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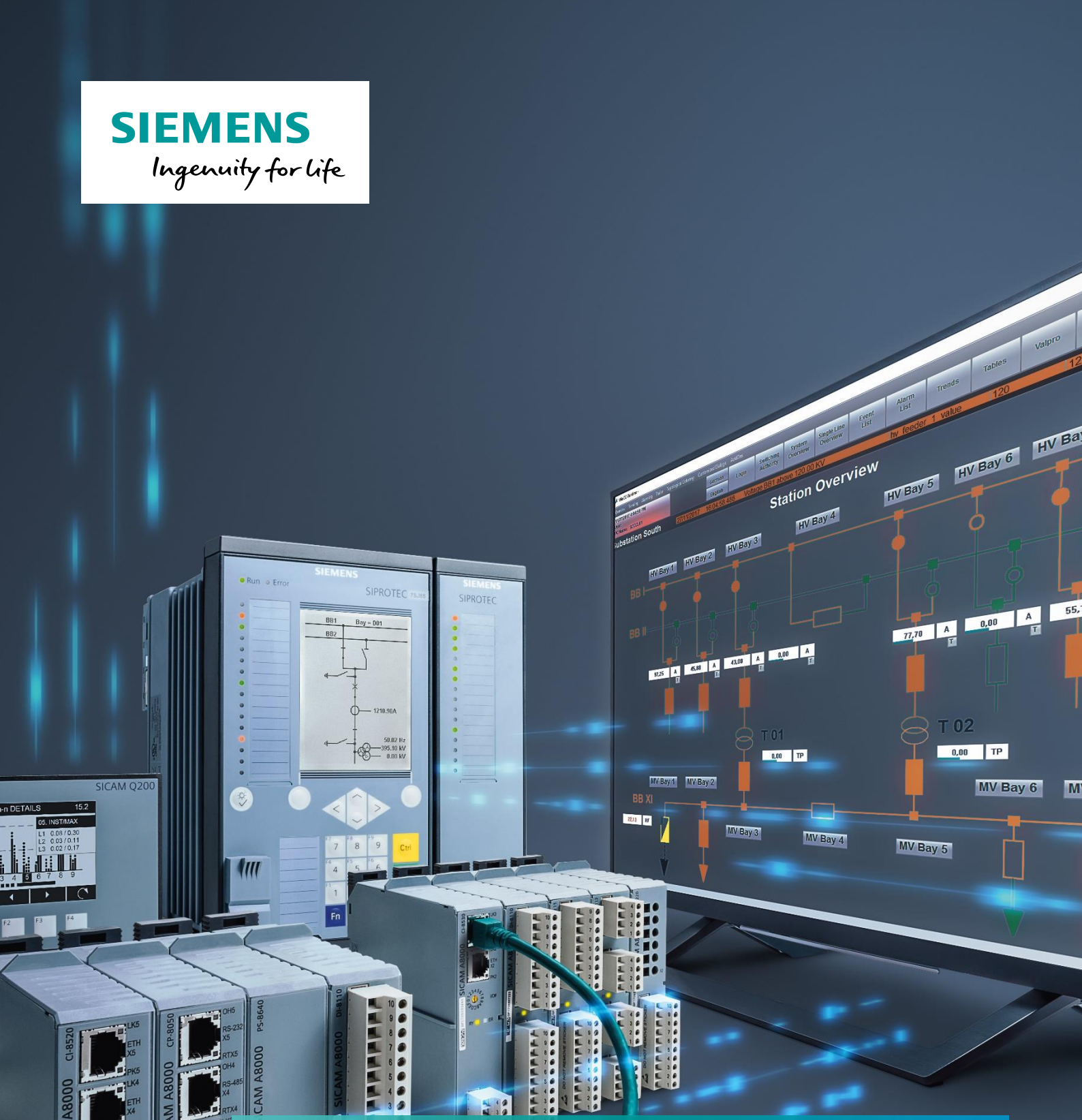


# High-Precision Time Synchronization using GPS

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# SIPROTEC Application

# High-Precision Time Synchronization using GPS

APN-067, Edition 1

## Content

# 1 High-Precision Time Synchronization using GPS

## 1.1 Introduction

Some applications of SIPROTEC devices, the SIPROTEC 5 device series, require high-precision time synchronization for all protection devices involved in one station or even several stations.
Classic application examples are Phasor Measurement Units, PMUs for short, or the line differential protection.

A differentiation must be made between applications that need a precision reference to a master clock time and those that do not need this master reference time. PMU applications, for example, reference a master reference time such as UTC. Process bus and differential protection applications, on the other hand, do not require a master reference time. The devices need only to be precisely synchronized to one another.

This application example discusses these 2 different requirements in detail.
The first example explores the secondary setup of time synchronization equipment, suitable for a PMU, with a master absolute time reference.
The second example discusses the secondary setup of time synchronization equipment suitable for line differential protection because this case only needs a master time reference but can work without an absolute time reference.

