Article

Measurement of 868MHz LoRa Radio Propagation in a Tunnel

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Abstract: In this article the measurement method and results for a measurement with LoRa in a tunnel is shown, using a custom LoRaWAN Data-Logger and DR0, in the LoRaWAN EU868 region at 868 MHz. After an initial attenuation of 66 dB for the Data-Logger and 49 dB for the Gateway, an attenuation of 14 dB/km for the RSSI of the Data-Logger and 17 dB/km for the RSSI of the Gateway was obtained. For this results the Data-Logger and Gateway were placed in the middle of the tunnel cross-section in a height of 1.7 m. If the Data-Logger was placed in one of the five diagonal transverse the signal degraded quickly by up to 40 dB. Additional tests with different positions of the Gateway and the Data-Logger in the cross-section of the tunnel showed the significant influence of placement in the cross-section. For all situations the suitability of LoRa in tunnels is shown. The tunnel had a usable length of 2400 m, a width of 8 m, and a rounded ceiling at 6 m. The walls and ceiling were a combination of natural stones and sprayed concrete, the floor was tarred. No active traffic was in the tunnel during measurement. The measured RSSI and the SNR values showed that the whole tunnel could be covered with a single LoRa Gateway at the tunnel portal.

Keywords: LoRa in tunnels; LoRaWAN in tunnels; RF propagation; Wireless measurement

1. Introduction

In our project we developed a wireless long life battery powered Data-Logger which is also used inside of tunnels. The Data-Logger uses different kinds of sensors to monitor the corrosion of the tunnel walls, ceiling, and floor. The collected data is then transmitted wirelessly to a central server to store, process, and visualise the results. In a tunnels not only data transmission over a longe range is needed, but also a long battery life to simplify installation and reduce operational cost. LoRa is a wireless communication protocol often used in IoT applications [1]. With its relatively long range and low power requirements LoRa is suitable for many IoT applications, including our Data-Logger. While some measurement results for LoRa in buildings and outdoor is available, not much information regarding the use of LoRa in tunnels is published. In order to investigate whether LoRa is suitable for our sensor network in tunnels, measurements with LoRa in a 2400 m tunnel where made. Especially the maximum range of the data transmission is of interest, since it determines the number of required LoRa Gateways. LoRa Gateways are a major cost factor for any LoRaWAN application which uses a separate private LoRaWAN network. We therefore carried out measurements with different location of the Data-Logger and Gateway in a tunnel.

This article presents the results of those measurement, and compares them with other measurement results from literature. Additionally our method used for the measurement is described, which is helpful to reproduce similar measurement in other locations. Such a extensive description of the measurement method is missing in many of the other publications.

2. Related Work

Different authors already made measurements in prior work with LoRa in real world environments (buildings, cities, etc.) [2–11]. They all used the RSSI and Rx SNR values of the LoRa transceiver. For the specific deployment in tunnels, only very slightly similar measurements are publicly available. Because of this lack of public measurement results, we focused our measurements on LoRa in tunnels.

In the article by Branch [12] LoRa measurements were done in a underground gold mine. The author also recognized the missing availability of data for LoRa transmission underground. The usable measurement length of the corridors in the gold mine was limited to 240 m, the width of the tunnel was 5 m, and the height 4 m. They used different SF (SF7, SF9, and SF12), with the RSSI and SNR values of the LoRa transceiver. In the tunnel middle with SF12 they measured an attenuation of $\approx$ 8 dB/100 m. At the tunnel wall a higher attenuation was measured. Additional measurements around a corner were done, showing a higher attenuation without line of sight.

Zhou et al. [13] have done more general measurements of tunnels and mines. The measurements where made at different frequencies. While not using LoRa itself, the results from the measurements at 915 MHz can still be applied to LoRa, because they have a relatively similar wavelength. A waveguide like behaviour could be reproduced for different frequencies. The measured attenuation was lower if the tunnel had a bigger diameter (closer to free space), and the wall finish was smoother. The polarization of the antenna can also have an influence. In a high tunnel (height > width) a vertical polarization had lower attenuation. For a wide tunnel (height < width) a horizontal polarization had lower attenuation. For a square tunnel (height $\approx$ width) the polarization does not matter.

Dudley et al. [14] measured a concrete railway tunnel, but where also not using LoRa. The tunnel was rounded with a flat floor, a width of 8.6 m, and a height of 7.9 m. The tunnel was straight and 3.5 km long. For 900 MHz an attenuation of 8.5 dB/km could be measured with a horizontal polarization antenna. The waveguide like behaviour for higher frequencies was also observed.

3. Materials and Methods

In this section the components of the measurement and the measurement location are described.

3.1. Hardware Overview

The central component of the Data-Logger was a low power STM32 microcontroller. The board can either be powered from a battery or from a USB connection which was also used as a serial console. As a LoRa Module the RFM95W [15] from HOPERF was used. The RFM95W is based on the Semtech SX1276 LoRa transceiver, with an external antenna. For the LoRaWAN software stack the LoRaMac-node V4.7.0 [16] was used. The Data-Logger was working as a LoRaWAN Class A device, the most energy efficient Class of LoRaWAN devices.

For the LoRa Gateway a MultiTech Conduit [17] (Firmware version 6.0.4), with a MTAC-LORA-H-868 LoRa transceiver module is used. The Conduit combines a LoRa Gateway, a LoRaWAN Server, and an end application server.

For the measurements simple omni directional dipole antennas (Pulse W1063RP [18]) with $\approx$ 1 dBi of gain and a vertical polarization were used on the Data-Logger and Gateway. Both, Data-Logger and Gateway, can reach the maximum allowed transmission power of 16dBm EIRP for the LoRaWAN EU868 region [19]. Therefore, when an antenna with a high gain is added, the transmit power needs to be reduced and the antenna gain would only provide a benefit on the receiver side.

Each device was mounted on a camera tripod in a height of $\approx$ 1.7 m. Figure 1 and 2 show the Data-Logger and the LoRa Gateway with a battery placed on the floor, respectively.

Figure 1. Data-Logger on the tripod.

Figure 2. LoRa Gateway on the tripod, with the battery placed on the floor.

3.2. Measurement Sequence

In order to collect the data in a real world environment the measurement where made with the actual used hardware, and not with dedicated measurement devices. Furthermore the results in both direction, from Gateway to Data-Logger and from Data-Logger to Gateway, are important to account for the different hardware used as the Data-Logger and Gateway. For our operation it is mandatory that the devices comply to the LoRaWAN standard for the EU868 region (LoRaWAN L2 1.0.4 Specification [20], and 1.0.3 LoRaWAN Regional Parameters [19]). Therefore, all settings were made in compliance with the EU868 region. The general setup for the measurement is shown in Figure 3.

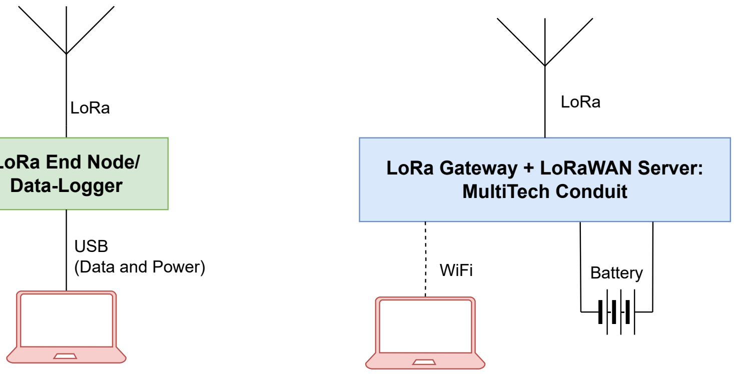

Figure 3. Measurement setup with the Data-Logger and LoRa Gateway.

