Wi-Fi installation in difficult environments

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Wi-Fi (more precisely the 802.11 radio standard) is proven, well-known, and deployed more and more. However, as access point density increases and the radio environment can be hostile, it can suffer from quite some problems related to the physical channel.

E.g. high-bay ware houses and mining tunnels can be quite difficult environments, but solutions exist. This paper looks at a way to optimize the physical channel for better performance in industrial environments. And it discovers a surprising cost synergy with other radio systems.

Challenging radio environments

In this chapter a number of challenging application aspects are looked at, that typically occur in industrial environments. The focus is on Wi-Fi 5 GHz, since most new installations look at this less crowded band. At the same time the 5 GHz band is also more challenging from a RF point of view.

Physical environment

Several application aspects and environments are challenging for Wi-Fi. This paper often refers to two extreme examples:

High-bay warehouse

An industrial hall, filled with either metallic elements that reflect electromagnetic waves or merchandise that absorbs the waves. Metallic elements could be machinery. In case of logistic high-bare warehouses, the steel structures that mount from the floor to the ceiling to stock endless amounts of parcels or spare parts impair the propagation. An additional challenge in these environments is, that the situation is time-varying: merchandise is moved around, metallic transport vehicles move to carry the merchandise. All in all, it is very hard to make a planning that optimizes the Wi-Fi installation for a specific propagation environment, so the only choice is, to create a Wi-Fi installation that copes optimally with any content in the hall.

Figure 1: high-bay ware house

Tunnel

A tunnel, be it for mining or trains, or just any kind of very extended linear volume, like production lines, corridors or elevator shafts. Electromagnetic waves travel along the tunnel, but decay with distance. The main problem is, that the tunnel is not always empty. As soon as a train or machine is in the tunnel, it becomes an almost blocking metallic obstacle that will prevent the waves from travelling beyond it. However, be it for safety or control reasons, a good coverage along the entire tunnel length is essential.

Figure 2: train tunnel

Wi-Fi cell changes

Wi-Fi uses an Access Point (AP) to client connection. Coverage of larger areas or lengthy tunnels obviously require the use of many APs, each creating its own Wi-Fi cell. Unlike cellular radio standards, 802.11 has not been defined to control handovers from the network side, which means the clients are more or less on their own to decide to which AP they connect. For predominantly fixed client locations this is perfectly fine. However, when either the clients move around a lot or the radio environment itself is time varying, clients will perceive changing quality of the radio link to any specific AP. Eventually the link quality is too bad to continue, so the client drops the link and tries to find a better positioned AP and builds up a new link. The entire process of dropping and reconstructing a link takes a certain amount of time and too much for many control applications, and on top the environment may have already changed again during the process.

MIMO (multiple-input multiple-output) systems are already widely deployed. The main objective of the introduction of MIMO was to increase the maximum achievable data rate. The fact that various data streams use different physical channels (also referred to as "diversity") does not increase the cell size or reduce the handover behavior, but makes the handover even more complex for the client.

As a consequence, a good Wi-Fi installation should try to minimize the number of times that a client typically has to change the AP it is connected to, or in other words the number of times to change the "Wi-Fi cell".

Too many overlapping cells

In high-bay warehouses, there are typically a lot of clients (people moving around with Wi-Fi-connected tablets or phones, but also DTS (driverless transport vehicles) controlled via Wi-Fi links to perform their duty. At the same time, there are also a lot APs or cells in order to reach coverage in every corner of the complex radio environment. While "dead zones" with no Wi-Fi coverage are obviously very bad for any application, the other extreme is similarly difficult: too many Wi-Fi cells visible by one client at the same time. If a client perceives many cells simultaneously it will also see their relative power change very frequently and this will trigger unnecessary handover operations. Some clients have even been shown to freeze their operation in the presence of too many cells.