## 1.2 Components of Time Synchronization Equipment

The following lists and briefly describes the individual components of time synchronization equipment.

**7XV5664-1AA00 – GPS Time Synchronization Unit**

The GPS time synchronization unit (or the GPS clock) determines the current time (with an accuracy of 200 ns) using the signals from GPS satellites.

With the optical output channels 'FO-Out 1' to 'FO-Out 3', various time signals may be output. As delivered, the following signals are routed to the outputs:

FO-Out 1: IRIG B

FO-Out 2: 1PPS

FO-Out 3: DCF77

**Figure 1-1** 7XV5664-1AA00 – GPS Time Synchronization Unit

**7XV5450-0BA00 – Mini Star Coupler**

The mini star coupler is used to distribute a single optical time signal to up to 5 additional devices. To do this, the star coupler operates in the multipoint-star configuration.

Older versions (up to and including /CC) can distribute up to 4 additional devices.

The time signal to be distributed, which is transmitted, for example, by the 7XV5664-1AA00, is fed to the optical input R1 and distributed to the subordinate devices using the transmit diodes T2 to T5.


**Figure 1-2** 7XV5450-0BA00 – Mini Star Coupler

**7XV5654-0BA00 – Sync Transceiver**

The Sync Transceiver converts the optical time signal into appropriate electrical time signals using +/- 24 V. Here, receive diode R1 is used for channel 1 and receive diode R2 is used for channel 2. Both channels are output by way of the 9-pin D-sub socket X1. Channel 1 uses pins the pins 1 and 3 and channel 2 uses pins 4 and 8.


**Figure 1-3** 7XV5654-0BA00 – Sync Transceiver

**Optical Connections**

Multimode fiber-optic cables with ST connectors, like the fiber-optic cable (6XV8100), are used for the optical connections between the time synchronization unit, the mini star couplers and the sync transceivers.

**Electrical Connections**

Various preassembled cables are used for the electrical connections between the sync transceivers and the protection devices:

- Y bus cable (7XV5104-0AAxx):
  For synchronization only on channel 1 (R1 or pins 1 and 3)
- Y bus cable (7XV5105-0AAxx):
  For synchronization on channel 1 (R1 or pins 1 and 3) and/or channel 2 (R2 or pins 4 and 8)
- T-adaptor cable (7XV5104-3AA00):
  For converting channel 2 (R2 or pins 4 and 8) to channel 1 (pins 1 and 3)

**Figure 1-4** 7XV510*-*AA00 – Synchronization Cable

## 1.3 Hierarchical Structure of Time Synchronization Equipment

To provide high-precision synchronization of devices, first it is crucial that all devices to be synchronized lie on the same hierarchical tier. Second, the connections between 2 tiers must be of a standard length if possible.

The GPS synchronization unit is always tier 0 in this respect. For switchgear that covers a wide area with devices that are spatially separated but must be synchronized, one or cascaded mini star couplers form the subordinate tier(s). These tiers may also be necessary if more than 6 (or 12) devices must be synchronized.

If devices are to be synchronized across different tiers, out-of-phase synchronization due to transmission time will necessarily occur. This increases with the number of tiers between the synchronized devices. This is not recommended, or even not permitted, for applications requiring high-precision time synchronization.

The following figure shows an example of the setup of the tiers by way of a synchronization unit for a station. The configuration shown can synchronize up to 24 protection devices with line differential protection using IRIG B and 1PPS.