Because the Data-Logger is a LoRaWAN Class A device, for every measurement point the measurement sequence was the following:

1. On the LoRa Gateway all responds packets to the Data-Logger are queued in the Gateway transmit queue. This queuing was needed to ensure that the send timing of the downlink packet is correct for a LoRaWAN Class A Device. The number of queued packets is depending on how many packets should be measured. The content of the packet was randomly generated.
2. The notebook controlling the Data-Logger generates a random packet and sends it over USB to the Data-Logger.
3. The Data-Logger sends the packet to the LoRa Gateway. The notebook connected saves the transmission details.

4. The packet is received on the LoRa Gateway. The notebook connected saves the reception details.
5. In the receive window 1 or 2 the LoRa Gateway sends one of the queued uplink packets back to the Data-Logger. The notebook connected saves the transmission details.
6. The packet is received on the Data-Logger. The notebook connected saves the reception details.
7. Step 2 to 6 are repeated for every packet sent for this measurement point.

This sequence allowed to measure both uplink and downlink in the same measurement, except when a packet is not received by the LoRa Gateway. If the LoRa Gateway does not receive a packet, the Gateway can not start the timer to send the downlink packet in receive window 1 or 2, and step 4 to 6 are skipped. After a timeout the measurement will then continue at step 2. If a packet is not receive by the Data-Logger only step 6 is skipped.

3.3. Measurement Values and Settings

RSSI, Rx SNR, and PER are the most impotent values to determine the quality of a LoRa link. Because of this RSSI and Rx SNR can be obtained easily from the LoRa transceivers and are mainly used in this article. As seen in Chapter 2 most other authors also use the RSSI and Rx SNR of the LoRa transceiver.

For the measurement DR0 (SF12 and bandwidth 125 kHz) in the LoRaWAN EU868 region was used. DR0 has the lowest bit rate with the longest range, and is therefore the best option to detriment the maximum range of LoRa in a tunnel. A DR is a combination of the LoRa Spreading Factor (SF) and the used frequency bandwidth. In the EU868 region DR0 to DR11 are standardised. The SF is a parameter of the LoRa modulation, bigger SF will cause a smaller bitrate and a higher transmission distance [19,21]. Using a constant DR also reduced the number of different parameters that need to be measured. This was important because the time available for measurements in the tunnel was limited.

In order to achieve the maximum distance, the transmit power was fixed to the maximum allowed value of 16 dBm EIRP [19] including the 1 dBi gain of the transmit antenna. ADR was turned off. If ADR had been activated, the transmission power and DR could change dynamically during the measurement, which could lead to a case where the maximum distance can not be determined reliably. Only the three mandatory channels for EU868 were used at 868.1 MHz, 868.3 MHz, and 868.5 MHz. This limited number of channels again reduce the number of variables which had to be tested. All packets were sent as as unconfirmed transmissions. Confirmed LoRaWAN transmissions are not suitable to measure PER, because a packets with a error would simply be send multiple times until a successful transmission occurred.

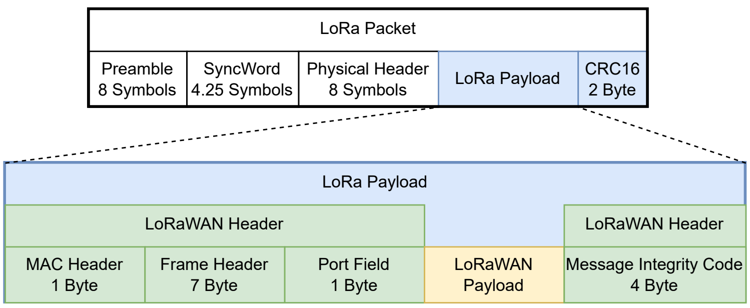

Figure 4. Overview of the headers and payload for a LoRaWAN packet.

To test a worst-case scenario (longest transmission time, therefore more time for an error to occur) all packets were sent with a random 50 Byte payload. The maximum packet size is limited by the implementation of the LoRa transceiver, and the regulatory requirements [19]. Additional error checking for the content was not needed. LoRaWAN uses a CRC16 checksum, plus an integrity check by the MIC, provided by the used AES128-CCM* (Note: the asterisk * is part of the name) encryption. Both, checksum and MIC, are shown in Figure 4. Packets with an error in the checksum or an error in the MIC are automatically dropped by the LoRa Gateway or the Data-Logger. Packets not received or packets received with an error are handled the same way, and are counted the same for the measurement.

As mention before, beside RSSI and SNR measurement of the PER would be interesting to determine the reliability of a connection. At least ten packet errors should be observed to get a meaningful PER. In the following the minimum measurement time to achieve ten errors is calculated. For this first the transmission time for one LoRa packet was calculated. From the transmission time of one LoRa packet, the round trip time to send a packet from the Data-Logger to the Gateway and back can be calculated. The minimum measurement time is important, because the time in which the tunnel was accessible for the measurements was limited. The used LoRa transceiver on the Data-Logger is specified to have a PER of <1 % [15]. Assuming we have a 1 % PER we need to send at least $10\,\text{ErrorPackets}/1\,\% = 1000\,\text{Packets}$ to get ten errors. The calculation of the transmission time of a single LoRa packet is specifies in the Semtech "LoRa Modem Designer's Guide" [21]. The time on air for one single LoRa symbol t_{sym} is given by equation 1 [21].

$$t_{\text{sym}} = \frac{2^{SF}}{f_{\text{BW}}} \tag{1}$$

with:
- t_{sym} : Transmission time for one symbol (s).
- SF : Spreading Factor of the DR.
- f_{BW} : Bandwidth of the DR (Hz).

For DR0 in EU868 the t_{sym} is 32.768 ms. The number of needed LoRa symbols for a specific payload can be calculated according to equation 2 [21].

$$n_{\text{payloadSymbol}} = \max\left(\left\lceil \frac{8 \cdot PL - 4 \cdot SF + 44 - 20 \cdot H}{4 \cdot (SF - 2 \cdot DE)} \right\rceil \cdot CR, 0\right) \tag{2}$$

with:
- $n_{\text{payloadSymbol}}$: Number of LoRa payload symbols, including symbols for the CRC16 checksum, in blue in Figure 4.
- PL : Payload size (Byte).
- H : $H = 0$ if the physical header is enabled, $H = 1$ if the physical header is disabled. LoRaWAN uses the physical header [19].
- DE : $DE = 1$ when the low data rate optimization is enabled, $DE = 0$ if the low data rate optimization is disabled. Low data rate optimization is enabled for $f_{\text{BW}} = 125\,\text{kHz}$, and SF ≥ 11 [21].
- CR : Coding Rate of LoRa used for the forward error correction. The coding rate is the denominator of the ratio of payload symbols to code symbols. LoRa supports ratios of $\frac{4}{5}$, $\frac{4}{6}$, $\frac{4}{7}$, and $\frac{4}{8}$ [21]. LoRaWAN uses coding rate 5 for the payload, and a coding rate 8 for the physical header [19].

