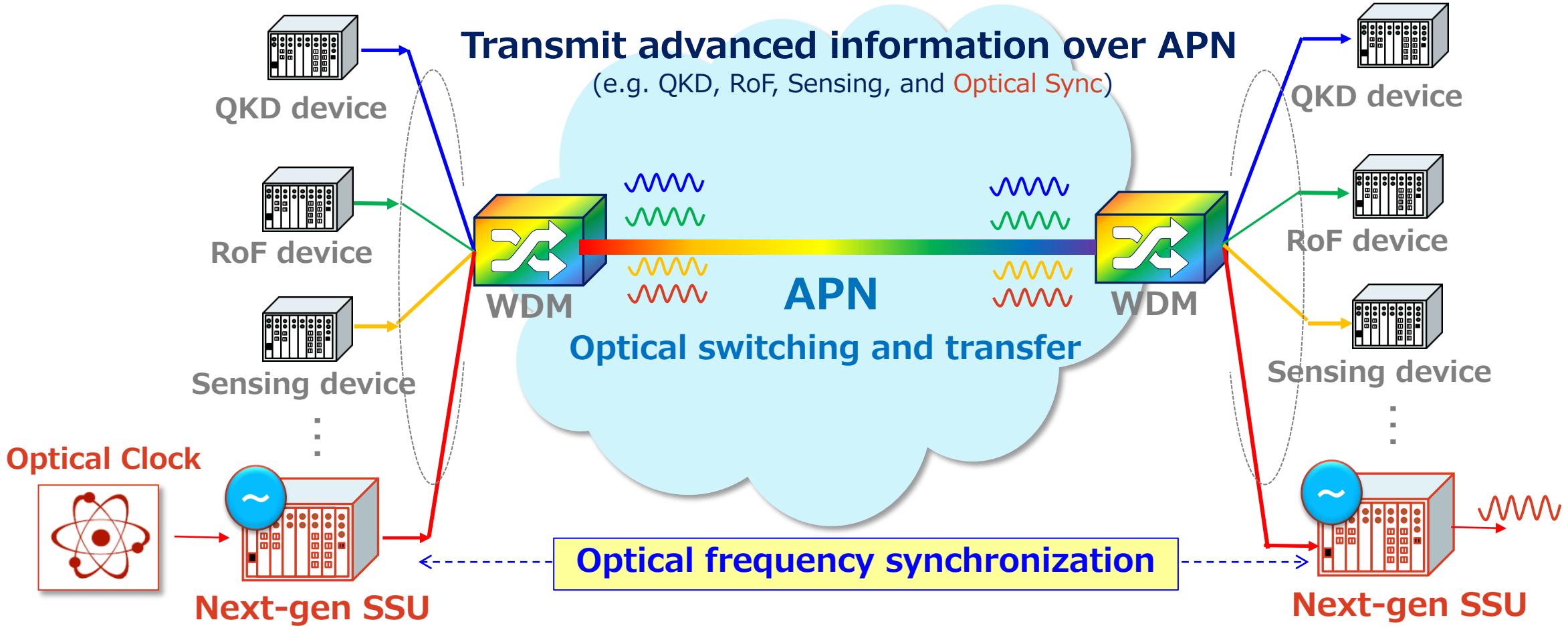
All-Photonics Network

Combine

All-Optical Synchronization Network

All-Optical Synchronization Network

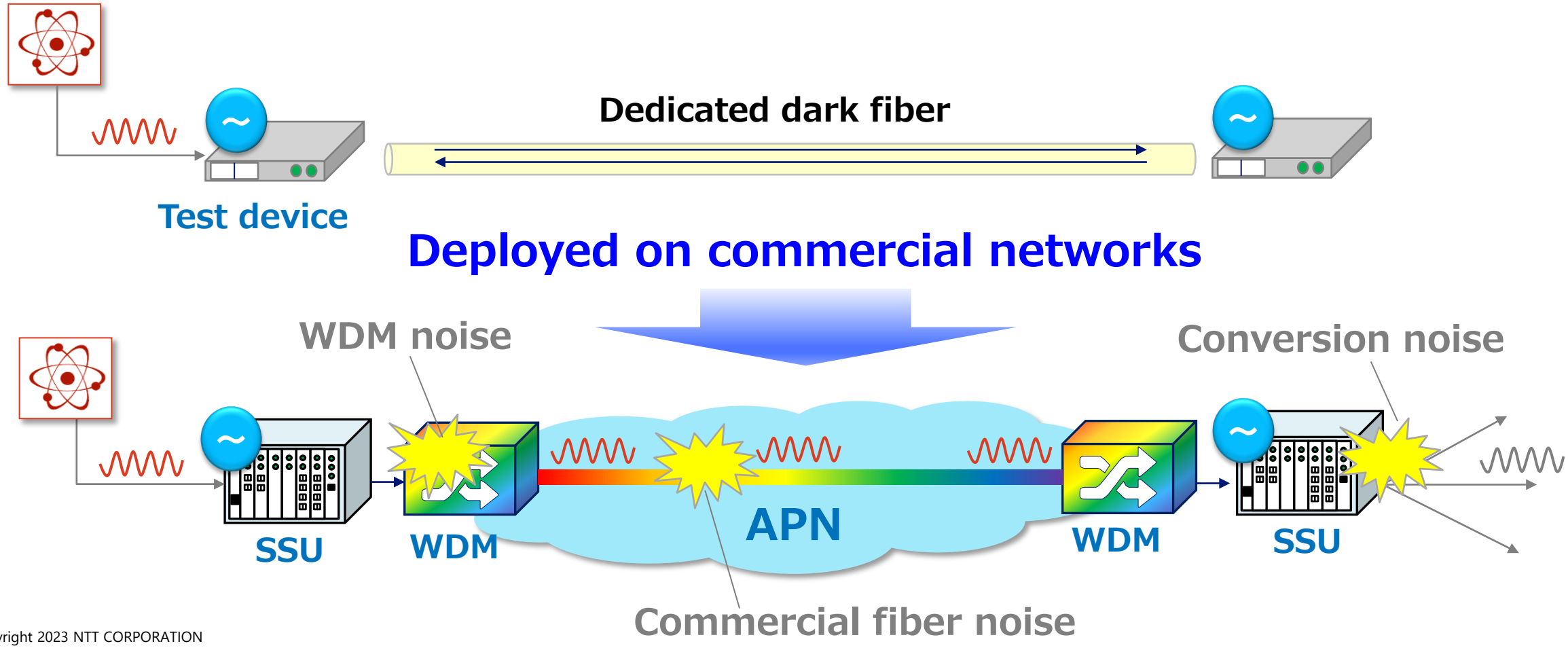
- **APN transfers information on advanced technologies** in addition to data traffic.
- Optical frequency is transferred over APN with synchronization.



