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TECHNICAL REVIEW

DAB+ Signal Propagation in Tunnels

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FOREWORD

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ABSTRACT

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Radiotelevisione italiana S.p.A. (RAI) is planning to extend DAB+ services to the most important Italian urban areas and to the motorways (including service continuity in tunnels). In a first Phase, the motorway coverage should involve the so-called “T-motorway” (i.e. the A4 in the East-West direction from Trieste to Turin and the A1 in the North-South direction from Milan to Naples).

In this context, service coverage for mobile and fixed receivers could be provided by a high-power-high-tower (HPHT) transmitting network with the integration, on motorways, of low-power-low-tower (LPLT) installations in critical mountainous areas (i.e. the Apennine valleys) and tunnels, where the HPHT signal cannot be received.

In November 2015, preliminary tests on the A5 motorway (between Turin and Aosta) confirmed the difficulty of achieving DAB+ service continuity in tunnels from HPHT installations located nearby (Col Courtil and Saint Vincent).

As is well documented, radio service transmission inside tunnels requires methods such as the installation of radiating cables (“leaky-feeders”) along the tunnel ceiling. This approach is costly, both in the case where a new radiating cable has to be installed and in the case of sharing cables already in use for other radio services (e.g. FM radio, mobile telephony, radio alerts, police, …).

The RAI Research Centre has investigated the feasibility of an alternative approach to providing DAB+ coverage inside tunnels, using “direct RF radiation” by means of antennas positioned outside the tunnel (not far from the entrance) or internally.

Technical literature regarding 200 MHz radiowave propagation inside tunnels is lacking and so in 2016 the RAI conducted a further DAB+ measurement campaign with the support of “Autostrade per l’Italia” (ASPI).

The results of all the measurements in tunnels (with and without traffic) are summarised in this article, together with a proposal for simplified design criteria for the “direct RF radiation” network and a comparison between the “direct RF radiation” and “leaky-feeder” approaches in terms of performance and implementation complexity and costs.

DAB+ RETRANSMISSION IN TUNNELS

For decades the RAI has, in cooperation with the main Italian motorway licensees (ASPI, ADF, AdP), provided a special radio programme for motorways called “Isoradio”, based on a single FM frequency (103.3 MHz). So far, “Isoradio” service transmission in tunnels has been achieved by means of radiating cables inside tunnels. The radiating cable approach ensures good FM service continuity in the frequency bands around 100 MHz, even in heavy traffic conditions and, by means of high power multiband combiners, it typically allows carriage of, other RF services (Police, Firefighters, …).

Due to the cable loss and attenuation, intermediate amplification for trunks longer than 1000 m is necessary; therefore, while tunnels up to 2 km could be fed by external amplification systems, very long tunnels will require several cable trunks and internal signal repeaters.

As an alternative to installing a new dedicated cable, DAB+ can be added on a radiating cable that is already carrying other RF services, but expensive RF branching modifications using multiband combiners are required.

To reduce implementation costs and system complexity, the RAI investigated the performance of “direct RF radiation” of DAB+, by means of antennas placed inside the tunnels or just outside the tunnel entrance (at a maximum distance of 300 m).

THE MEASUREMENT CAMPAIGN

To address the lack of published information of propagation data (measurements or models) in tunnels for DAB+ in the 200 MHz band, a measurement campaign was carried out by the RAI in cooperation with ASPI (Autostrade per l’Italia) in the Apennine section of the A1 motorway between Bologna and Florence. The measurement campaign, involving both the old route (OR) and the brand new route (NR - also known as “Variante di Valico”), was divided into two Phases:

- **Phase 1**
  In November 2015, since the NR was still under construction, tests were run to evaluate DAB+ propagation without vehicular traffic.

- **Phase 2**
  In March 2016 a new campaign was organized on the A1 (OR and NR) in presence of vehicular traffic.

Additional tests were also performed in the Turin region to confirm the aforementioned campaign results (see ‘Further Tests’ section).