Cell frequency planning is a typical strategy to get some order into the multitude of cells (Figure 3). Neighboring Wi-Fi cells can be configured to use different non-overlapping frequencies (Wi-Fi "channels"). This can help somewhat, but the number of non-overlapping channels is very low, especially in the 2.4 GHz Wi-Fi band (only 3 non-overlapping channels of 20 MHz bandwidth). And with increasing bandwidth per channel (to achieve high data rates), the number of non-overlapping channels is decreasing. In some high-bay warehouses Wi-Fi APs are not even installed in one plane, but also on different levels to cover the height of the hall, making the cell-planning strategy three-dimensional and even more complex.

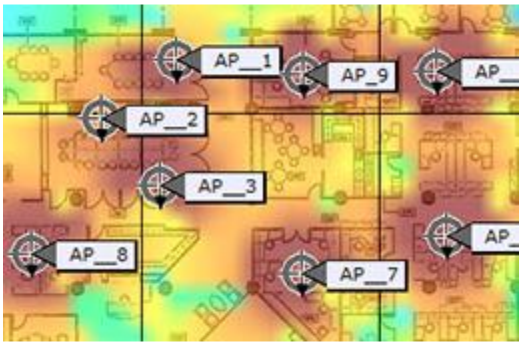

Figure 3: complex and dense Wi-Fi AP layout (graphic courtesy of LMJ Consulting)

Stringent real-time requirements

Industrial applications sometimes require a fixed maximum delay between request and response, e.g. to be sure that machines controlled via the network react with a defined latency. Wi-Fi (still based on the original Ethernet) is a "best-effort" technology, in other words, it does the best it can to reach a client and to get the client's response. However, the basic technology does not give any guarantee to what the maximum latency will be.

This problem has been addressed by a specific Wi-Fi variant in the protocol ("PCF"). Variants of PCF have been implemented by some vendors, but with proprietary protocols, e.g. Siemens industrial APs use so-called "iPCF". The drawback of these protocols is two-fold: on one hand they reduce the overall data bandwidth available, by allocating specific time slots to each client (whether the client wants to communicate or not), and on the other hand, a handover (or better a dropped link to be rebuilt) is even more problematic in this setup (can even take more time). Still iPCF-type solutions are a very popular choice in industrial installations.

There are higher layer SW solutions and implementations with complete redundancy ("PRP" protocol), that address this by creating virtually two links to each client, with the idea to never drop both of them simultaneously, but from a system point of view, this is more a work-around than a solution and it is also very expensive in terms of necessary network equipment.

A typical practical consequence of a dropped link in the case of a remote controlled DTS is, that it will pause its operation (safety first) and lose precious time before it starts moving again.

An optimized installation

This chapter introduces a method to optimize the installation with respect to the above challenges. One of the key elements to optimize the situation is the antenna technology. The second key element is a reduction of the number of cells necessary for covering the entire application volume, translating to the need of larger cells. It turns out that an installation using radiating cable as antenna (Figure 4) together with booster technology (Figure 5) to increase the cell size offers additional advantages that translate to opportunities to save cost and simplify the installation.

Radiating cable with signal boosters

Radiating cable is a technology only recently picking up in installations for GHz-type communication systems. Previously they had mostly been used for safety radio and tunnel installations in the sub-GHz range. On the one hand better cables have been developed, more adapted to the Wi-Fi frequency bands and on the other hands a complementary technology, the “Wi-Fi inline signal booster” is now available that allows to compensate for the biggest weakness of radiating cables at high frequencies: the limited maximum length of the cable at a given frequency and link budget.

A very good article about all the aspects of using radiating cable as antenna can be found in (ref. 1, in German). It also includes ways to use radiating cables with MIMO capabilities.

If your interest goes deeper into the technology and related planning considerations with respect to link budget, you are welcome to jump to the detailed appendix of this white paper, where quantitative analysis for the two challenging radio environments is presented.