In addition to the 50 Byte random payload (yellow in Figure 4) used as test data, LoRaWAN requires at least 13 Byte [20] of headers (green in Figure 4), for a total payload size of $PL = 63$ Byte. The number of payload symbols for the transmission of a packet with 63 Byte payload at DR0 in EU868 is $n_{\text{payloadSymbol}} = 65$ Symbols. The transmission time for one LoRa packet is then given by Equation 3 [21]. The different parts of the LoRa packet are shown in Figure 4 in white.

$$t_{\text{OnAir}} = t_{\text{sym}} \cdot (n_{\text{preamble}} + n_{\text{syncWord}} + n_{\text{physicalHeader}} + n_{\text{payloadSymbol}}) \tag{3}$$

with:
- t_{OnAir} : Transmission time of one LoRa packet (s).
- n_{preamble} : Number of preamble symbols. For LoRaWAN this is fixed to 8 symbols [19].
- n_{syncWord} : Number of synchronization symbols. For LoRaWAN this is fixed to 4.25 symbols [19].
- $n_{\text{physicalHeader}}$: Number of symbols for the physical header. For LoRaWAN this is fixed to 8 symbols [19].

The transmission time for this 65 Symbols is $t_{\mathrm{OnAir}} \approx 2.8\,\mathrm{s}$. Equation 4 calculates the transmission time for one packet from Data-Logger to Gateway and back, assuming the packet from the Gateway back to the Data-Logger is send in the LoRaWAN receive window 2. Rounding the result up to give some margin, the transmission needs $t_r \approx 8\,\mathrm{s}$.

$$t_r = t_{\mathrm{OnAirGateway}} + t_{w2} + t_{\mathrm{OnAirDataLogger}} = 2.8\,\mathrm{s} + 2\,\mathrm{s} + 2.8\,\mathrm{s} = 7.6\,\mathrm{s} \quad (4)$$

with:

t_r : Transmission round trip time (s).
$t_{\mathrm{OnAirGateway}}$: Transmission time Data-Logger to Gateway (s).
t_{w2} : Delay for receive window 2 (s), 2 s is the LoRaWAN default value [19].
$t_{\mathrm{OnAirDataLogger}}$: Transmission time Gateway to Data-Logger (s).

The minimum measurement time to get ten error packets with 8 s per transmission is then $1000\,\mathrm{Packets} \cdot 8\,\mathrm{s/Packet} = 8000\,\mathrm{s} \approx 2.22\,\mathrm{h}$. 2.22 h per measurement point is relatively long. Especially when multiple points should be measured, and the available measurement time on the test location is very limited. Therefore the decision was made to prioritize more test points over the collection of enough packets for a meaningful PER. Per Data-Logger or Gateway position 10 packets were sent (uplink and downlink). This still allows to collect a rough estimation of the PER for one position (is it only barely working or at least stable for 10 packets). While the time for one measurement position is still relatively short with only 80 s.

3.4. Measurement location

The measurement was made in an old railway tunnel in Switzerland with a usable length for the measurement of 2400 m. Because the tunnel is only used as a service and emergency exit, no active traffic was in the tunnel during measurement. The tunnel is 8 m wide, 6 m high, has a rounded ceiling, and no significant curvature. Figure 5 and Figure 7 show the walls and ceiling of the tunnel, which are a combination of natural stones and sprayed concrete, the floor was tarred. When the tunnel was originally built, every 50 m on both sides a personal protection niches (Figure 9) was added. Some of the niches were filled up during renovation. The niches had a height of $2-3\,\mathrm{m}$, a width of 2 m, and a depth of $1.5-3\,\mathrm{m}$. Additionally, five large diagonal transverse (Figure 10) are available every $330-490\,\mathrm{m}$. The diagonal transverse had a width of 5 m and a height of 4 m.

For the measurements the Gateway was placed inside the tunnel at the portal, see Figure 6. Every 100 m a measurement was made with the Data-Logger in the centre of the tunnel (Figure 7), on the right and left wall (Figure 8), and if still available in the left and right personal protection niches (Figure 9). Additional measurements where made in the diagonal connections (Figure 10).

Figure 5. View inside the tunnel. On the wall the natural stones are shown, the tunnel ceiling is covered in sprayed concrete, and the floor is tarred.

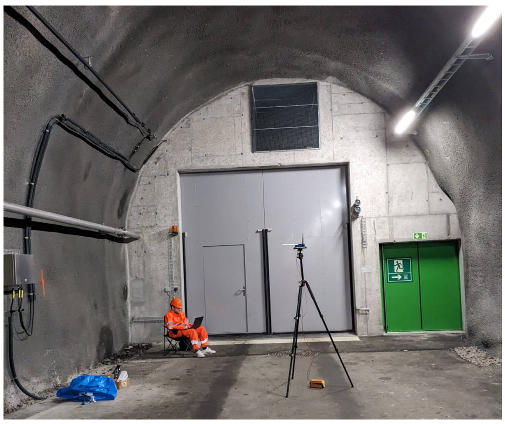

Figure 6. The LoRa Gateway during measurement inside the tunnel at the tunnel portal.

Figure 7. Data-Logger during measurement in the middle of the tunnel. The tunnel walls and ceiling are covered in sprayed concrete

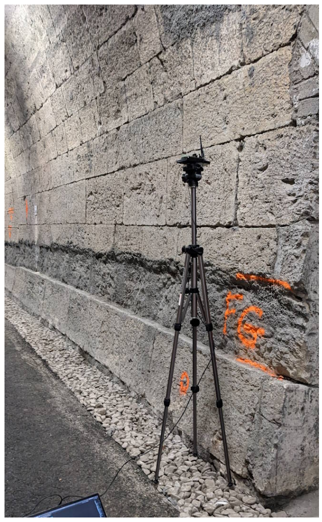

Figure 8. Data-Logger during measurement at the tunnel wall. The natural stone walls is shown.

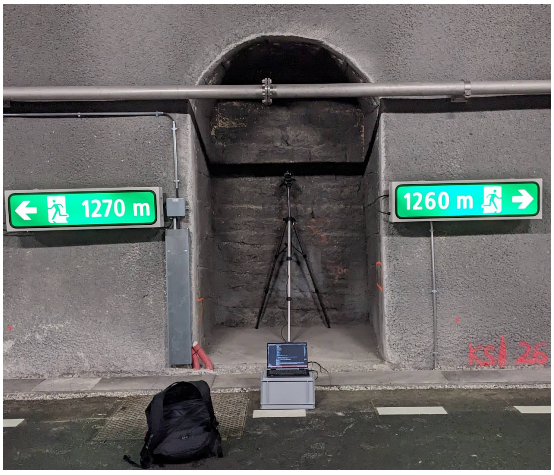

Figure 9. Data-Logger during measurement in a niche at the halfway point of the tunnel.

Figure 10. Data-Logger during measurement at the entrance of one of the five large diagonal transverse.

4. Results

In this chapter the results of the different measurements are presented. Figure 11 to 14 show a schematic top view of the tunnel. The black dot on the left represents the LoRa Gateway at the tunnel portal. The positions of the Data-Logger is show by the other dots, where the colour of the dots represents the median value of the RSSI or Rx SNR for the different positions inside the tunnel. The median value was chosen since it is more robust against outliers than the mean value. Figure 11 shows the RSSI and Figure 12 Rx SNR of the Gateway, while Figure 13 shows the RSSI and Figure 14 the Rx SNR of the Data-Logger.

From the ten packets sent for every measurement point, nine or more packets where received for most location. Only for the measurement points in the middle and at the end of the large diagonal traverses at 1210 m, 1700 m, and 2160 m a clear increase in packet loss was observed. In some cases two or less packets where received. This corresponds to the reduction of the SNR values, as shown in Figure 12 and 14 for the same positions. With a lower SNR receiving of packets gets more error prone and therefore a increase in PER is expected.