SSU: Synchronization Supply Unit

Toward Commercial Network

- Optical frequency transfer has been demonstrated with **dedicated networks** such as dark fibers and direct connections.
- In commercial networks, **the condition can be more complex** because there are many devices and shared fibers. These effects have to be considered.



Technical Points of All-Optical Sync Network

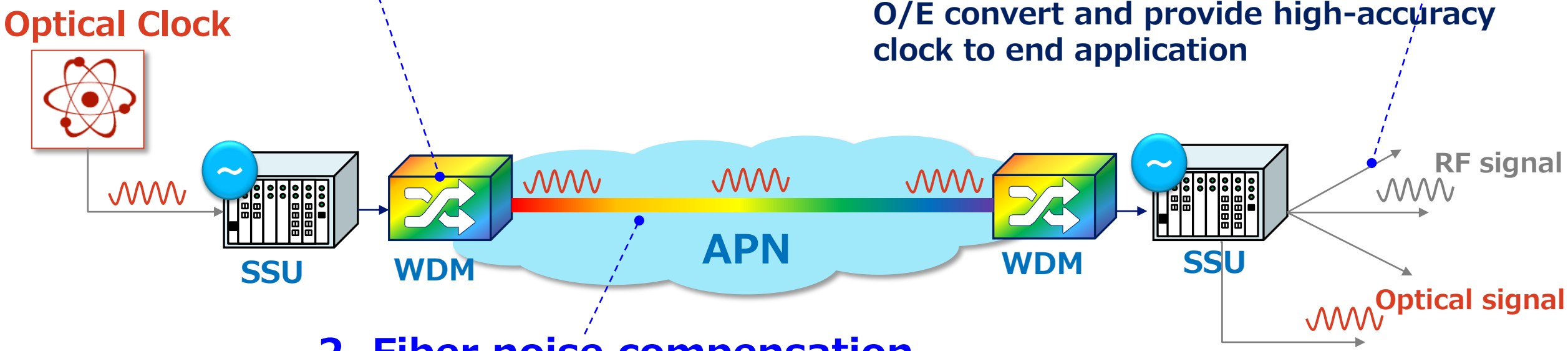
- There are three technical points to achieve optical sync network.

1. Optical frequency transfer over WDM

Reduce noise generation
and transfer while maintaining accuracy

3. Frequency distribution

O/E convert and provide high-accuracy
clock to end application



2. Fiber noise compensation

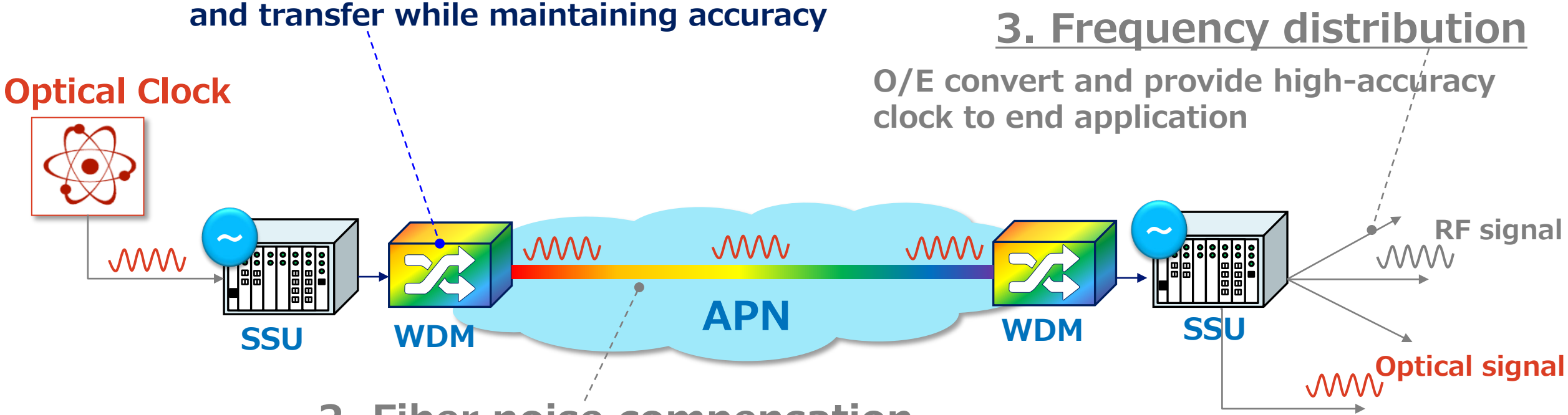
Estimate and eliminate noise in the case of commercial fiber

Technical Points of All-Optical Sync Network

- First topic is “Optical frequency transfer over WDM”.