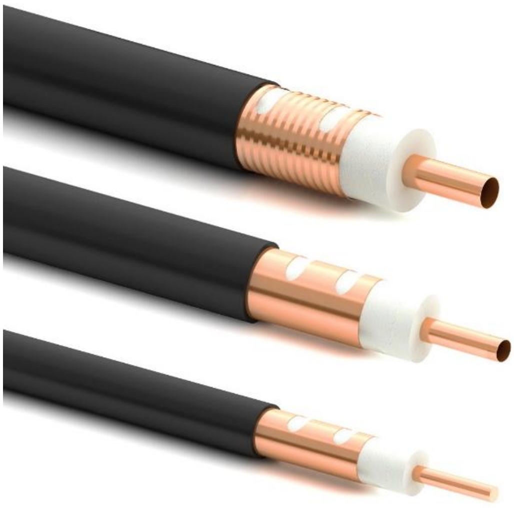

Figure 4: Radiating cables

In a nut-shell radiating cables allow to distribute the Wi-Fi signal more homogeneously compared to other antenna types. But only the combination of radiating cables with boosters allows to extend this homogeneous coverage to cells of a much larger size than previously possible. As a consequence, fewer Access Points cover a bigger area with good link quality, reducing the amount of cell changes and simplifying the cell planning.

In a high-bay warehouse, there will be no need to put APs on multiple levels reducing cell-planning to a 2-dimensional problem. On top the linear shape of radiating cable cells fits rather well with the aisles of warehouses. Even the longest aisles can be covered by a single Wi-Fi cell. The number of APs seen by a client will be much lower and drastically reduce the number of cell changes required by the client.

In the tunnel application, the spacing of APs can be significantly higher and become more in line with the usual spacing of installation points around every 1000 m. The cost for in-between installation points with access to power and network can be saved. On top fast-moving clients (e.g. on trains) will have to perform cell changes at a much lower frequency.

Figure 5: inline Wi-Fi booster installation example

Cost synergies with other radio systems

Once the radiating cable is the antenna of choice, it offers the additional possibility to serve as well as antenna for lower frequency systems, like low-band cellular or PMR. In many of the installations these mostly voice-oriented systems are required anyway and have been installed on top of and independent of the Wi-Fi system. By sharing the same antenna, significant material and installation cost can be saved. As the frequencies are lower, the radiating cable antenna can be significantly longer for these communication systems without boosting the signal.

The Wi-Fi boosters considered in this paper offer a "by-pass" for lower frequencies, so that the cellular or PMR system would not even be affected in case of failure of a booster device. Sharing the antenna has no negative impact on safety aspects of the system.

Summary

Using radiating cable and booster technology results simultaneously in

- Better, more homogeneous coverage of the entire application
- Lower number of APs needed to achieve this coverage
- Lower cost through fewer AP installations (networking cabling, power supply cabling) and by avoiding additional antennas needed for cellular, safety radio or 2.4 GHz Wi-Fi
- Compatibility to iPCF-type applications with fixed response times

The result is lower overall cost of installation of a combined system, while at the same performing significantly better in the challenging radio environments described above.

The signal gain that the Wi-Fi booster introduces to the system can be used to compensate for low signal levels due low output power of the AP and attenuation introduced by the radiating cable along its length (longitudinal attenuation). On top it can also be used to eliminate the attenuation resulting from power splitters.

Outlook to Wi-Fi 6

Wi-Fi 6 (or 802.11ax), the newest version of the 802.11 family of standards, which is currently rolled out (first equipment is available) is trying to make some progress in "Wi-Fi efficiency". A good easy-to-read summary on Wi-Fi 6 can be found in ref. 2. But the fundamental principle of 802.11, which is to keep the control of the AP choice of a client under client control, has not been changed. It will make it easier to serve many clients efficiently from one AP, but it will not change the overhead introduced by changing cells. Therefore, the optimized installation described above will carry over to Wi-Fi 6 without change.

Wi-Fi 6 comes back with a more standardized approach to coordinate the clients, which should help to get define response-time from the clients. It remains to be seen, whether Wi-Fi 6 will be both from a performance and from an availability point of view a solution that can replace the proprietary protocols to address real-time constraints (iPCF-type).

Wi-Fi 6 APs will likely consume more power than current APs. Having a power supply next to the AP may therefore be advantageous over PoE (Power over Ethernet) and has the additional advantage that it can drive all the Wi-Fi boosters from the same supply as the AP.