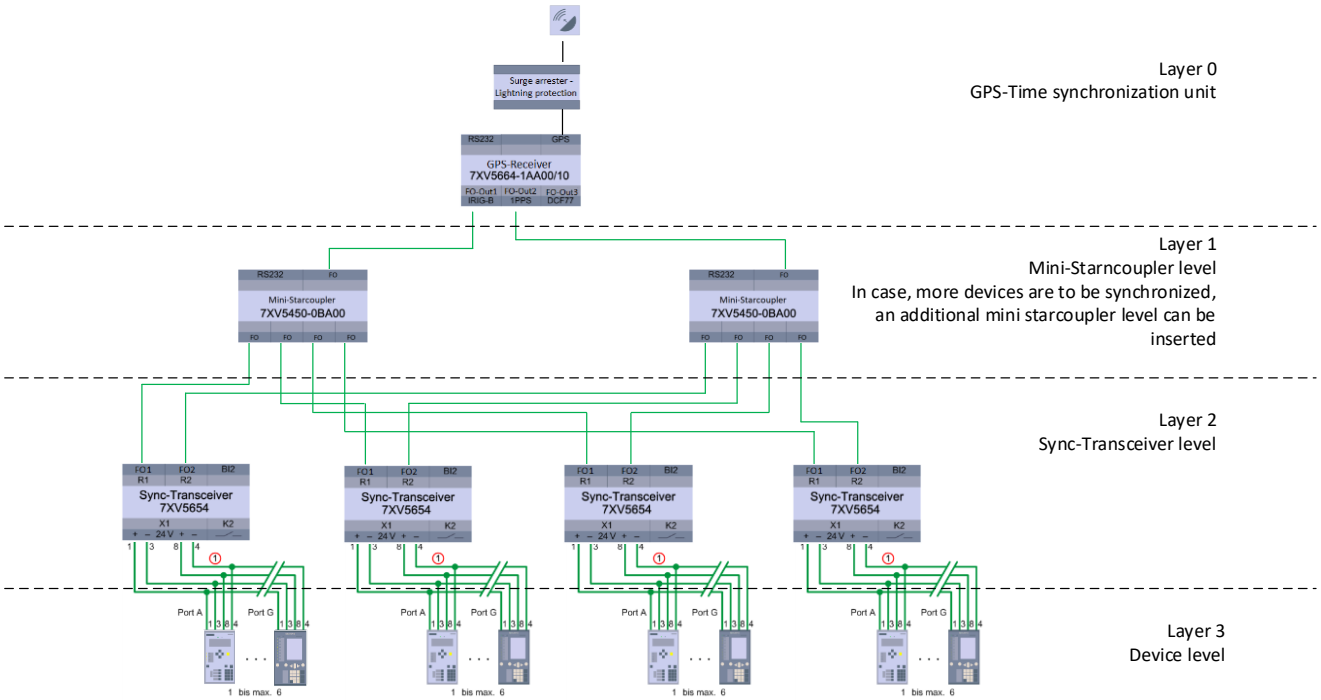



**Figure 1-5** Synchronization Unit for Up to 24 Devices Using 1PPS and IRIG B

### 1.3.1 Transmission Time Fluctuations and Differences

Every component of the synchronization equipment affects the transmission times between the synchronization unit and the (protection) devices. If the total transmission time from the time source to the receiver is important or not for synchronizing the devices is depending on the application.

If the reference requires a specific deviation with respect to a master time (for example, UTC), the device internal transmission times (delay times) must be included in the calculation of the total deviation. For example, this is required for PMU applications. However, if synchronization is only between individual devices without reference to an absolute time (for example, with 1PPS), the internal delays play no role with a standard setup of the synchronization equipment. Synchronization is determined only by the potential transmission-time differences between the corresponding terminal equipment.

The transmission-time differences of individual devices or components are a function of temperature and aging. The difference between the minimum and maximum transmission time is known as skew.

For electrical cables, the transmission time is determined by the cable length and the number of devices it supplies in parallel. For optical cables, the length is the essential factor because only point-to-point connections are possible here. With these cables, different lengths for connecting between 2 tiers lead to a difference in transmission time that, while not being affected by aging or temperature, is still to be considered like the propagation-time differences of components and, for this reason, can also be considered as skew. If, as in Figure 1-5, we consider only one station, the synchronization unit on layer 0 makes no contribution to skew. Only the following tiers have an effect. The table below summarizes the worst case for skews occurring on the components of the synchronization unit. In the case of copper and fiber-optic cables, only the differences in the lengths used must be considered, not the length they have in common.

| Device type (MLFB number) | Skew [ns] | Minimum transmission time | Maximum transmission time |
|---|---|---|---|
| Synchronization unit (7XV5664-1AAx0) | < 200 ns | 50 ns | < 250 ns |
| Mini star coupler (7XV5450-0BA00 up to /DD) | < 611 ns | 100 ns | 711 ns |
| Mini star coupler (7XV5450-0BA00 /DD and later in 'enhanced mode') | < 171 ns | 100 ns | 271 ns |
| Sync transceiver (7XV5654-0BA00) | < 40 ns | 60 ns | 100 ns |
| Protection devices, internal (SIPROTEC 5) | < 103 ns | 27 ns | 130 ns |
| Protection devices, internal (SIPROTEC 4, only for 1PPS!) | < 103 ns | 27 ns | 130 ns |
| Fiber-optic cable (for example, 6XV8100-*) assumed | 5 ns / m | -- | -- |
| Y bus cable (7XV5104-0AAxx) assumed | 6 ns / m | -- | -- |
| T-adaptor cable (7XV5104-3AA00) assumed | 6 ns / m | -- | -- |

**Table 1-1** Transmission Times and Derived Worst-Case Skew

The skew to be expected in the worst case is the sum of the relevant individual skews. The skews realistically occurring on the switchgear will be considerably smaller.

For applications without an absolute time reference (such as differential protection) that are synchronized using 1PPS, the lead time to be considered and the skew are reduced for the star coupler in the first layer by the values of the optical input components. As these are identical for all subordinate devices. The fluctuations for the output components, however, must be taken into consideration.