1. Optical frequency transfer over WDM

Reduce noise generation
and transfer while maintaining accuracy



3. Frequency distribution

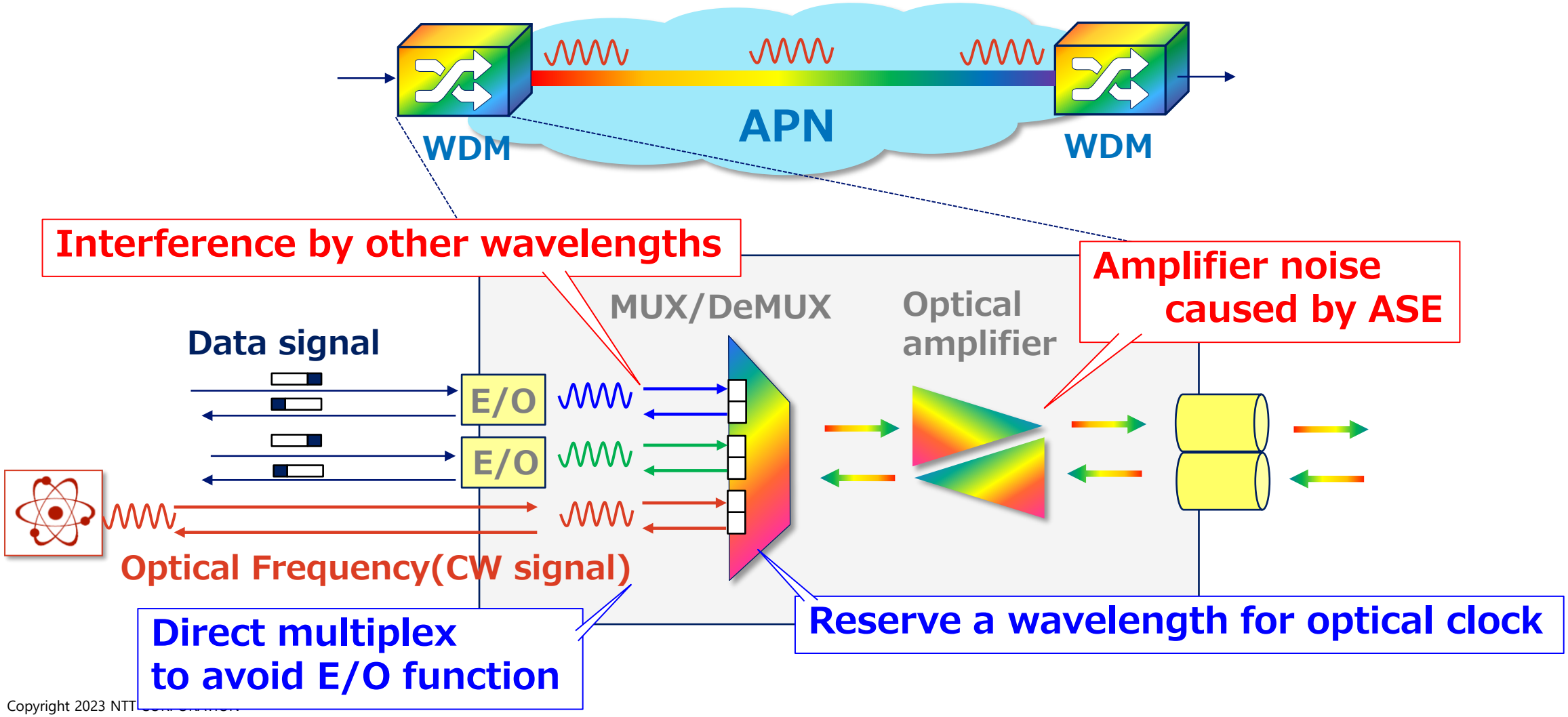
O/E convert and provide high-accuracy
clock to end application

2. Fiber noise compensation

Estimate and eliminate noise in the case of commercial fiber

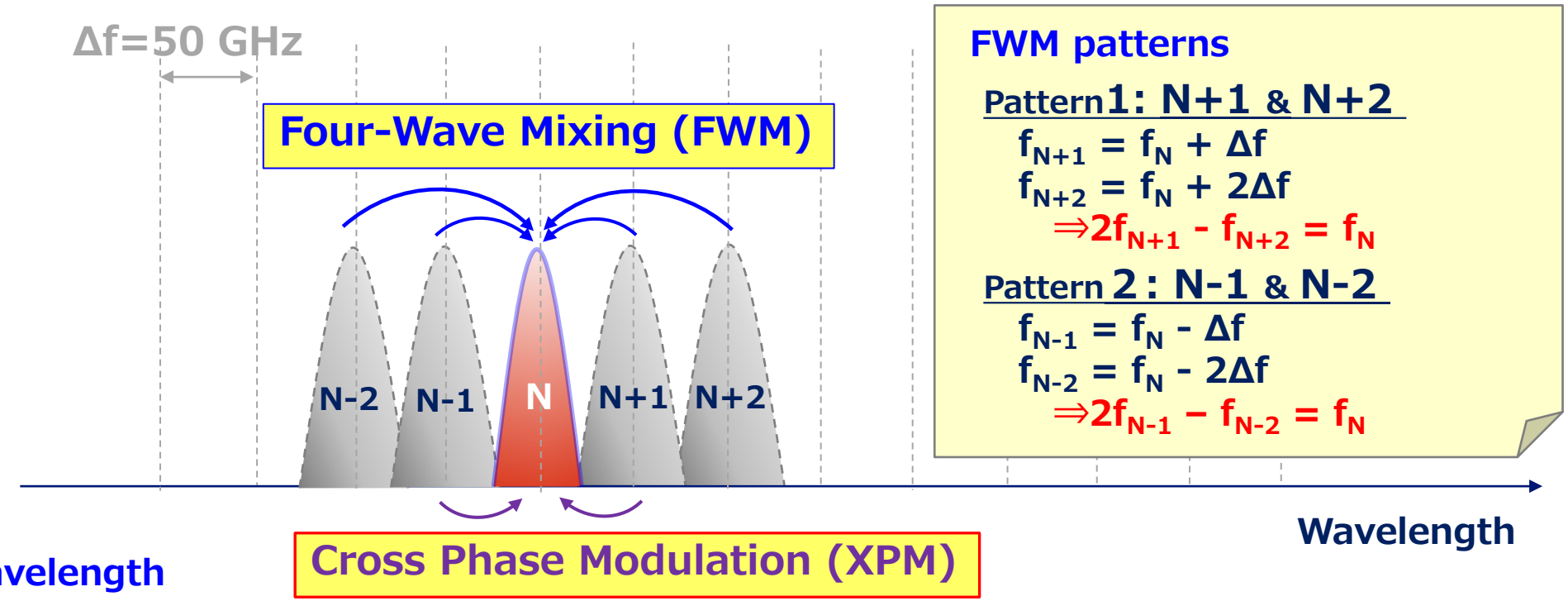
Optical Frequency Transfer Method over WDM