Appendix: Details and Quantitative Analysis

Radiating cable

Compared to other antenna types radiating cables have quite different properties:

- More homogeneous field strength in the coverage area
- Higher fundamental link loss from the antenna to the receiver ("coupling loss")
- Lower increase of the attenuation over distance along the cable ("longitudinal loss")
- Lower increase of the attenuation with distance radial from the cable (1/r instead of $1/r^2$ for other antennas)

As a consequence, the coverage planning follows a quite different process and the possibility to boost the signal inline in the radiating cable run changes the concept even more – but with very promising results both in theory and in practice.

However, the resulting choices to be taken even differ between the tunnel and the warehouse application!

Wi-Fi and radiating cable

Typical APs deliver an average output power of about 10…15 dBm. When higher modulation schemes are used, the output power is more on the 10 dBm side.

The receiver sensitivity also depends on the modulation scheme, some values can be seen in Figure 6 and is roughly in the range of -65 dBm to -80 dBm.

Modulation	Coding Rate	Channel bandwidth $B = 20$ MHz	Channel bandwidth $B = 40$ MHz
BPSK	1/2	−82	−79
QPSK	1/2	−79	−76
QPSK	3/4	−77	−74
16-QAM	1/2	−74	−71
16-QAM	3/4	−70	−67
64-QAM	2/3	−66	−63
64-QAM	3/4	−65	−62
64-QAM	5/6	−64	−61

Receiver minimum input level sensitivity of IEEE 802.11n. Modulation-Coding Scheme (MCS) Minimum signal power, S [dBm]

Figure 6: Receiver sensitivity depending on modulation

The resulting link budget for a simple modulation scheme (in other words for low data rates) is about 95 dB = 15 dBm - (-80 dBm). For high modulation schemes (or high data rates) it is about 75 dB = 10 dBm - (-65 dBm).

Assuming a case with high download rates and low uplink rates, boosting the AP power by 15 to 20 dB is possible to compensate for losses in the channel. Even in a symmetrical case, we have seen that boosting 5 to 10 dB is still increasing performance.

When using radiating cable, the higher output power of an AP will not violate regulation, as the high coupling loss is anyway limiting the emitted power level.

The most relevant propagation impairment in Wi-Fi in our chosen scenarios is multipath fading. The fading drops are well-known to deepen with increased distance from standard antennas, as depicted in Figure 7. This is true also for radiating cable, but only with respect to the less relevant distance from the cable. The fading drops do not significantly change along the cable. This is the real reason behind the previously quoted “homogenous field strength” which is the single most important advantage of radiating cable.

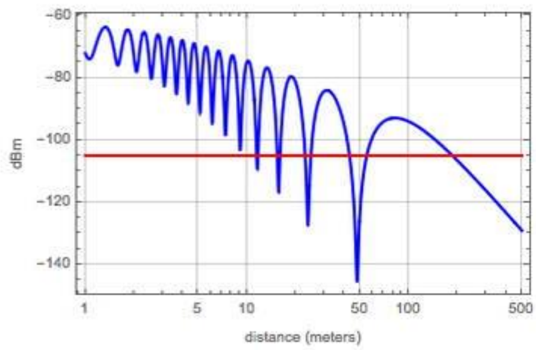

Figure 7: Fading as function of distance (simulated example)

Wi-Fi booster technology

As the length of the radiating cable is constrained by its longitudinal attenuation, a bidirectional amplifier can boost the signal at the end of the cable and then feed an additional segment of radiating cable. Boosting and extending the cable length can be done multiple times. The Wi-Fi booster is an active electronic component, it needs to be supplied with power. Specific Wi-Fi boosters (ref. 5) obtain the power from a DC-voltage carried by the radiating cable itself (so called “phantom voltage”). Using this technology, no additional infrastructure or cables are needed when extending the radiating cable to more segments. On top the product is designed to bypass lower frequencies carried on the same cable. The application diagram in Figure 11 shows an installation scheme with TETRA and 5 GHz Wi-Fi.