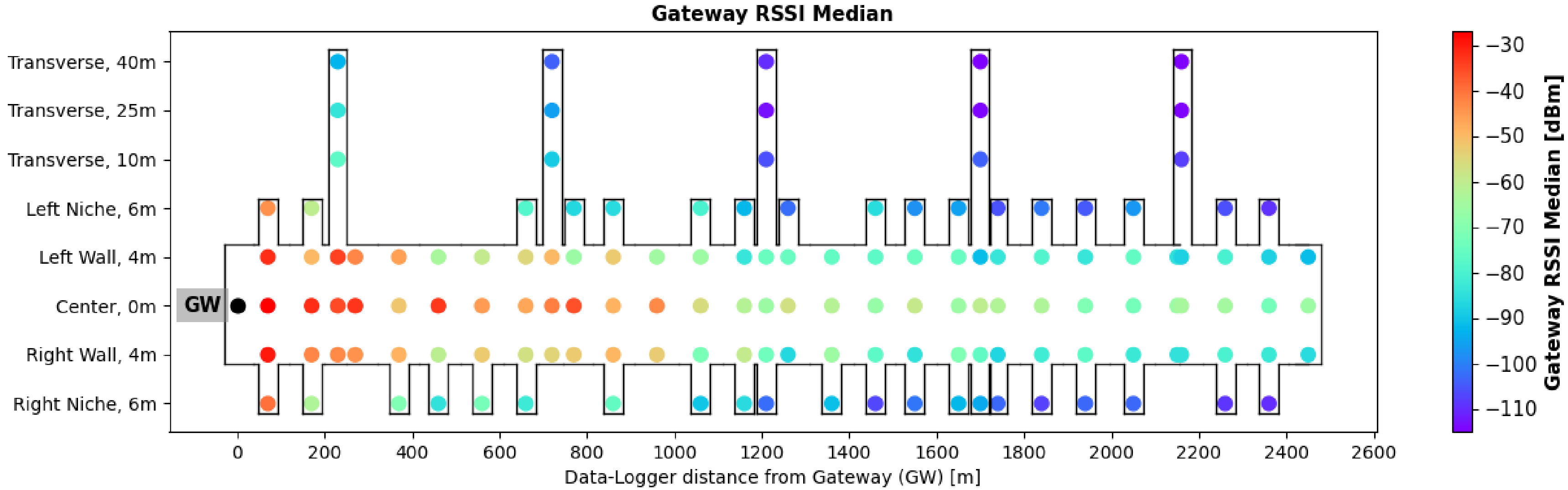

Figure 11. Schematic top view of measurement results in the old railway tunnel. The colours of the points represent the **Gateway median RSSI** value, if the Data-Logger was placed at this point. The Gateway itself was placed in the centre of the tunnel portal (black dot).

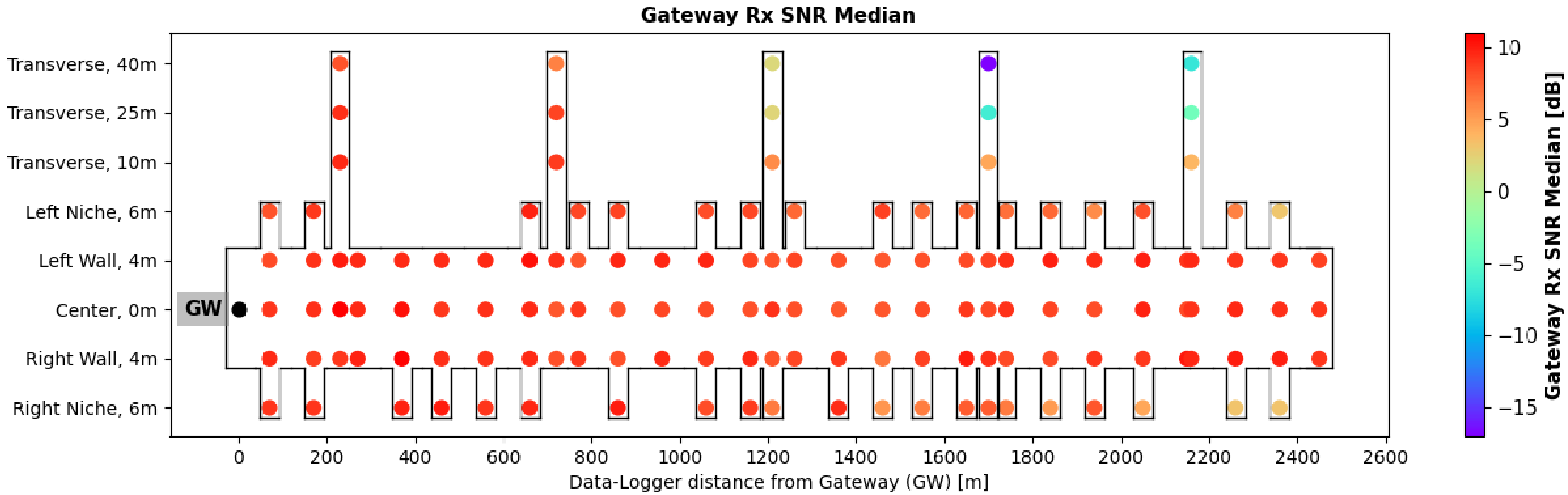

Figure 12. Schematic top view of measurement results in the old railway tunnel. The colours of the points represent the **Gateway median Rx SNR** value, if the Data-Logger was placed at this point. The Gateway itself was placed in the centre of the tunnel portal (black dot).

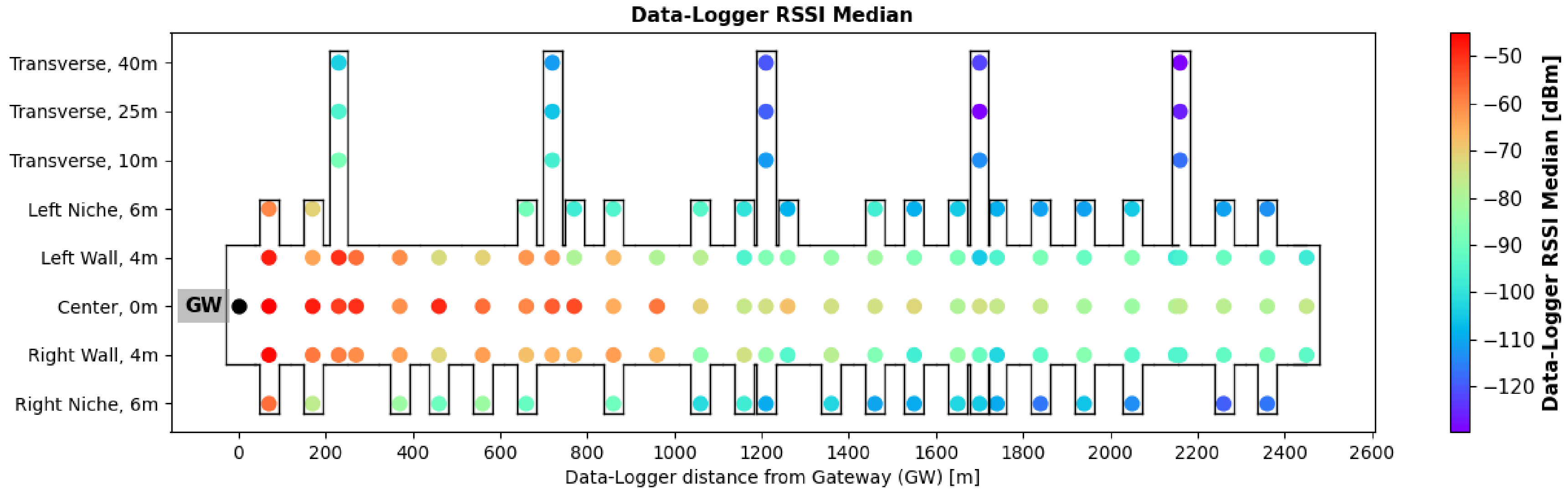

Figure 13. Schematic top view of measurement results in the old railway tunnel. The colours of the points represent the **Data-Logger median RSSI** value, if the Data-Logger was placed at this point. The Gateway was placed in the centre of the tunnel portal (black dot).