- We consider a transfer method using a dedicated wavelength for an optical clock.
- There are some degradation factors caused by an amplifier and other wavelengths.



Interference by WDM

- There are two types of interference phenomena, XPM and FWM.
- This time, we measure the XPM effect in the case of 50 GHz frequency spacing.

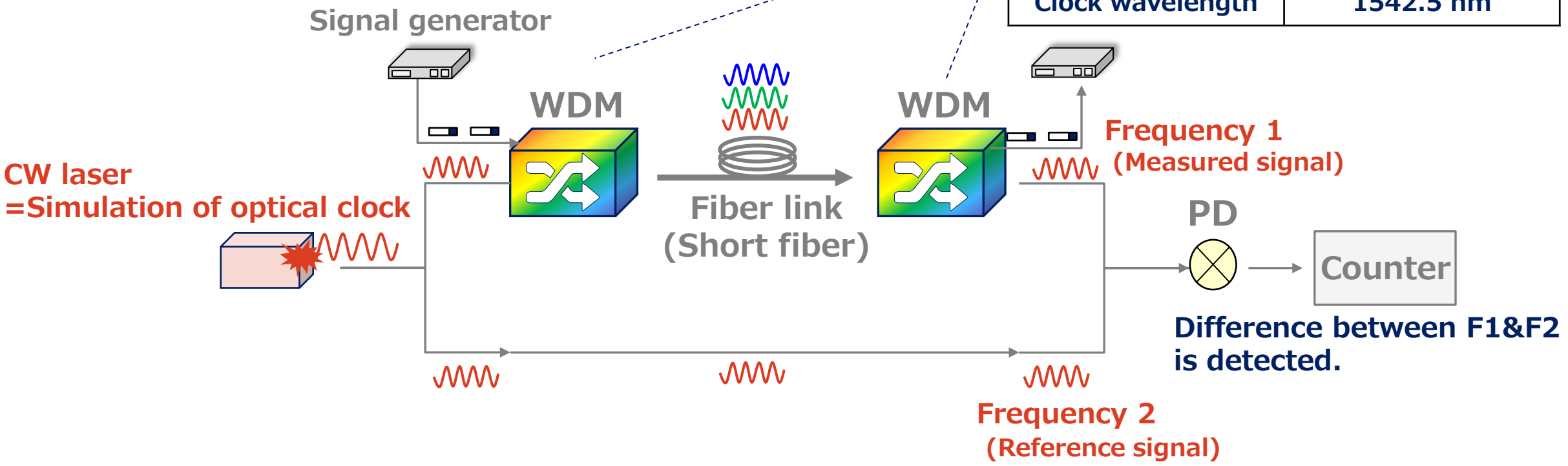


Experiment

- **We measured frequency variations due to WDM by changing wavelength assignments and compared the results.**