During all campaigns each test was repeated 2 - 3 times in order to increase the statistical reliability; furthermore, different tests were carried out varying specific parameters as follows:

- Transmitted power (1 W, 4 W)
- TX antenna location (inside/outside the tunnel)
- Polarization (H, V)

Three measurements were made during the tests:

- Electro-Magnetic (EM) field strength sampled every 10 cm, by a professional measurement test set and with GPS + odometer position recording (outside/inside tunnels).
- EM field measurements every second by using a professional DAB+ receiver.
- Subjective signal evaluation by listening to an integrated automotive consumer receiver (in a Fiat 500), in order to identify the real service threshold in terms of signal power.

The RF signal was received on a roof-top vertical whip antenna ($\lambda/4$). It must be noted that the overall receiving system (car + antenna) exhibited some directivity, thus the measurements were somewhat dependent on the driving direction of the car. A log-periodic directional antenna was used for transmitting the DAB+ signal (described in '*DAB+ mobile transmitter system*' section).

Phase 1: tests without traffic

Tests were carried out in three tunnels of the new Appenine trunk of the A1 motorway between Bologna and Florence, each representative of a specific tunnel typology:

- The so called "Base" tunnel (very long tunnel, 8900 m approx.)
- Puliana tunnel (long tunnel, 1300 m approx.)
- Largnano tunnel (medium tunnel, 700 m approx.)

Figure 1: tests in "Base" tunnel without traffic

Most Italian motorway tunnels can be represented by the Puliana and Largnano tunnels, in which tests were run transmitting a RF signal from outside both the entrances.

In the very long "Base" tunnel (representing a small number of Italian tunnels), the transmitting antenna was placed at the mid point inside the tunnel and signal was radiated in both directions, to simulate cases where intermediate illumination is required to ensure service continuity.

Figure 2: Puliana tunnel, example of external transmission

A summary of the results is given in Table 1, for a transmission power of 4 W at the antenna. It was found that tests transmitting 1 W signal power can be assumed as not being relevant for the present discussion.

In the “Base” tunnel, the TX antenna was first pointed towards Bologna, covering the North route trunk, then towards Florence, covering the South route trunk; the car travelled the two trunks in both directions, generating four test results.

Table 1: summary of the Phase 1 test campaign (without traffic)

Tunnel	Tx Antenna location	Car Direction	Tunnel coverage	
			H Pol.	V Pol.
Base North route	Inside	Florence	1300 m	1130 m
Base North route	Inside	Bologna	1200 m	700 m
Base South route	Inside	Florence	1100 m	800 m
Base South route	Inside	Bologna	1250 m	770 m
Puliana	Inside (entrance)	Florence	full	Full
Puliana	Inside (entrance)	Bologna	full	Full
Puliana	Outside (D=170 m)	Florence	700 m	670 m
Puliana	Outside (D=170 m)	Bologna	800 m	690 m
Largnano Southern tunnel	Outside (D=170 m)	Florence	560 m	540 m
Largnano Southern tunnel	Outside (D=170 m)	Bologna	630 m	510 m
Largnano Southern tunnel	Inside (entrance)	Florence	full	-
Largnano Southern tunnel	Inside (entrance)	Bologna	full	-
Largnano Northern tunnel	Outside (D=200 m)	Florence	full	630 m
Largnano Northern tunnel	Outside (D=200 m)	Bologna	full	400 m

*D=TX antenna distance from tunnel entrance; Coverage criteria: minimum field strength **>45 dBµV/m***