The following reduced values come from the variants of the mini star coupler:

| **Mini star coupler (7XV5450-0BA00 up to /DD)** | **< 443 ns** | **100 ns** | **543 ns** |
|---|---|---|---|
| **Mini star coupler (7XV5450-0BA00 /DD and later in "enhanced mode")** | < 158 ns | 100 ns | 258 ns |

**Table 1-2** Transmission Times and Derived Worst-Case Skew for Mini Star Couplers in the first synchronization layer

The following table contains measured delay values coming from the Y bus cable combinations listed. As the measured times show, the total delay in the bus cables is also a function of the total number of devices the cables supply.

| Cable length of the entire bus | Delay from X1 to the end of the cable (* calculated value) | Topology |
|---|---|---|
| **3 m** | 18.5 ns | 1 cable (3 m), 1 device, measured @ 3 m |
| **6 m** | 39 ns | 2 cables (3 m), 1 device, measured @ 6 m |
| **9 m** | 60.0 ns | 3 cables (3 m), 1 device, measured @ 9 m |
| **12 m** | 78.5 ns | 4 cables (3 m), 1 device, measured @ 12 m |
| **15 m** | 100.5 ns | 5 cables (3 m), 1 device, measured @ 15 m |
| **20 m** | (26 ns)* | 6 cables (1 x 5 m+5 x 3 m), 1 device, measured @ 3 m |
| **20 m** | (48.5 ns)* | 6 cables (1 x 5 m+5 x 3 m), 1 device, measured @ 6 m |
| **20 m** | (69.5 ns)* | 6 cables (1 x 5 m+5 x 3 m), 1 device, measured @ 9 m |
| **20 m** | (92 ns)* | 6 cables (1 x 5 m+5 x 3 m), 1 device, measured @ 12 m |
| **20 m** | (113.5 ns)* | 6 cables (1 x 5 m+5 x 3 m), 1 device, measured @ 15 m |
| **20 m** | 131 ns | 6 cables (1 x 5 m+5 x 3 m), 1 device, measured @ 20 m |
| **20 m** | (26 ns)* | 6 cables (1 x 5 m+5 x 3 m), 6 devices, measured @ 3 m |
| **20 m** | (48.5 ns)* | 6 cables (1 x 5 m+5 x 3 m), 6 devices, measured @ 6 m |
| **20 m** | (69.5 ns)* | 6 cables (1 x 5 m+5 x 3 m), 6 devices, measured @ 9 m |
| **20 m** | (92 ns)* | 6 cables (1 x 5 m+5 x 3 m), 6 devices, measured @ 12 m |
| **20 m** | (113.5 ns)* | 6 cables (1 x 5 m+5 x 3 m), 6 devices, measured @ 15 m |
| **20 m** | 131 ns | 6 cables (1 x 5 m+5 x 3 m), 6 devices, measured @ 20 m |

**Table 1-3** Delays Due to the Time Synchronization Bus Cable

## 1.4 Example of Switchgear with PMU Function

SIPROTEC 5 (protection) devices with PMU functionality are synchronized at D-Sub 9 with time signals in the IRIG-B format. As a result, the phasors obtained from the measurements can be superimposed with adequate accuracy for additional applications. For PMU applications, high accuracy is required of the measured values. Since these errors are composed of amplitudes and angle errors, time synchronization having an accuracy of < 1 µs is required to limit the angle error caused by the time synchronization. As PMU applications frequently extend over wide areas and different electrical power system sections, reference to a standard absolute time is always demanded here.

UTC time signals using the IRIG-B format and having an accuracy of < 200 ns are generated by the GPS synchronization unit (7XV5664-1AA00/10). The sync transceiver has a maximum signal delay of 100 ns. The required maximum deviation of the UTC time signal of < 1 µs is maintained together with the delays from the sync bus cables of < 150 ns and the delays internal to the protection devices of < 105 ns.

Up to 6 SIPROTEC 5 protection devices with PMU functionality per channel can be synchronized with high precision by the sync transceiver. Up to 12 devices can be synchronized using the option of doubling the signals, received on channel 1, on channel 2. If more than 12 devices must be synchronized in the switchgear, the optical IRIG-B signal must be sent to the 2 additional optical outputs of the GPS synchronization unit. In this way, the number of devices that can be synchronized for PMU applications increases to 36.