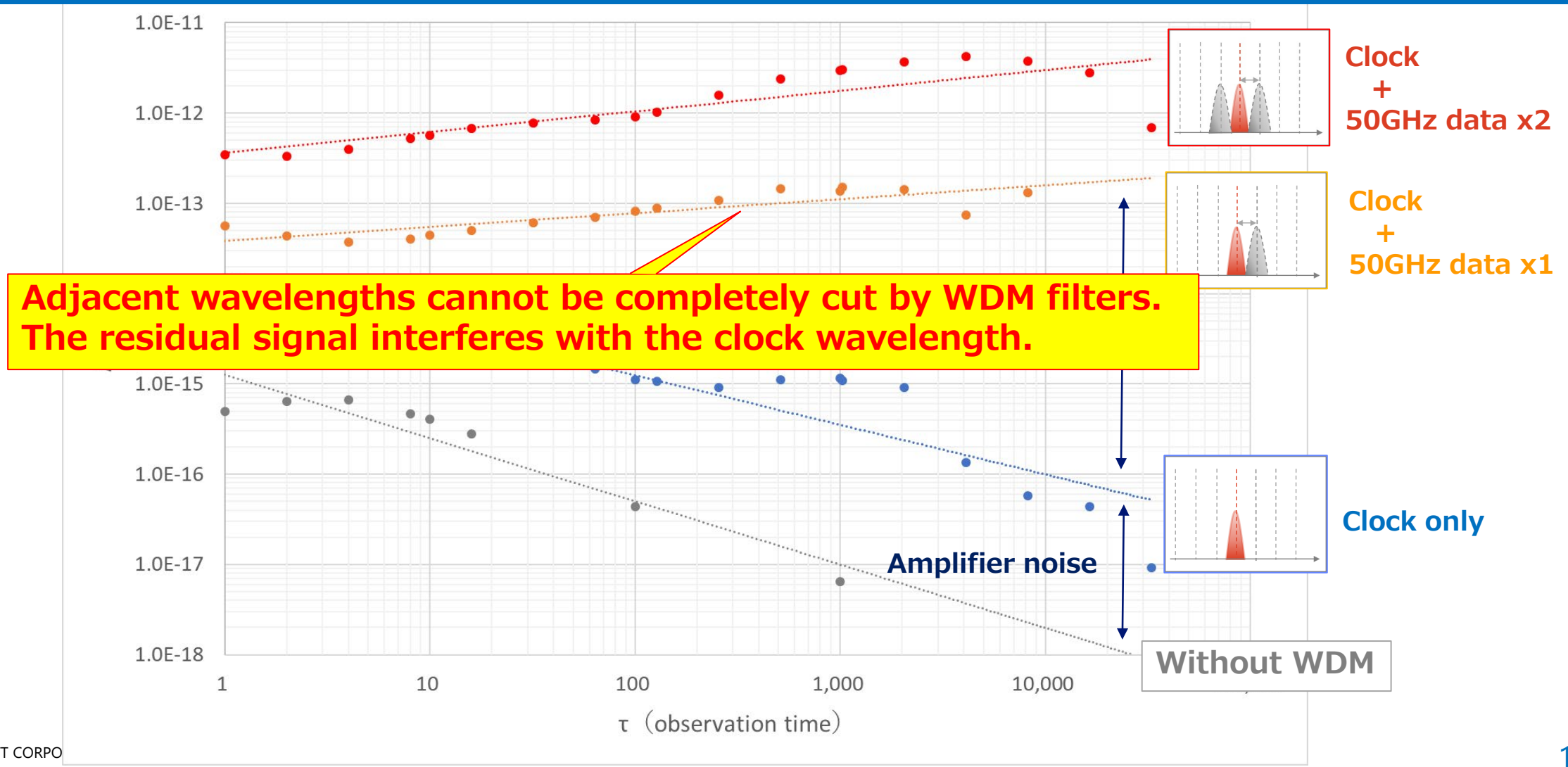
Experimental setup

WDM setting list	Parameter
Frequency spacing	50 GHz
Modulation	16QAM
Bit rate of data	200 Gbps
Clock wavelength	1542.5 nm



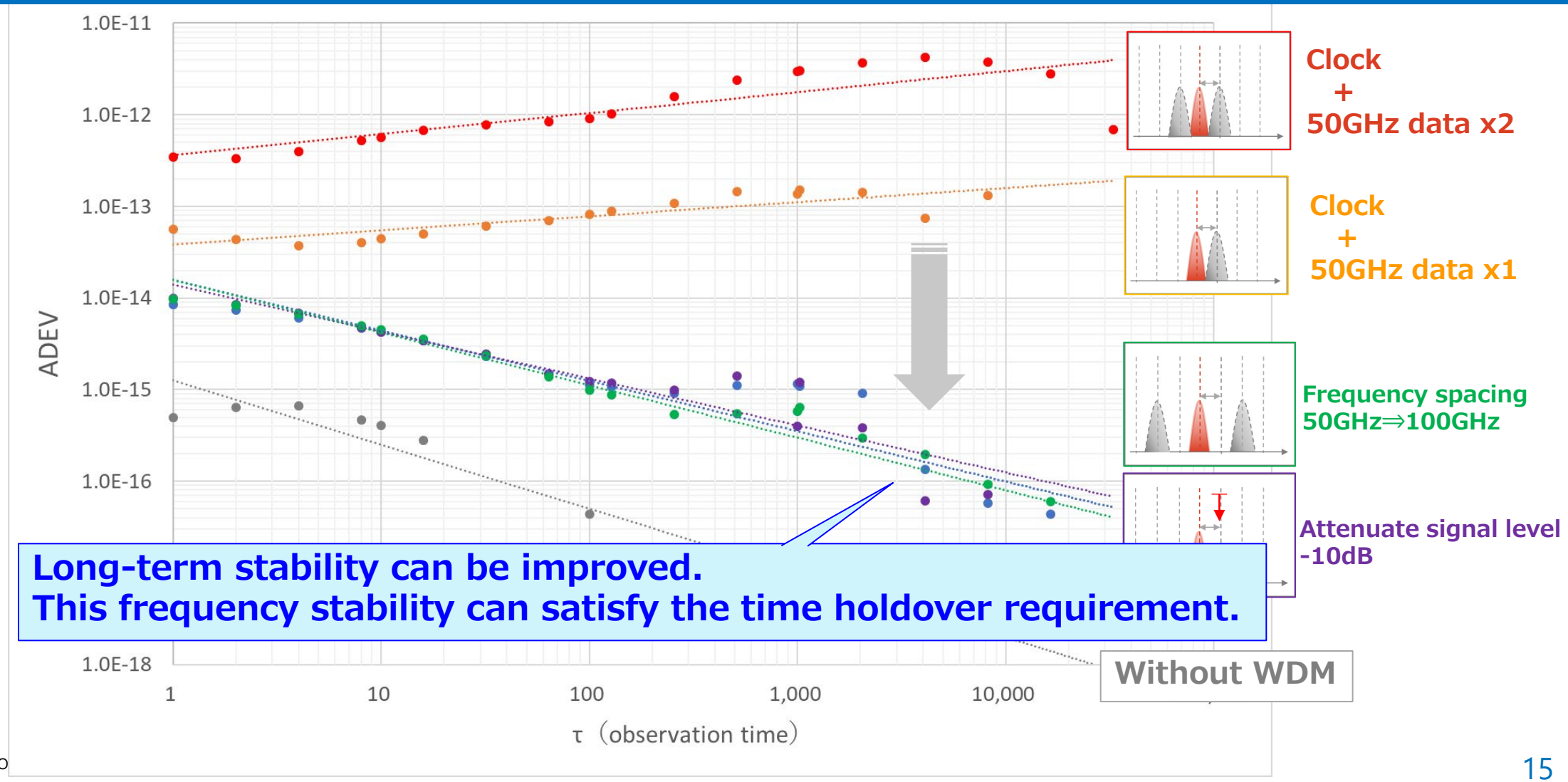
Relative Frequency Stability

- Frequency degradation is caused by optical amplifier and XPM.
- Especially, the XPM effect impacts long-term stability.