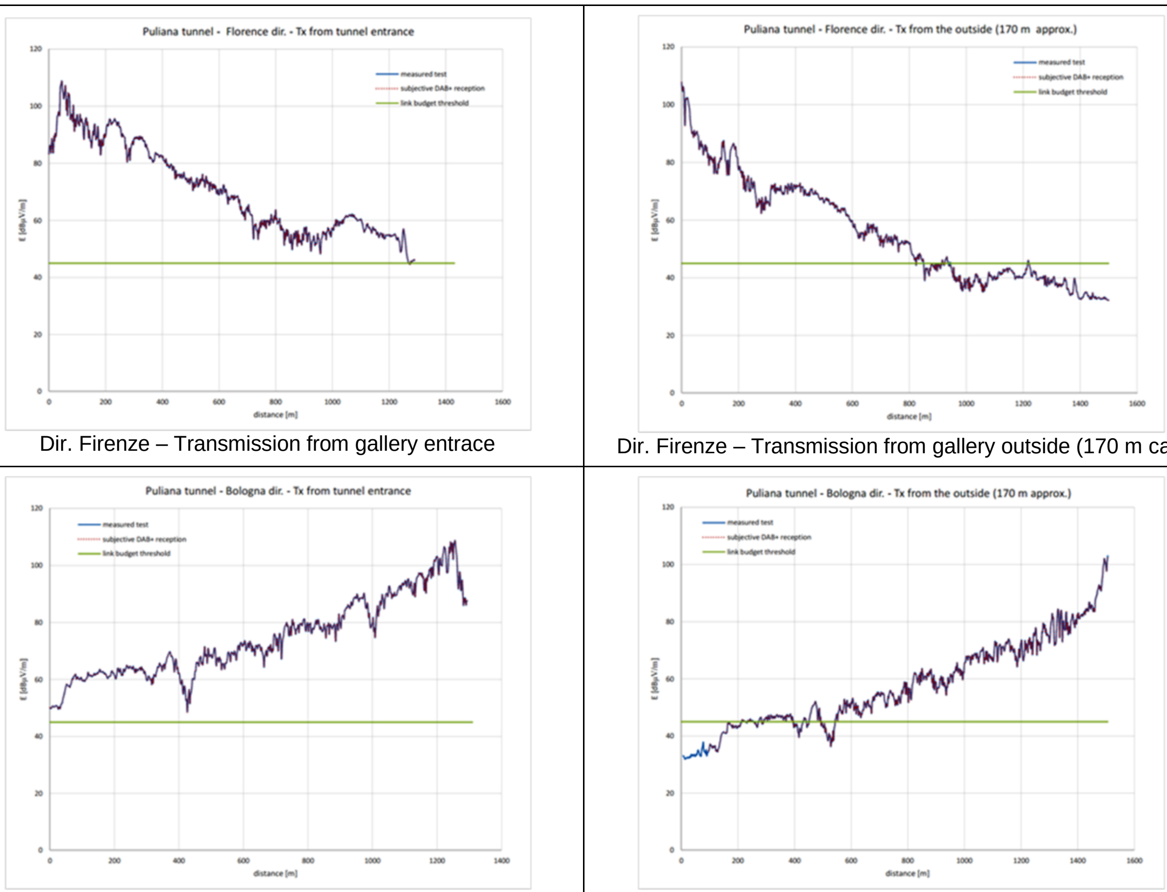
The reported coverage figures refer to a minimum mean field strength of about 45 dBµV/m. In fact (see ‘*Coverage Criteria and Receiver Budget*’ section) modern DAB+ receivers require a minimum field strength of 32 dBµV/m, and in typical HPHT DAB+ outdoor service planning 12.8 dB of margin is adopted to guarantee a 99% location probability [1].

Analyzing the measured combined fading signal variations, we have decided to retain the same 13 dB margin as for “outdoor” planning, to guarantee the needed in-tunnel service continuity. Direct listening to our commercial DAB+ radio confirmed that the service continuity can be guaranteed down to 32 dBµV/m.

The results indicate that horizontal polarization is the most suitable for signal propagation even if the receiving antenna has vertical polarization. As an example for the “Base” tunnel, transmitting in both directions and in H polarization, coverage of about 2400 m can be obtained (summing the North and the South routes).