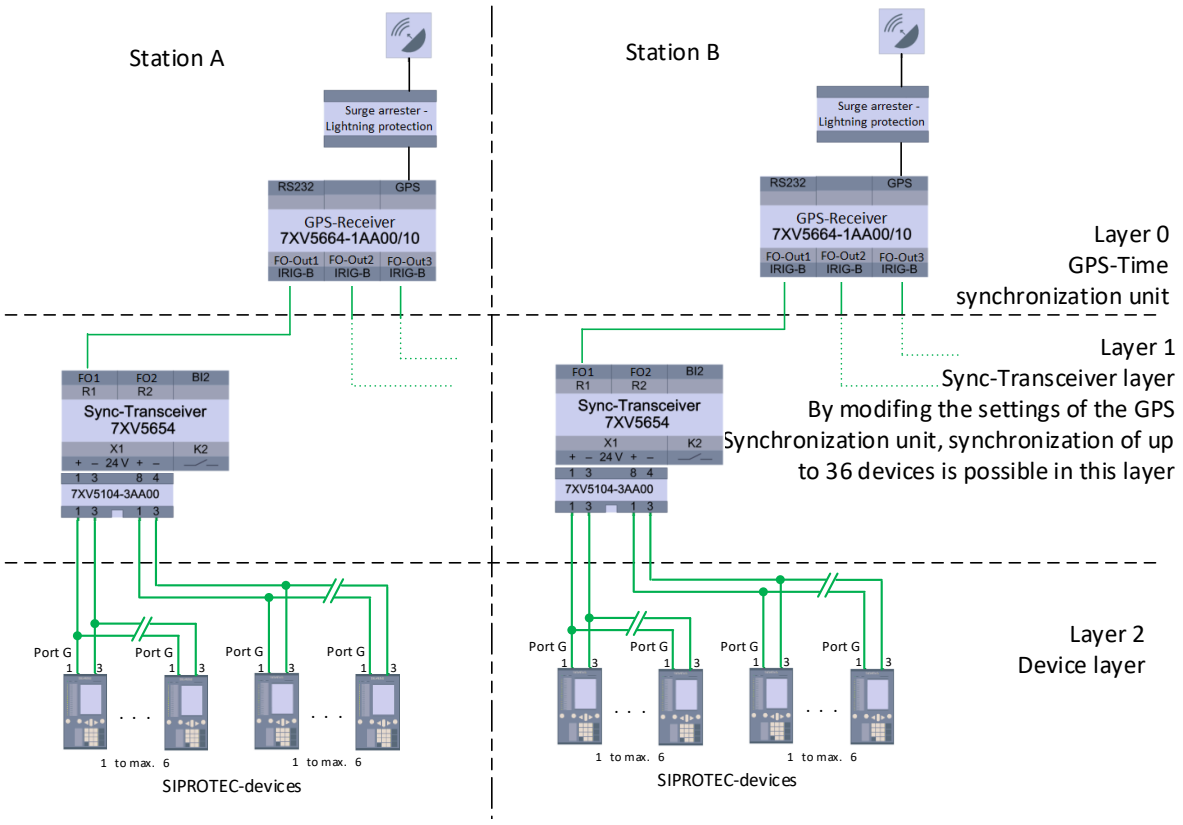



**Figure 1-6** IRIG-B Synchronization for Devices with PMU

Mini star couplers should not be used to further propagate the time signal because, for PMU applications, synchronization of the measured values via UTC is required to be less than 1 µs.

## 1.5 Example of Line Differential Protection Devices for Switchgear

SIPROTEC line protection devices with line differential protection are synchronized by way of the time synchronization port, Port A in SIPROTEC 4 and D-Sub 9 in SIPROTEC 5, using 1PPS signals.

The following Figure 1-7 shows the synchronization equipment of 2 stations. In this example, only the 1PPS signal is distributed through the station. 2 synchronization channels can be distributed as shown in Figure 1-5.