Improvement of Stability

- **We achieved long-term stability under laboratory conditions.**
- **We will try to do this in the field by using IOWN devices and long distance fibers.**



Technical Points of All-Optical Sync Network

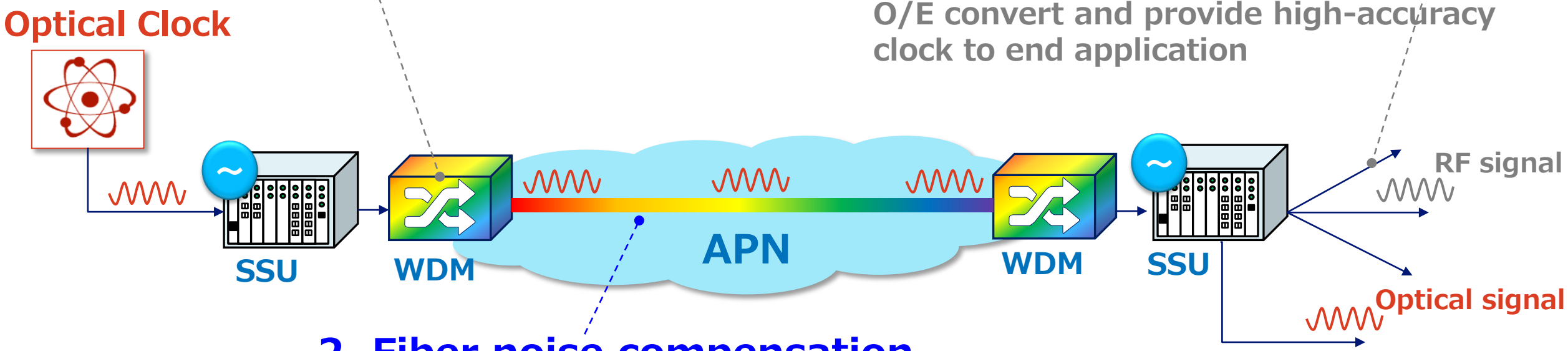
- **Next topic is “Fiber noise compensation”.**

1. Optical frequency transfer over WDM

Reduce noise generation
and transfer while maintaining accuracy

3. Frequency distribution

O/E convert and provide high-accuracy
clock to end application



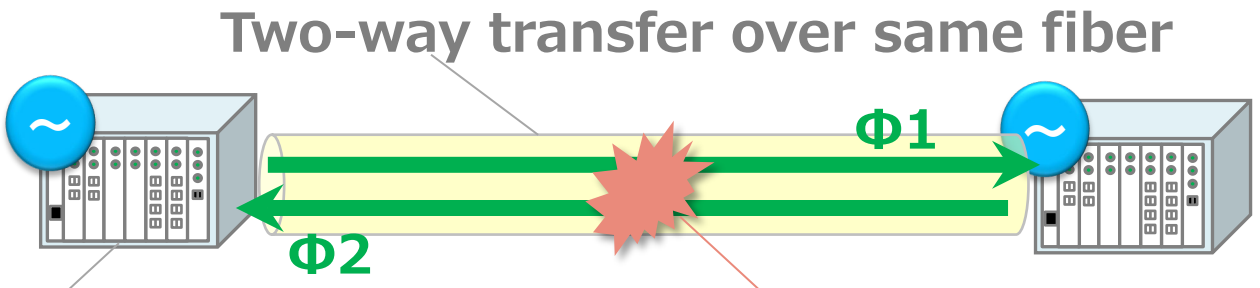
2. Fiber noise compensation

Estimate and eliminate noise in the case of commercial fiber

Issue of Fiber Noise Compensation

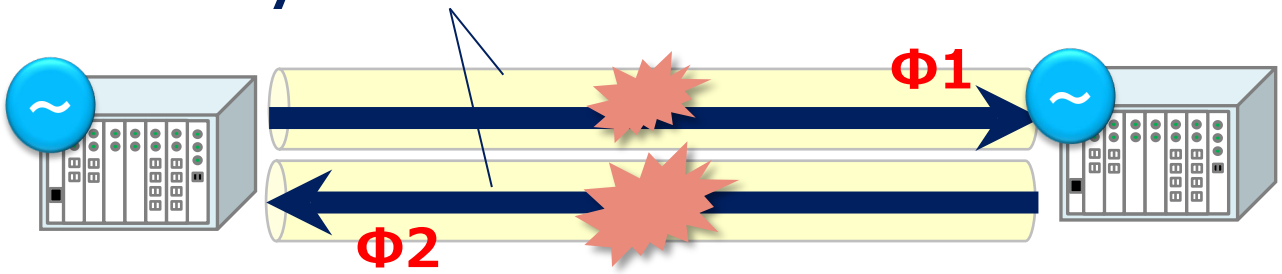
- Optical frequency transfer has been demonstrated by using the round-trip signal on the same fiber to detect the one-way noise.
- However, commercial networks have different up and down fibers, making it difficult to fully compensate for the noise.

Existing method



Φ1=Φ2
Detect one-way phase shift Φ1 by round trip on same fiber

Two-way transfer over different fibers

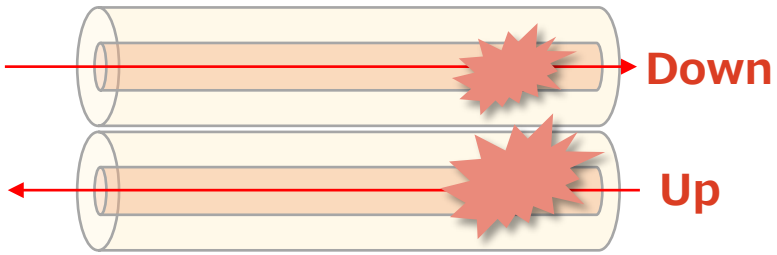


Φ1≠Φ2
Difference in phase shifts caused by two fibers in different environments

Challenge to Commercial Fiber

- In the case of two-way transfer over different fibers, the existing method cannot be used because the residual error may degrade frequency accuracy.
- One future solution is a multi-core fiber, in which bi-directional transfer on the same fiber can be achieved by using different cores.