In Puliana tunnel (1300 m), according to the minimum signal strength criteria, transmission from the tunnel entrance is required to ensure complete coverage. On the other hand, subjective test evaluations confirmed complete coverage even when outside transmission (both H and V polarizations) is used.

In Largnano tunnel (700 m), transmitting from a single tunnel entrance ensures full coverage according to the minimum field strength criteria. Actually, the less demanding subjective tests verified that an external transmission (D ≅ 200 m, H pol) could also ensure complete tunnel coverage.



Dir. Firenze – Transmission from gallery entrace

Dir. Firenze – Transmission from gallery outside (170 m ca.)

Dir. Bologna – Transmission from gallery entrance

Dir. Bologna – Transmission from gallery outside (170 m ca.)

Figure 3: tests in Puliana tunnel, H pol.

Table 2 shows the signal attenuation in the Puliana tunnel; in the case of internal transmission, the overall attenuation is larger due to the signal peak at the tunnel entrance when the vehicle passes below the transmitting antenna. The same phenomenon was detected in Largnano tunnel.

Table 2: power loss in Puliana tunnel (1300 m)

	H Pol.	V Pol.
Internal Tx – Florence dir.	55 dB	62 dB
External Tx – Bologna dir.	43 dB	54 dB

Phase 2: tests with traffic

The Phase 2 test campaign involved both the new and the old routes of the A1 motorway in presence of traffic. The following tunnels were explored:

- Puliana tunnel (new route, long tunnel, 1300 m approx.)
- Largnano tunnel (new route, medium tunnel, 700 m. approx.)
- Banzole tunnel (old route, long tunnel, 1200 m approx.)
- Monte Mario tunnel – northern entrance (very long tunnel, 2200 m approx.)

Figure 4: tests in presence of heavy traffic in Puliana (left) and Monte Mario (right) tunnels

Table 3 summarizes the results collected during the Phase 2. Due to the Phase 1 results, only H polarization was considered in Phase 2.

Table 3: summary of the Phase 2 test campaign results (H pol. only) in non-blocking conditions

Tunnel	Tx Antenna location	Car Direction	Tunnel Coverage with traffic	Loss w.r.t. no traffic
Puliana	Inside	Florence	700 m	600 m
Puliana	Outside (D=170 m)	Florence	550 m	150 m
Largnano Southern tunnel	Inside	Florence	full	0 m
Largnano Southern tunnel	Outside (D=300 m)	Florence	310 m	250 m
Largnano Northern tunnel	Outside (D=300 m)	Bologna	400 m	300 m
Banzole Bologna entrance	Outside (D=75 m)	Florence	650 m	75 m
Banzole Florence entrance	Outside (D=50 m)	Florence	650 m	20 m
Monte mario Nord	Outside (D=75 m)	Bologna	1100 m	-

D=TX antenna distance from tunnel entrance; Coverage criteria: minimum field strength ***>45 dBµV/m***

In the Puliana, Largnano and Monte Mario tunnels, in case of very dense traffic with trucks along both lanes and blocking the TX-RX line-of-sight, a total shielding effect was observed, preventing the receiver to lock/track the DAB+ signal. Similar service interruption problems also occurred on mobile telephony services. The results in Table 3 exclude such blocking conditions, which require further statistical investigation (planned for mid-2017).

In the Banzole tunnel (old route) tests were run both with and without traffic: the traffic had no influence on performance because since the new A1 route has been opened, traffic over the old route has reduced by about 80%, thus avoiding dense traffic conditions.

An example of how RF propagation varies with traffic can be observed in Figure 5, representing the Monte Mario enviroment. In case of dense traffic over all lanes, including a great number of trucks and heavy vehicles between transmitter and receiver, the receivers suffered from significant synchronization problems, providing a coverage of only 700 m (test 1, green line) with respect to the 1100 m coverage observed in non critical conditions (test 2, violet line). A similar situation was also verified in the NR tunnels (Puliana and Largnano).