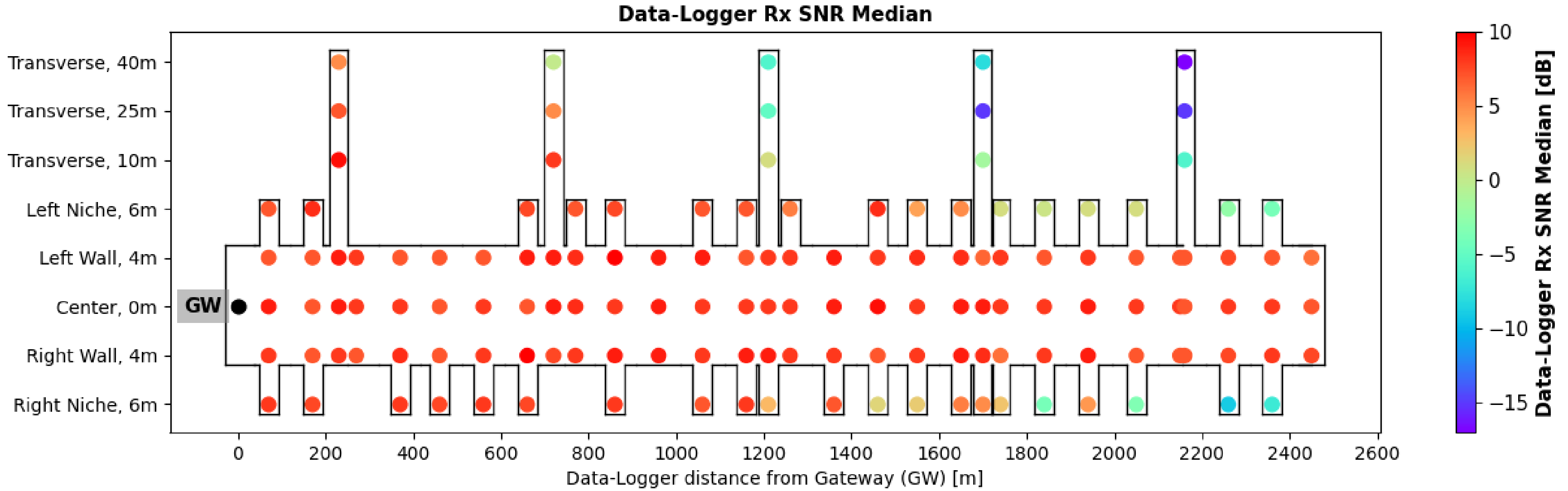

Figure 14. Schematic top view of measurement results in the old railway tunnel. The colours of the points represent the **Data-Logger median Rx SNR** value, if the Data-Logger was placed at this point. The Gateway was placed in the centre of the tunnel portal (black dot).

In all results, for the same position the RSSI of the Data-Logger is lower then the RSSI of the Gateway. This is caused by communication link not being symmetrical. While the transmit power is the same (16 dBm EIRP), and the same type of antenna is used, the hardware implementation is different between the Data-Logger and the Gateway. They use different LoRa transceiver, different analog front-ends, and different oscillators.

4.1. Data-Logger position in tunnel

The graphs in Figure 15 show the change of the RSSI value over the tunnel length. The solid points show the median RSSI strength. The small dashes above and below the points show the minimal and maximal RSSI of each measurement point. The area between the small dashes is lightly coloured for better visibility. Values measured by the Data-Logger are blue, values from the Gateway are orange. The Gateway was placed inside the tunnel at the portal, in the middle of the tunnel cross-section. In every graph (a-e) in Figure 15 the values for the same location of the Data-Logger in the tunnel cross-section are grouped. The violet and brown lines show a fit to the median RSSI values. They were obtained using the Theil-Sen-Estimator. The Theil-Sen-Estimator is a method for fitting a line to points, which is robust against outliers. For this the Theil-Sen-Estimator determinants the median of the slopes of all lines that can be drawn through any two data points, calculated according to equation 5 [22]. The credibility interval was calculated with bootstrapping [23] at 2000 samples.

$$m_{TS}(x,y) = \underset{\substack{k,l \in \{1,\ldots,n\} \\ x_k \neq k_l}}{\text{median}} \left(\frac{y_l - y_k}{x_l - x_k} \right) \tag{5}$$

From the fit with the Theil-Sen-Estimator presented in Figure 15, the attenuation for different positions in the cross-section are derived and are show in Figure 16. Figure 16 a) shows attenuation per km and the graph in Figure 16 b) shows the initial attenuation calculated at the tunnel portal (0m distance from Gateway) for a Tx power of 16dBm EIRP. If both (Gateway and Data-Logger) were placed in the centre of the tunnel, after an initial attenuation of ≈ 66 dB for the Data-Logger and ≈ 49 dB for the Gateway, the attenuation was ≈ 14 dB/km for the RSSI of the Data-Logger, and ≈ 17 dB/km for the RSSI of the Gateway. This results are also summarised in Table 1.

Placing the Data-Logger on the wall increasers the attenuation by $3 - 4$ dB/km compared to the center position. Additionally the initial attenuation is $6 - 12$ dB higher. Placing the Data-Logger in a niche increases the attenuation by $2 - 5$ dB/km, and the initial attenuation by $26 - 32$ dB compared to the center position. The increase in attenuation is summarised in Table 2. This shows that the attenuation caused by the distance is almost constant, independently of the Data-Logger position in the cross-section of the tunnel. But a placement not in the center will add a almost constant amount of attenuation, which is not distance dependent.

Table 1. Summery of the initial attenuation and the attenuation per km for different positions in the cross-section of the tunnel.

	Data-Logger	**Gateway**
Left niche initial attenuation	94 dB	81 dB
Left wall initial attenuation	74 dB	60 dB
Center initial attenuation	66 dB	49 dB
Right wall initial attenuation	72 dB	57 dB
Right niche initial attenuation	92 dB	78 dB
Left niche attenuation	16 dB/km	19 dB/km
Left wall attenuation	18 dB/km	20 dB/km
Center attenuation	14 dB/km	17 dB/km
Right wall attenuation	18 dB/km	20 dB/km
Right niche attenuation	19 dB/km	21 dB/km