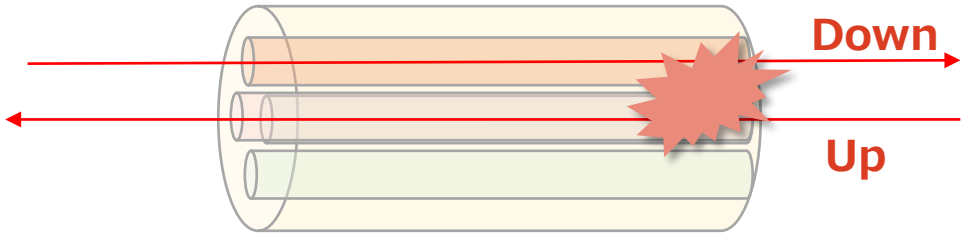
Single-core fiber



Asymmetry between up and down fibers

☹ Difficult: Asymmetry is dynamic due to unexpected noise factors.
⇒Check the performance of existing method
If not, need new method

Multi-core fiber



Up and down signals can be transferred on different cores of same fiber.

☺ Good:
Same noise in each direction with common fiber
⇒Can use existing method

Technical Points of All-Optical Sync Network

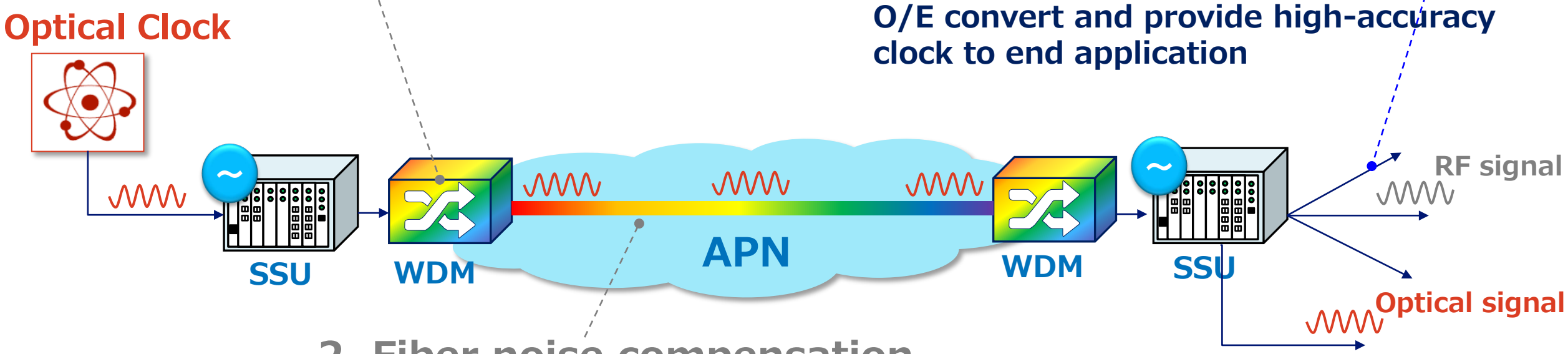
- **Final topic is “Frequency conversion”.**