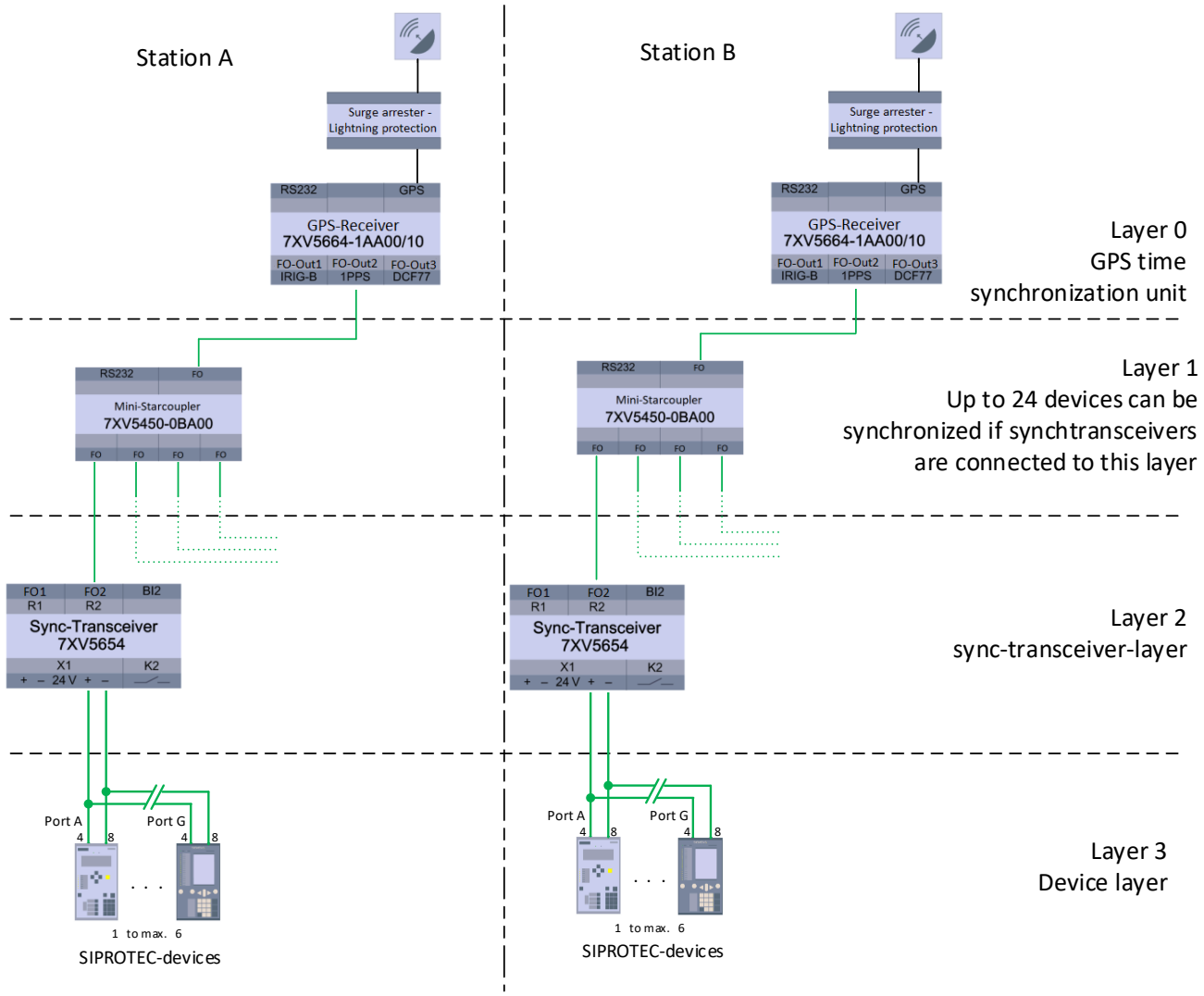



**Figure 1-7** 1PPS Synchronization for Differential Protection Applications

Because connecting the sync transceivers to different mini star coupler layers, as already mentioned in chapter 1.3, leads to a systematic transmission-time difference and the associated increased inaccuracy in time synchronization, it is emphatically recommended that the synchronization unit be built identically in all switchgear of one differential protection topology.
Assuming that the time synchronization equipment is built identically in all switchgear involved in one differential protection topology and that all devices are synchronized from the same hierarchical layer, only the potential transmission-time differences, not the overall transmission time of the synchronization signal, must be taken into consideration.
Different lengths in the fiber-optic cable and/or copper connections can be offset with the delay parameters. Then, only the sum of the skews of the devices involved must be taken into consideration for the synchronization accuracy. In the example shown here, the synchronization accuracy is composed of the following components: accuracy of the GPS synchronization unit (7XV5664) of < 200 ns

- Skew of one mini star coupler of < 611 ns (old version /CC)
- Skew of the sync transceiver of < 165 ns
- Skew of the protection device of < 103 ns

For this setup, this yields a synchronization accuracy certainly better than 1.079 µs. This is more than sufficient for differential protection applications because the angle error caused by synchronization resulting from this is significantly less than the angle error of the current transformers.

## 1.6 Settings on the Protection Device

### 1.6.1 SPIROTEC 4

Time synchronization using IRIG B is provided in SIPROTEC 4 in the standard.

This is selected in DIGSI by way of the menu Time synchronization => Time synchronization source => IRIG B time signal.

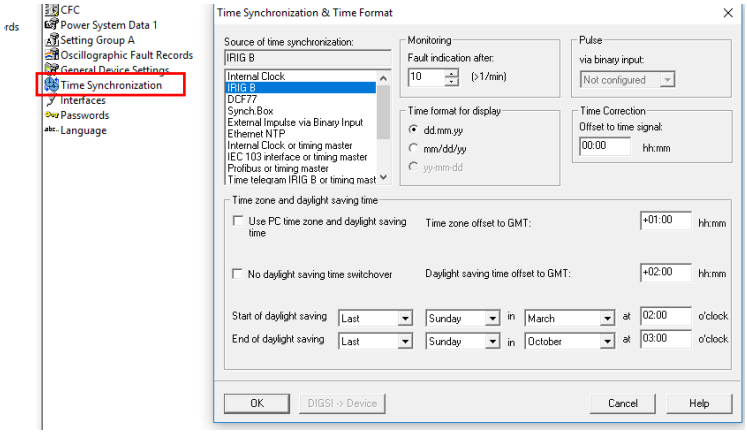
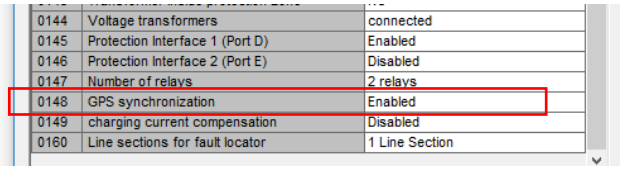