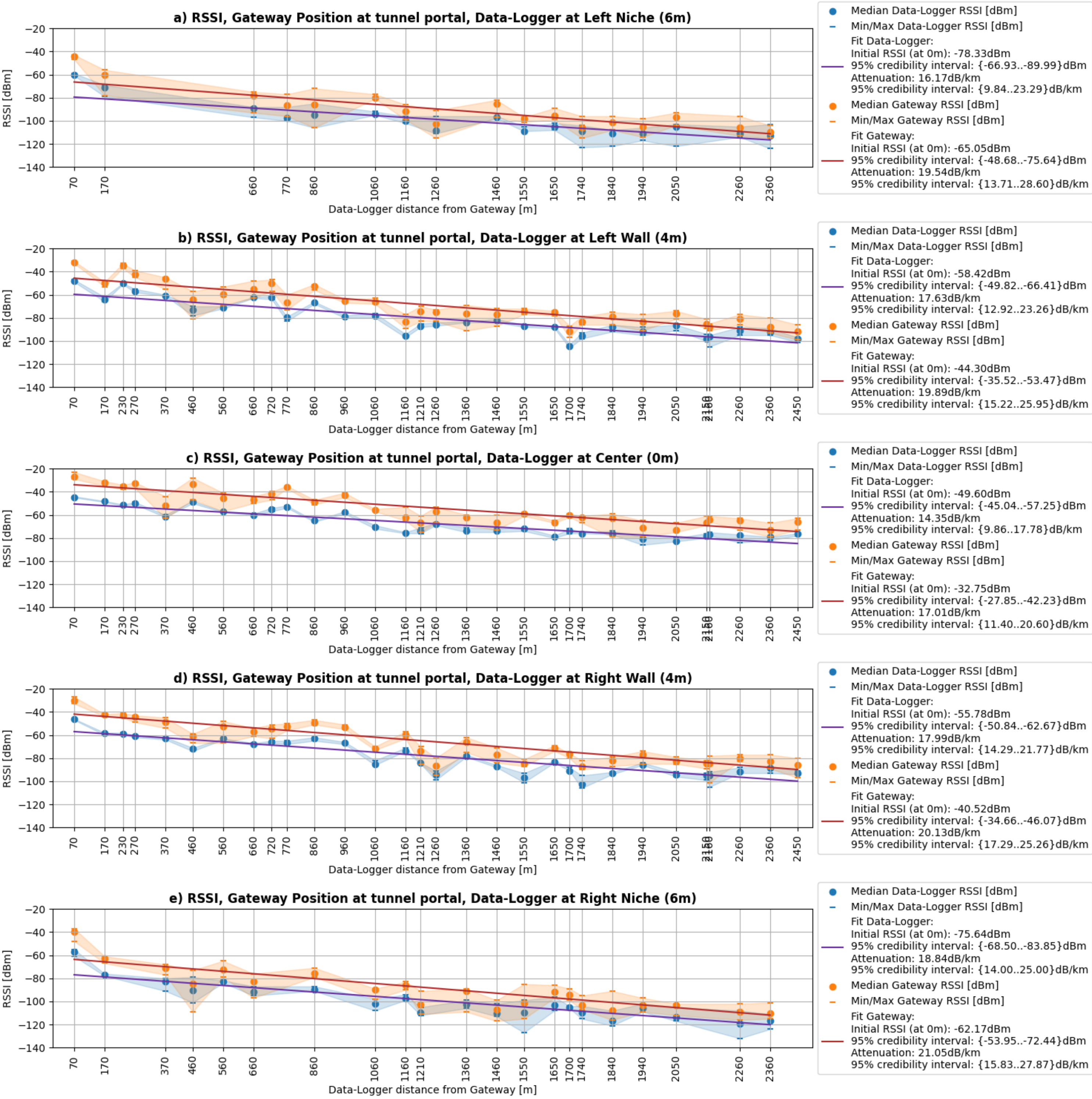

Figure 15. The graphs shows the RSSI value over the tunnel length. In every graph the values from the same point of the tunnel cross-section are grouped. The lines show a fit of the values in the graph. They where obtained using the Theil-Sen-Estimator. The credibility interval was calculated with Bootstrapping at 2000 samples.

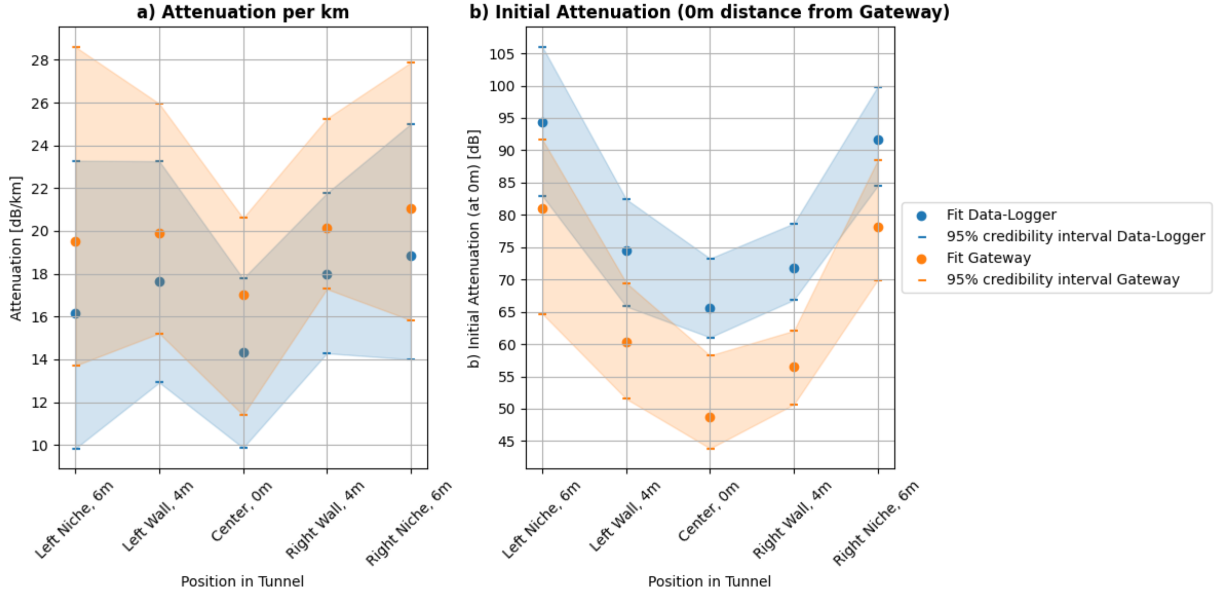

Figure 16. The graph a) shows the result of the fit from Figure 15, for the attenuation per km for different positions in the cross-section of the tunnel. The graph b) shows the initial attenuation calculated at the tunnel portal (0 m distance from Gateway) with the used Tx power of 16 dBm EIRP, for the different positions in the cross-section of the tunnel.

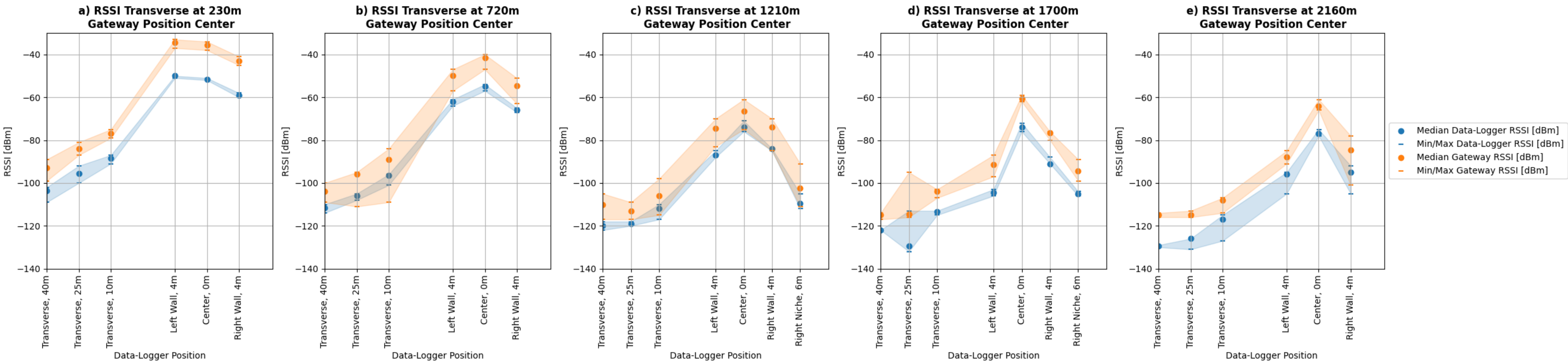

Figure 17. RSSI value of the Data-Logger and Gateway for the cross-section of the tunnel with the Data-Logger place in the five diagonal transverses.