The resulting cell from a multi-segment radiating cable can therefore be multiple times larger than without boosting the signal. This is not only interesting in industrial hall application, but also in tunnels, or even in a linear vertical construction, like a lift/elevator in skyscrapers.

A big cost item in tunnels is the conducts to take the infrastructure (power, network, radio signals) to the entry points of the radiating cable. Driving 2x 500 m from a single AP allows to space the installation niches at about 1000 m from each other, which is similar to what is used today for installing the safety radio in traffic tunnels.

A client roaming parallel to the radiating cable will see the same AP along the entire cable run without having to switch cells. Considering a train moving along a tunnel this will mean that the client will have to change cell only every km and not every 200 m.

Radiating cable and boosters

The power boosters investigated in this paper provide an average output power of 20 dBm even for high modulations, so the design target is to insert about 20 dBm into the radiating cable at the output of the booster.

In many installation examples the radiating cable of choice has been the one with the lowest longitudinal loss to be able to create large cells, specifically in the tunnel application. But the availability of inline boosters changes the situation: inserting a booster into the cable compensates for a longitudinal loss, here by adding 20 dB to the signals both in uplink and downlink. Naturally noise performance will slightly degrade but in comparison to other impairments (like fading) this is almost irrelevant. In practice 5 boosters in series in one radiating cable run have successfully been demonstrated.

Case 1: high-bay warehouse

High-bay warehouses are literally high. The specification of coupling loss of radiating cable typically gives values for 2 m radial distance. The distance from the ceiling-mounted radiating cable to a DTS moving on the ground will be 10 or even 15 m. Due to the 1/r property of the radiating cable this will introduce up 6…9 dB additional coupling loss. In the following paragraphs the key parameters for a system design with radiating cable and boosters is derived for this high-bay warehouse.

Comparing radiating cables for 5 GHz Wi-Fi (see ref. 3 and 4), the better choice is the one with lower coupling loss (Figure 8). The coupling loss from the cable to the DTS on the ground amounts to up to 60...70 dB. Please note that the coupling loss data given in the datasheets include already some statistics reflecting fading loss.

Frequency	Longitudinal Loss	Coupling Loss	
	dB/100m (dB/100ft)	C50% (dB)	C95% (dB)
2400 MHz	12.3 (3.75)	67	77
5200 MHz	24.6 (7.50)	62	71
5500 MHz	26.3 (8.02)	60	61
5800 MHz	29.4 (8.96)	55	59

Figure 8: radiating cable datasheet RMC 12-CH (extract)

The minimum power at any point in the radiating cable must therefore be around 0 dBm for higher modulation schemes.

Let us assume that the AP is mounted at ground level where power and ethernet are easily accessible. Maybe 2-3 dB are already lost from the AP to the entry point of the radiating cable at the ceiling. So, the radiating cable is fed with about 7-8 dBm. About 25 m from the feeding point, the signal level has fallen to around 0 dBm in the cable, so the first booster is introduced. It can drive about another 80 m. For a high-bay warehouse with aisles of 100 m length, the single radiating cable run will be sufficient to cover the entire warehouse length. The received signal level has been simulated and can be seen in Figure 9.

Comparison with normal antenna for high-bay warehouse example

Figure 9 shows a comparison of the received power level in case 1 of a radiating cable with a normal antenna on the AP at 5.5 GHz, 10 dBm average AP output.