**Figure 1-8** Time Synchronization Using IRIG B in SIPROTEC 4/DIGSI 4

For synchronization using GPS, this property must be present in the device. This can be derived from the MLFB number. GPS synchronization is shown in the following using the 7SD523 Line Differential Protection Device as an example.

The GPS synchronization function must be available by way of the MLFB number 16 = 'with GPS sync...' and it must be activated by way of parameter **0148 GPS synchronization** = 'present'.



| | | |
|---|---|---|
| 0144 | Voltage transformers | connected |
| 0145 | Protection Interface 1 (Port D) | Enabled |
| 0146 | Protection Interface 2 (Port E) | Disabled |
| 0147 | Number of relays | 2 relays |
| 0148 | GPS synchronization | Enabled |
| 0149 | charging current compensation | Disabled |
| 0160 | Line sections for fault locator | 1 Line Section |

**Figure 1-9** Setting of the Functional Scope in the 7SD523*

Synchronization via 1PPS is made available using the active settings group, here for example, 'Settings group A' => 0045 'Protection interfaces' => GPS => '4801 GPS synchronization' = 'On'. Now, synchronization of the line differential protection is set with the telegram mode and/or GPS by setting the parameter **4511** 'PI1 synchronization mode' or **4611** "PI2 synchronization mode."

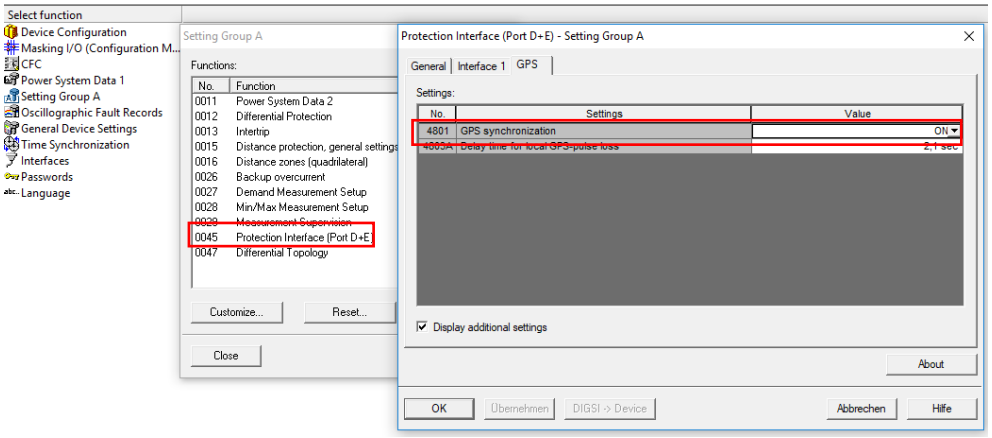



**Figure 1-10** Synchronization via 1PPS (GPS)

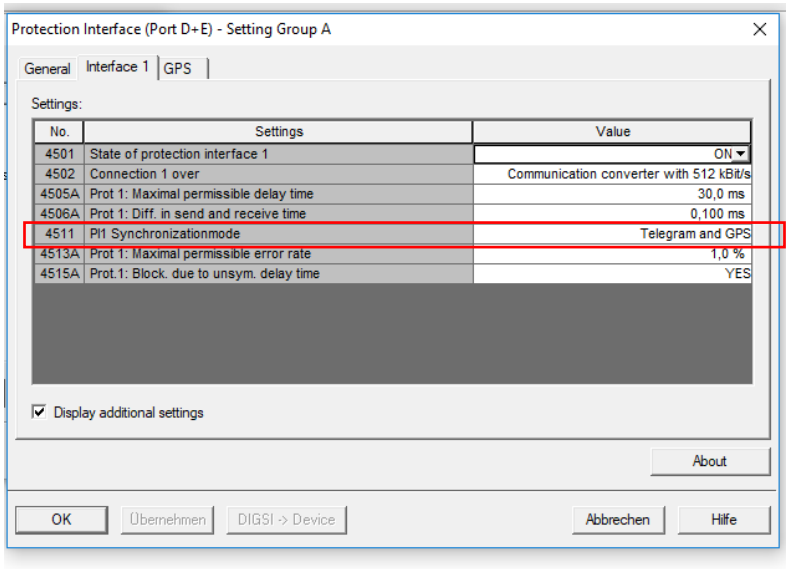



**Figure 1-11** Selecting the Synchronization Mode

If maximum asymmetry cannot be guaranteed in the transmit and receive direction for protection interface communication by way of communication paths, we recommend the setting 'Telegram and GPS'.