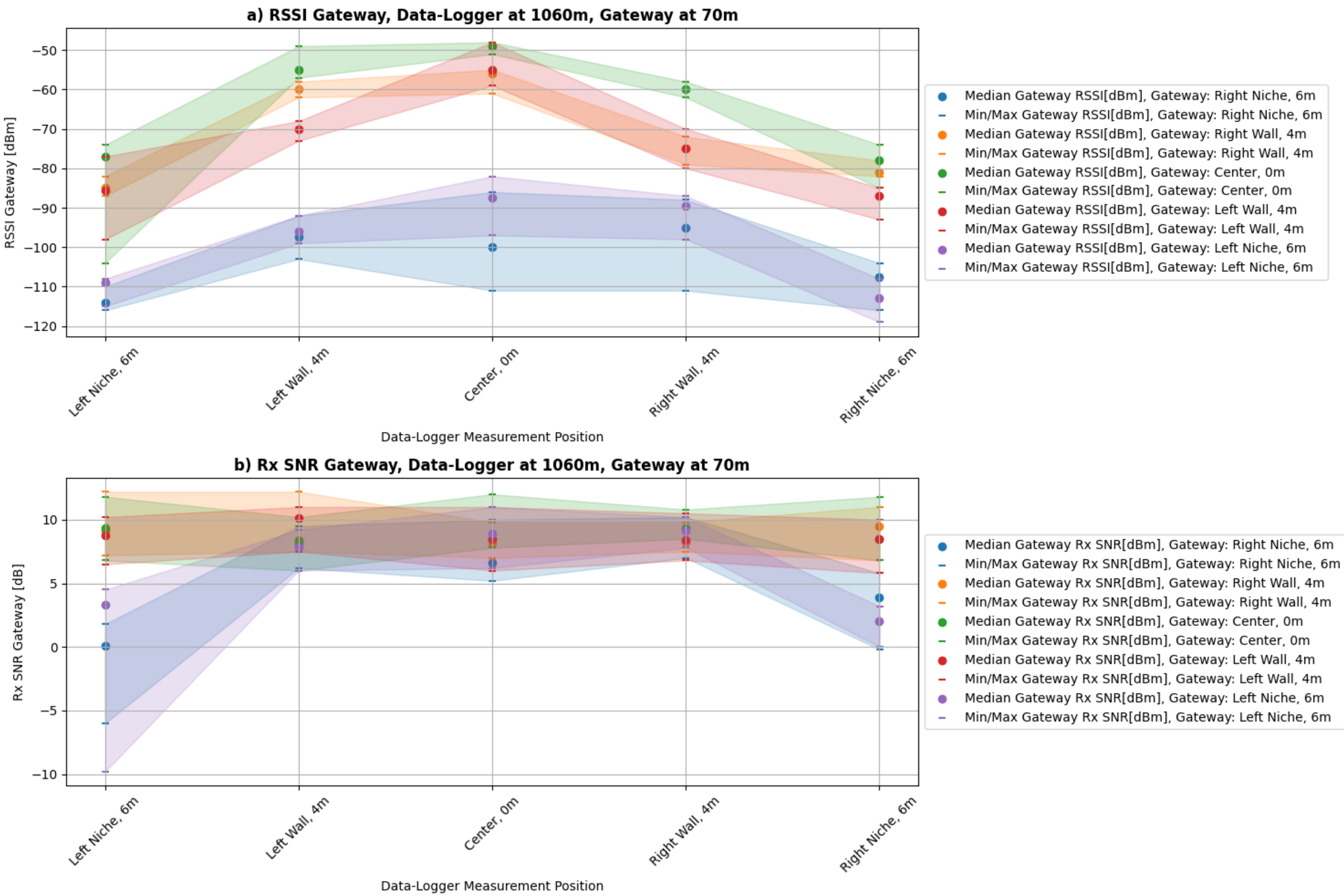

Figure 18. Cross-section showing the influence of the Gateway position. Then measurements were made with the Data-Logger placed at the different positions in 1 km distance of the Gateway. The shown values are the RSSI and Rx SNR of the **Gateway**.

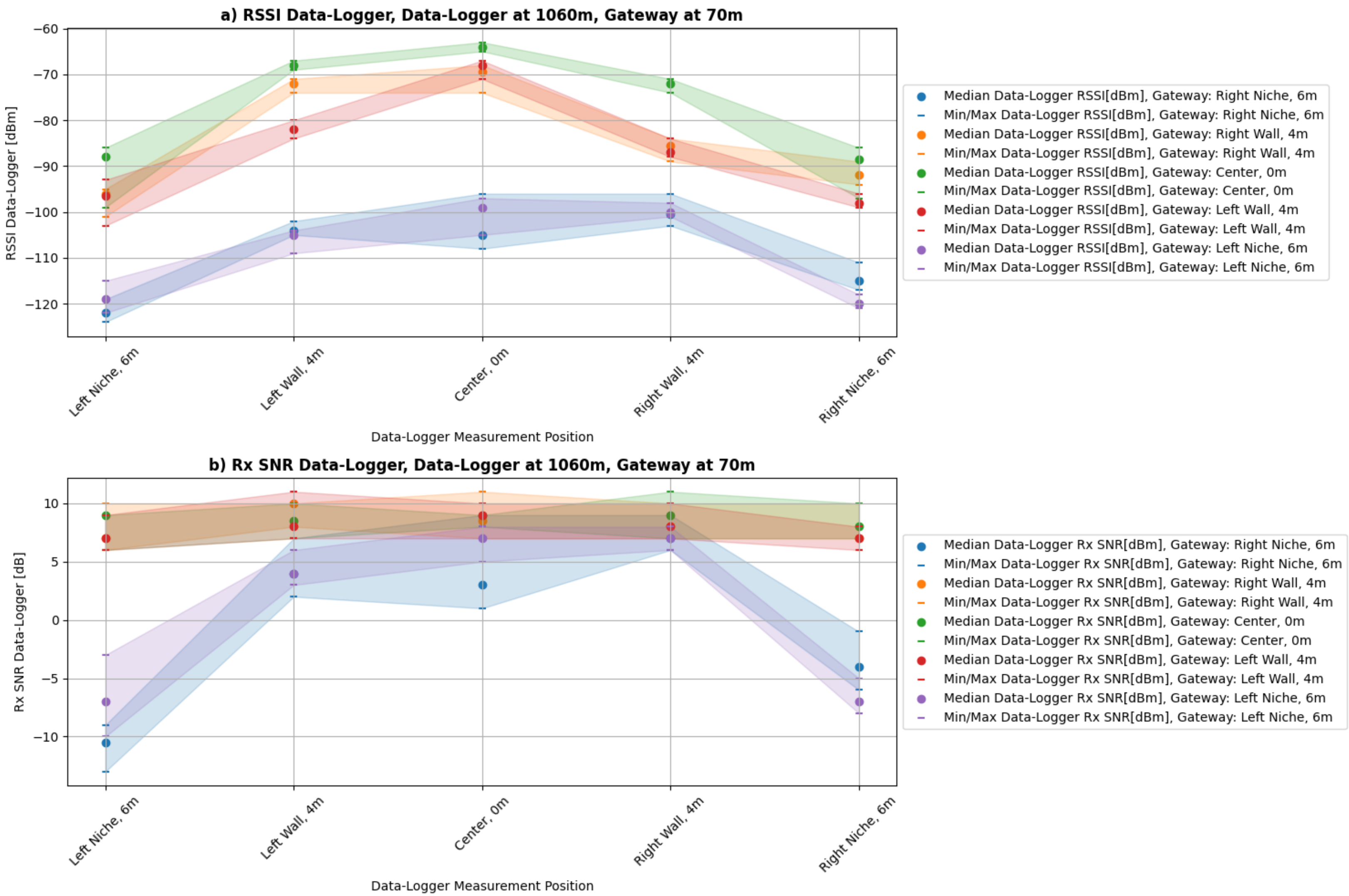

Figure 19. Cross-section showing the influence of the Gateway position. Then measurements were made with the Data-Logger placed at the different positions in 1 km distance of the Gateway. The shown values are the RSSI and Rx SNR of the **Data-Logger**.