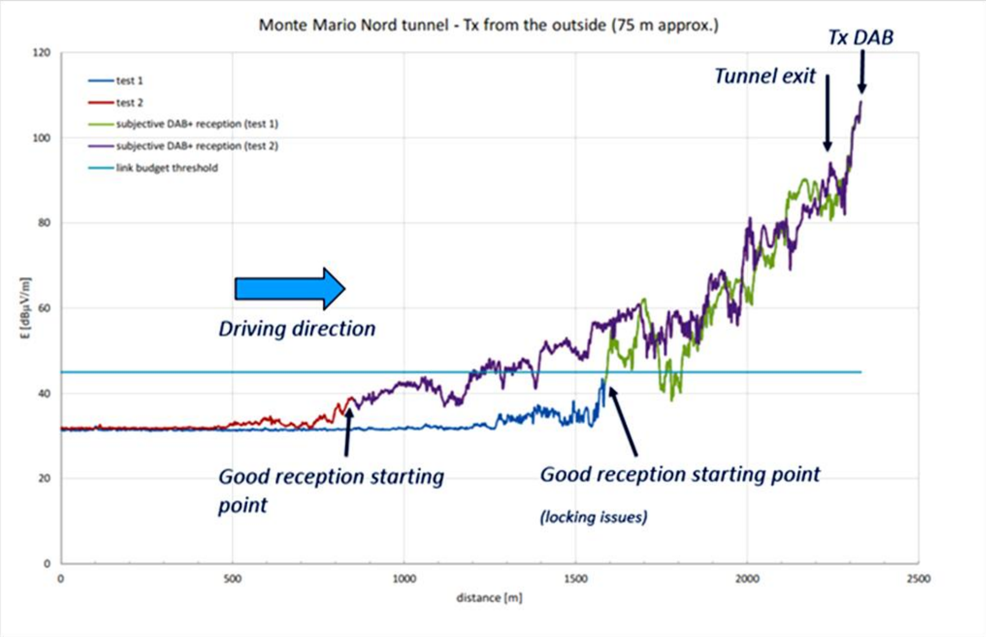


Figure 5: tests in Monte Mario tunnel

Table 4 provides a summary of all the main tests on the A1 motorway tunnels

Table 4: Summary of measurement results without and with traffic (*=worst case)

Test	Traffic condition	Coverage (m)
A1 - NR	No traffic	1300 (D=0 m) 700 (D=170 m)
A1 - NR	Vehicular traffic	700 (D=0 m) 550 (D=170 m) 310 (D=300 m) (*)
A1 - OR	No traffic	725 (D=75 m)
A1 - OR	Vehicular traffic	650 (D=75 and 50 m) (*)
A1	Vehicular traffic (Monte mario tunnel)	1100 (D=75 m)

D=TX antenna distance from tunnel entrance; Coverage criteria: minimum field strength ***>45 dBµV/m***

SIMPLIFIED DESIGN CRITERIA FOR THE "DIRECT RADIATION" NETWORK FOR TUNNELS

An optimized network design criteria for tunnel coverage would require a case-by-case tunnel evaluation, taking into account entrance diameter, rectilinear or curved shape of the road, wall material, …

Nonetheless, taking into consideration that the majority of tunnels are quite short, a simplified design approach based on "worst cases" can be applicable as shown below (derived from the test results of Table 4), leaving the more sophisticated design approaches to the few long tunnels.

Simplified network design criteria for DAB+ "direct radiation" coverage of tunnels (*)	
Tx from tunnel entrance (D=0 m)	700 m
External transmission (D <300 m approx.)	300 m

(*) 4 W TX power; excluding the very dense traffic case that needs separate investigation (% blockage during a day)

COMPARISON BETWEEN THE "RADIATING CABLE" AND THE "DIRECT RADIATION" APPROACHES

As aforementioned, the RAI, in cooperation with the main Italian motorway licensees (ASPI, ADF, AdP), installed the "Isoradio" radio service along the major national motorways (including tunnels). This service is transmitted in frequency modulation with a single frequency technique and the transmission inside tunnels is totally achieved by means of radiating cables installed all along the walls.