This is not needed for direct protection interface communication using a permanent fiber-optic connection.

### 1.6.2 SIPROTEC 5

Synchronization using both IRIG B and GPS (1PPS) is always available in SIPROTEC 5 devices. Both modes are configured using the parameter => Time settings. D-Sub 9: IRIG B is set as time source 1 for the timer. The second pulse (D-Sub 9) is always evaluated. In this case, only a latency time can be set.

The latency times can be set in increments of 0.01 µs. Corresponding inputs are necessary in this case only if the synchronization equipment (including the cabling) was not built uniformly as described above.

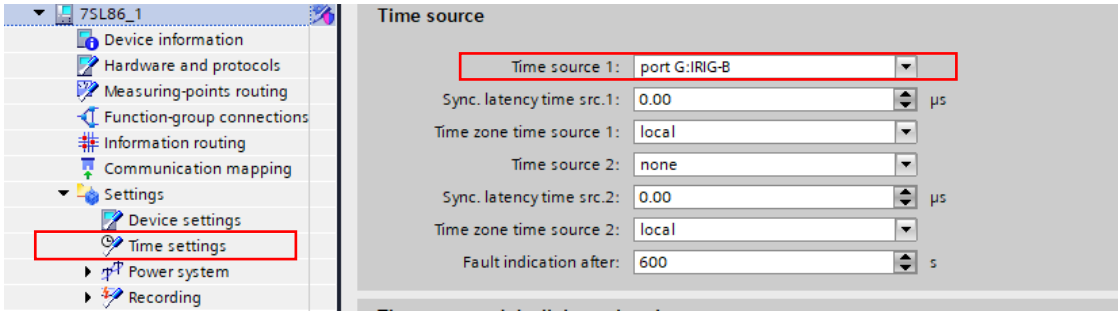



**Figure 1-12** Time Source Settings for the Timer in SIPROTEC 5 /DIGSI 5

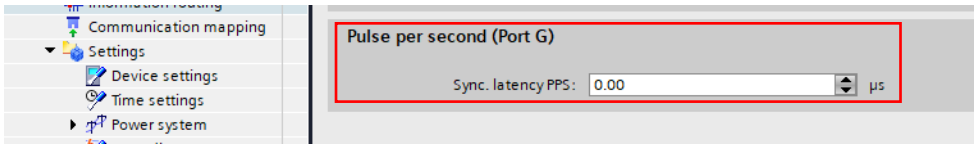



**Figure 1-13** Settings for the Second Pulse in SIPROTEC 5 /DIGSI 5

The USART A* *FO modules are configured under Hardware and protocols. At least one of the two possible protection interfaces must be configured for the line differential protection. Synchronization using the second pulse is chosen in the settings for the protection interface(s). As for SIPROTEC 4 devices, synchronization using telegram mode and 1PPS is always recommended as soon as the protection interface communication can be asymmetrical and maximum or permissible asymmetry cannot be guaranteed.

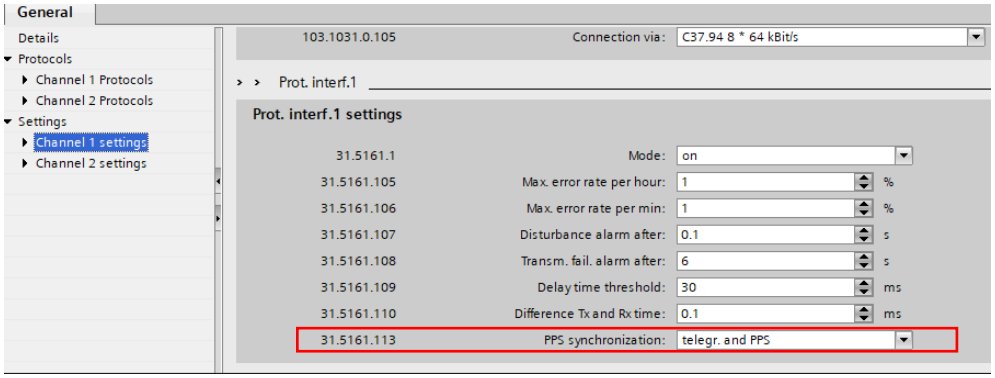



**Figure 1-14** Synchronization Mode Settings in SIPROTEC 5/DIGSI 5

## 1.7 Conclusion

This application provides support in selecting the devices and the setting values, since high-precision time synchronization using GPS for all protection devices of a station involved or even several stations is an essential condition for the correct applications of PMU (real-time synchronization) and for line differential protection (relative synchronization).

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