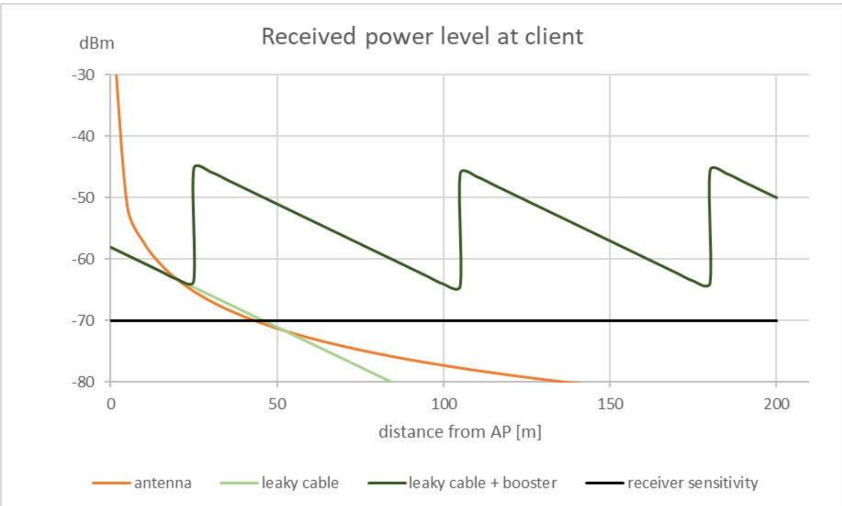

Figure 9: comparison of radiating cable with antenna in high-bay warehouse

The simulation assumes a 70 dB coupling loss. The orange line shows the $1/r^2$ of the normal antenna, assuming a 3 dBi antenna gain (for an AP mounted to the wall). The black line indicates the minimum received signal level at the Wi-Fi client. Clearly at a distance of about 40 m the received signal level is not acceptable anymore and this does not even reflect any fading drops. As a consequence, installation of several APs along the length of the hall is required, even for a hall of 100 m length.

The light green line shows the signal level when using the same input power to the radiating cable, but without booster technology.

Finally, the dark green line shows the effect of booster technology. The received signal level is kept in a 20 dB band along the entire length of the cell driven by the same AP. In changes in saw-tooth shape along the radiating cable run. Please note that in the case of radiating cable, the fading drops are already taken up in the simulated values, unlike with a normal antenna!

Case 2: Tunnel installation

As a second case we assume a mining tunnel, which has rails on which some transport vehicle needs Wi-Fi connectivity. By installing the antenna on the vehicle correctly, the distance from client antenna to radiating cable running on the ceiling is just 2m. In this case even -10 dBm in the cable are acceptable.

Here we are interested in covering the longest possible tunnel segment with a single AP. Installing APs in a tunnel is costly, because power and network need to be carried to each AP and potentially special niches need to be built to install the AP to allow for easier maintenance.

The radiating cable with lower longitudinal loss is preferred here, as it allows to create longer Wi-Fi cells. The coupling loss in Figure 10 is still acceptable due to the small distance between antenna and radiating cable.

Frequency	Longitudinal Loss	Coupling Loss	
	dB/100m (dB/100ft)	$C_{50\%}$ (dB)	$C_{95\%}$ (dB)
2400 MHz	8.07 (2.46)	73	80
2600 MHz	8.47 (2.58)	71	76
2700 MHz	8.66 (2.64)	71	77
3500 MHz	10.23 (3.12)	72	82
5200 MHz	14.37 (4.38)	67	78
5500 MHz	15.37 (4.69)	66	76
5800 MHz	16.49 (5.03)	64	73

Figure 10: radiating cable datasheet RMC 58-CH (extract)

One radiating cable segment is up to 130 m and using multiple boosters, the same Wi-Fi cell can span easily 500 m on each side of the AP.

Conclusion from above examples

Using radiating cable as antenna for Wi-Fi has some significant impacts on the installation:

1. The radiating cable antenna can be driven with higher input power from the access point as compared to normal antennas. There are even applications, where it is interesting to use a Wi-Fi booster also on the client side to improve the uplink, especially when using small radiating cable antennas for reduced coupling loss and when the application focuses on high data rates in the uplink.
2. Even high-bay warehouses can be completely covered by radiating cable on the ceiling, due to the weaker loss of 1/r instead of 1/r2 with r indicating the distance between transmitting antenna and receiver.
3. The radiating cable is a formidable carrier of frequency bands other than the Wi-Fi bands. The same radiating cable can simultaneously represent the antenna for other systems, e.g. cellular communication, safety radio (TETRA) or analog radio.
4. The coverage area (when looking at the 2-dimensional cell size) is constrained by the longitudinal attenuation. However, this limit is significantly reduced when using inline booster technology.
5. In some installations power splitters are used to drive several antennas from the same AP, be it radiating cable or other antenna types. A one-to-four power splitter will introduce more than 6 dB

loss into the link, a one-to-eight even more than 9 dB. Using a Wi-Fi booster, the attenuation can be compensated to remove any negative impact of the power splitter. This is depicted in Figure 12.