1. Optical frequency transfer over WDM

Reduce noise generation
and transfer while maintaining accuracy

3. Frequency distribution

O/E convert and provide high-accuracy
clock to end application

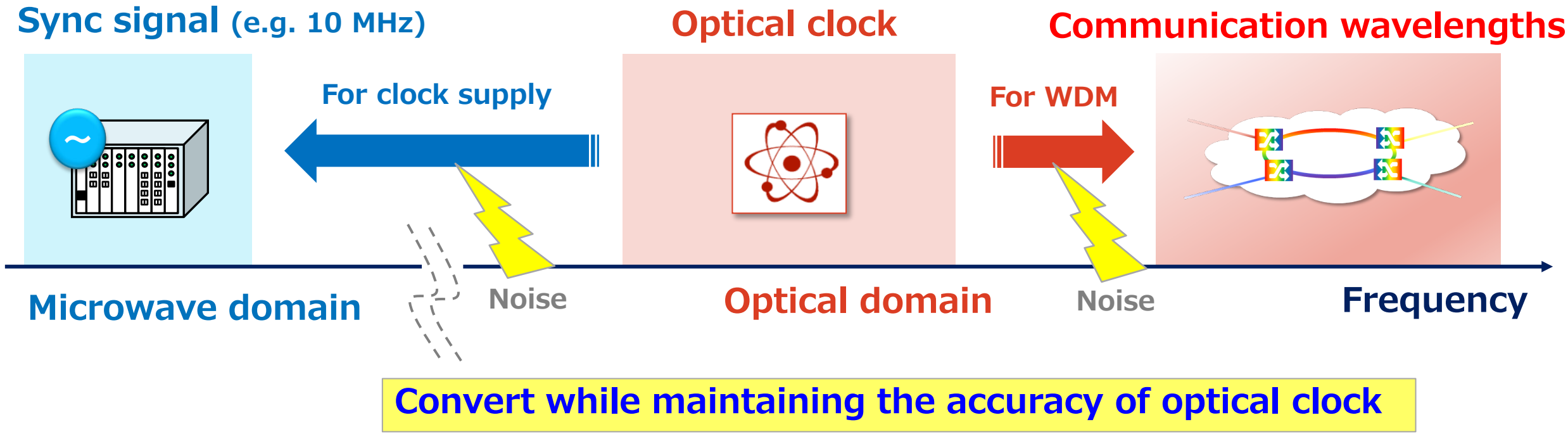


2. Fiber noise compensation

Estimate and eliminate noise in the case of commercial fiber

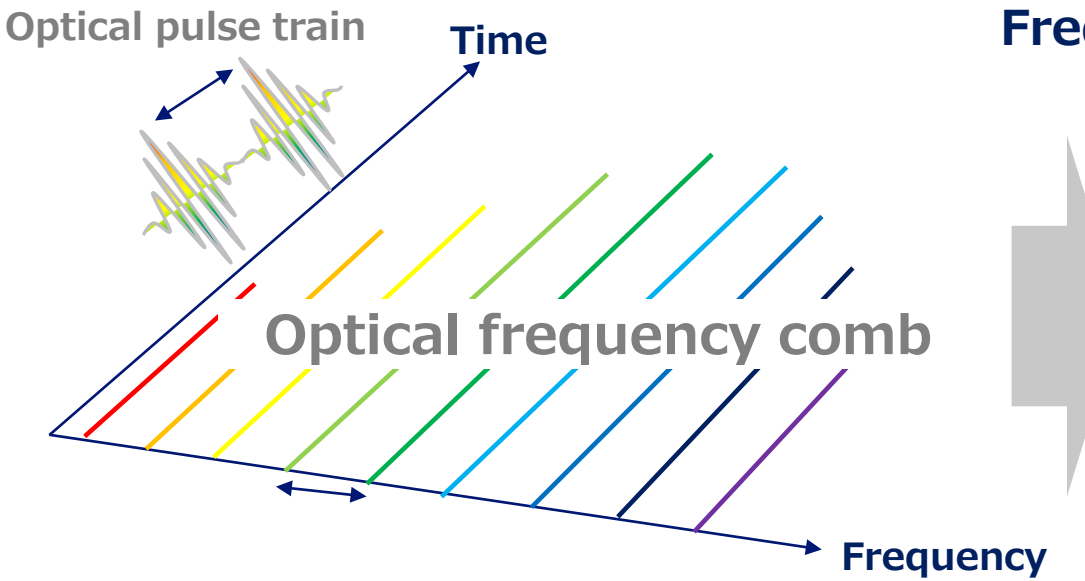
Issue of Optical Frequency Conversion

- The frequencies of major optical clocks differ between communication regions.
- To use the high-accuracy frequency for WDM transfer and clock synchronization, **frequency conversion with low noise** is needed.



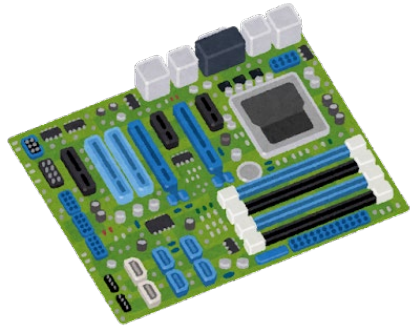
Development of Advanced Optical Devices

- **Optical frequency comb** is one of the key technologies to achieve optical frequency conversion. However, the technology is still immature.
- For developing next-generation SSU, the optical frequency comb needs to be **smaller and more robust than current devices.**



Optical comb technology that links optical and microwave frequencies with high accuracy
⇒Used for both optical and microwave conversion

Frequency conversion module



Next-gen SSU

Chip-scaled and robust package to equip to telecom devices

Solutions & Future Key Technologies

1. Optical frequency transfer over WDM

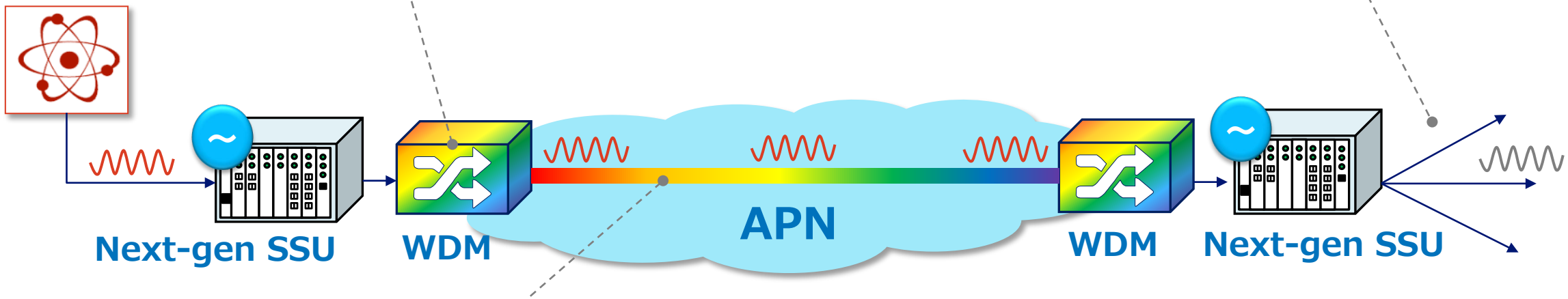
Achieved frequency transfer with long-term stability in laboratory

✓ **Adjust frequency spacing to avoid XPM effect**

3. Frequency distribution

Develop small and robust devices

✓ **Optical frequency comb for SSU**



2. Fiber noise compensation

Depend on types of fiber

✓ **Single-core fiber: New compensation method is needed**

✓ **Multi-core fiber: Existing method can be used**

Summary

[Background & Concept]

- Optical clocks are under development worldwide.
- IOWN is NTT's future concept and APN is an essential technology.
- Optical clock x IOWN = All-Optical Synchronization Network

[Use cases]

- High-accuracy timing measurement in various scientific fields
- Height difference measurement for disaster
- Backup of GNSS for time synchronization in mobile
  - Remote PRC configuration for ePRTC was agreed in ITU-T

[Challenges & Key technologies]

- Optical frequency transfer over WDM
  ⇒ Long-term stability achieved in the laboratory
- Fiber noise compensation
  ⇒ Multi-core fiber is one of the potential solutions
- Frequency distribution
  ⇒ Need to develop optical frequency comb

Your Value Partner