4.2. Diagonal transverses

Figure 17 shows the RSSI values measured with the Data-Logger placed in different position in one of the five diagonal transverses. The Gateway was placed inside the tunnel at the portal (same place as in Figure 11). The points show the median RSSI value, while small dashes above and below the points show the minimal and maximal RSSI for this measurement point. Values measured by the Data-Logger are blue, values from the Gateway are orange.

These results show that the transmission around a corner into a diagonal transverse leads to a clear drop of $30 - 40$ dB in RSSI. This behavioured is more pronounced in the transverses closer to the Gateway. At the end of transverses further away from the Gateway the packet loss starts to increase. The packet loss corresponds to the reduction of the Rx SNR values (Figure 12 and 14) for the same positions.

4.3. Changed gateway position

To investigate the influence of the gateway position, the Gateway was brought 70 m inside the tunnel where the first niches where available. Then measurements where made with the Data-Logger placed at the different positions in 1 km distance. The results from this measurements are shown in Figure 18 and 19. The different coloured lines show the Rx SNR and RSSI values for different positions of the Gateway in the tunnel cross-sections, depending on the placement of the Data-Logger in the tunnel cross-sections. For this, Figure 18 a) shows the RSSI value of the Gateway and Figure 18 b) Rx SNR value of the Gateway. Figure 19 a) shows the RSSI value of the Data-Logger and in Figure 19 b) the Rx SNR value of the Data-Logger.

The results from Figure 18 and 19 show a clear increase in attenuation for placing the Gateway on the wall or in a niche. At 1 km measuring distance, and placing the Gateway at the wall caused $5 - 15$ dB of additional attenuation. Placing the Gateway in a niche caused additional $34 - 50$ dB of attenuation. This values are in the same range as the attenuation in Figure 16, cause by placing the Data-Lagger on the wall or in the niche. The increase in attenuation is also summarised in Table 2.

Table 2. Summery of the attenuation increase obtained by the evaluation of the result from the different measurements in the tunnel.

	Value
Initial attenuation increase center to wall	$6 - 12$ dB
Initial attenuation increase center to niche	$26 - 32$ dB
Attenuation increase center to wall	$3 - 4$ dB/km
Attenuation increase center to niche	$2 - 5$ dB/km
Attenuation increase into diagonal transverse	$30 - 40$ dB
Attenuation increase for Gateway position center to wall	$5 - 15$ dB
Attenuation increase for Gateway position center to niche	$34 - 50$ dB

5. Discussion

Our measurement results showed that a reliable LoRa communication was possible for the complete tunnel having a length of 2400 m. Therefore it was not possible to measure the maximum range of LoRa in the old railway tunnel. The only exception to the reliable LoRa communication was found at the end of the traverses. If a even longer tunnel should be covered, positioning the LoRa Gateway on the halfway point of the tunnel, and not at the portal, could additionally increases the achievable transmission distance. This position at the halfway point brings the potential new challenge of providing the uplink for the data from the LoRa Gateway to a central server. At the tunnel portal such a uplink is in many cases more easily available (e.g. availability of a cellular network).

The attenuation of ≈ 14 dB/km for the Data-Logger and ≈ 17 dB/km for the Gateway obtained with the measurements are in good agreement with the values measured in the related work. Comparing this with the values from Zhou et al. [13], the tunnel measurements in this article has a much lower attenuation. This is mainly because the measurements by Zhou et al. [13] were done in mines, which had a smaller cross-section and a much rougher wall surface. The same is also true for the goldmine measured by Branch [12]. The tunnel in which measurement by Dudley et al. [14] were made had a bigger cross-section than the old railway tunnel and had a smoother wall surface. Therefore the attenuation of 8.5 dB/km is lower than the one measured for the tunnel in this article. While no measurement in tunnels with different sized cross-section where done in this article, the results obtained do support the general rule of a lower attenuation if the tunnel has a bigger diameter (closer to free space), and lower attenuation if the tunnel has smoother surfaces.

A position without line of sight between Gateway and the Data-Logger in one of the five traverses caused a quick degradation of the Rx SNR and RSSI, leading to an increased packet loss. This was also shown by Branch [12], and therefore mounting of the device without line of sight should be avoided for real deployments.

The positioning of the Gateway or Data-Logger in the cross-section of the tunnel is an additional challenging aspect. Figure 16 shows that the attenuation caused by the distance is almost constant, independently of the Data-Logger position in the cross-section of the tunnel. But a placement not in the center will add significant amount of attenuation to the signal. The same is also the case for placing the Gateway not in the center, as shown in Figure 18 and 19. Hence for the best performance, the Gateway and Data-Logger should be placed in the center of the tunnel. But this space is usually used by trains, cars, etc. and can not be used to place Data-Loggers or Gateways. Therefore a compromise between a good performance and feasible mounting position must be found for a real world deployment. All tests in the tunnel were also made without traffic in the tunnel. Additional traffic will for sure increase the attenuation in the tunnel.

6. Conclusions

In this article we showed measurement of LoRa in a tunnel and the suitability of LoRa for the use in tunnels. In an empty tunnel at least 2400 m can be covered with one LoRaWAN Gateway placed at the tunnel portal. This allows the deployment of the Data-Logger in tunnels while still only one LoRaWAN Gateway is needed and therefore reducing cost. Mounting of the Gateway or Data-Logger inside the wall or in a niche without direct line of sight to the other device should be avoided. These results give us confidence for future projects where our Data-Logger is deployed inside tunnels for corrosion monitoring.

The test in the tunnel were carried out when the tunnel was not in active use. Therefore some uncertainty regarding the influence of traffic exists, and could be studied in future measurements. Also, future measurements with a smaller distance (< 100 m) between the measurement locations, in a different tunnels, or with more packets for a better PER measurement could be of interest. Additional measurements regarding the polarization effects, especially close to the wall or in a niche, could also be done.

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Abbreviations

The following abbreviations are used in this manuscript:

ADR	Adaptive Data Rate
AES	Advanced Encryption Standard
CCM	Counter with Cipher block chaining Message authentication code
CRC	Cyclic Redundancy Check
DR	Data Rate
EIRP	Equivalent Isotropically Radiated Power
EU868	LoRaWAN Region Europe, in the 868MHz Band
IoT	Internet of Things
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
MIC	Message Integrity Code
PER	Packet Error Rate
RSSI	Received Signal Strength Indication
Rx	Receive
SBB	Schweizerische Bundesbahnen
SF	Spreading Factor
SNR	Signal to Noise Ratio
Tx	Transmit
USB	Universal Serial Bus

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