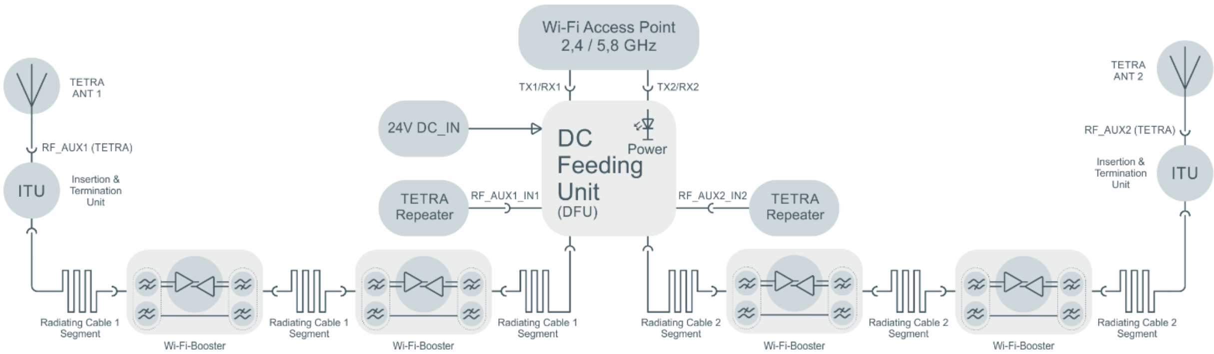

Figure 11: Block diagram of implementation with radiating cable - Wi-Fi + TETRA

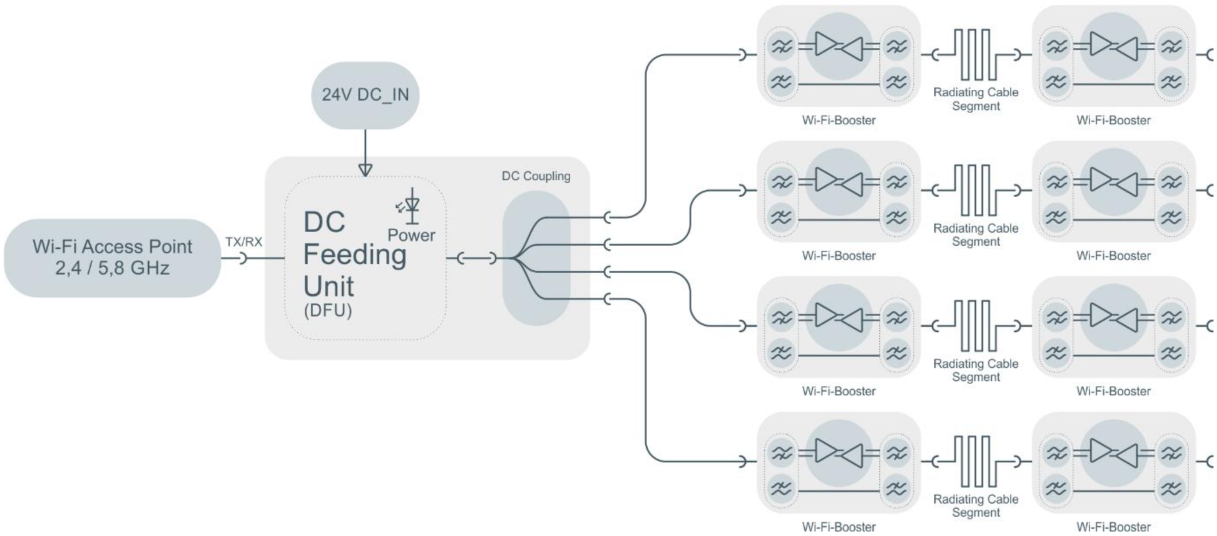

Figure 12: Appilcation of power splitter and booster

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