Furthermore, the radiating cable in tunnels is often also used to deliver services in other radio frequency bands to Civil Defence, Firefighters and the Police (henceforth we shall term them "hidden services", since they are not intended for the general public).

Due to the signal attenuation (at 200 MHz, the transversal loss within the cable is 2 - 5 dB/100 m and the coupling loss between cable and receiver is 60 - 70 dB), the typical maximum radiating cable length is about 1000 m; this means that tunnels up to 2 km can easily be served with external transmission points (Figure 6), while longer tunnels require more cable trunks and internal transmission points.

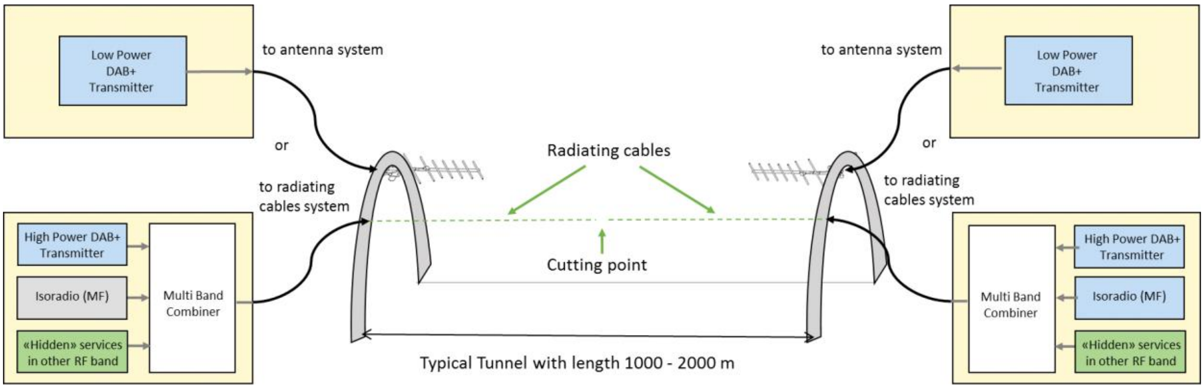


Figure 6: Block diagrams of "radiating cable" and "direct radiation" approaches compared

All existing radio frequency signals, both "Isoradio" and hidden services, are merged by means of a complex Multi Band Combiner (MBC - branching) before reaching the radiating cable; thus, adding a new DAB+ service would require significant modification of the MBC in each transmission point.

Additionally, for technical reasons, MBCs have sufficient insertion losses (10 dB or more) that in order to guarantee the correct DAB+ radio frequency link budget inside the tunnel a high power DAB+ transmitter (more than 10 W) should be considered in each transmission point.

"Direct radiation" technique can reduce the implementation costs (up to 50%) and system complexity because no MBC modification is required and low power transmitters can be used.

Table 5 summarizes the advantages / disadvantages of "direct radiation" over radiating cables.

Table 5: Direct Radiation and Radiating Cables – advantages and disadvantages

	Direct Radiation		Radiating cables (existing cables)		Radiating cables (new installation)	
Sensitivity to heavy traffic	Yes	☹	no	☺	no	☺
Need for MBC	No	☺	yes	☹	no	☺
Need for High power transmitters	No	☺	yes	☹	yes	☹
Need for intermediate transmitters	Every 1400 m	😐	Every 2 km	☺	Every 2 km	☺
HW cost & installation	(antenna) medium	☺	(cable) no	☺	(cable) high	☹
Maintainence required	Only amplifiers	😐	Only for amplifiers	😐	Only for amplifiers	😐
Impact to other services	No	☺	Reduction of reliability on MBC	😐	no	☺

FURTHER TESTS

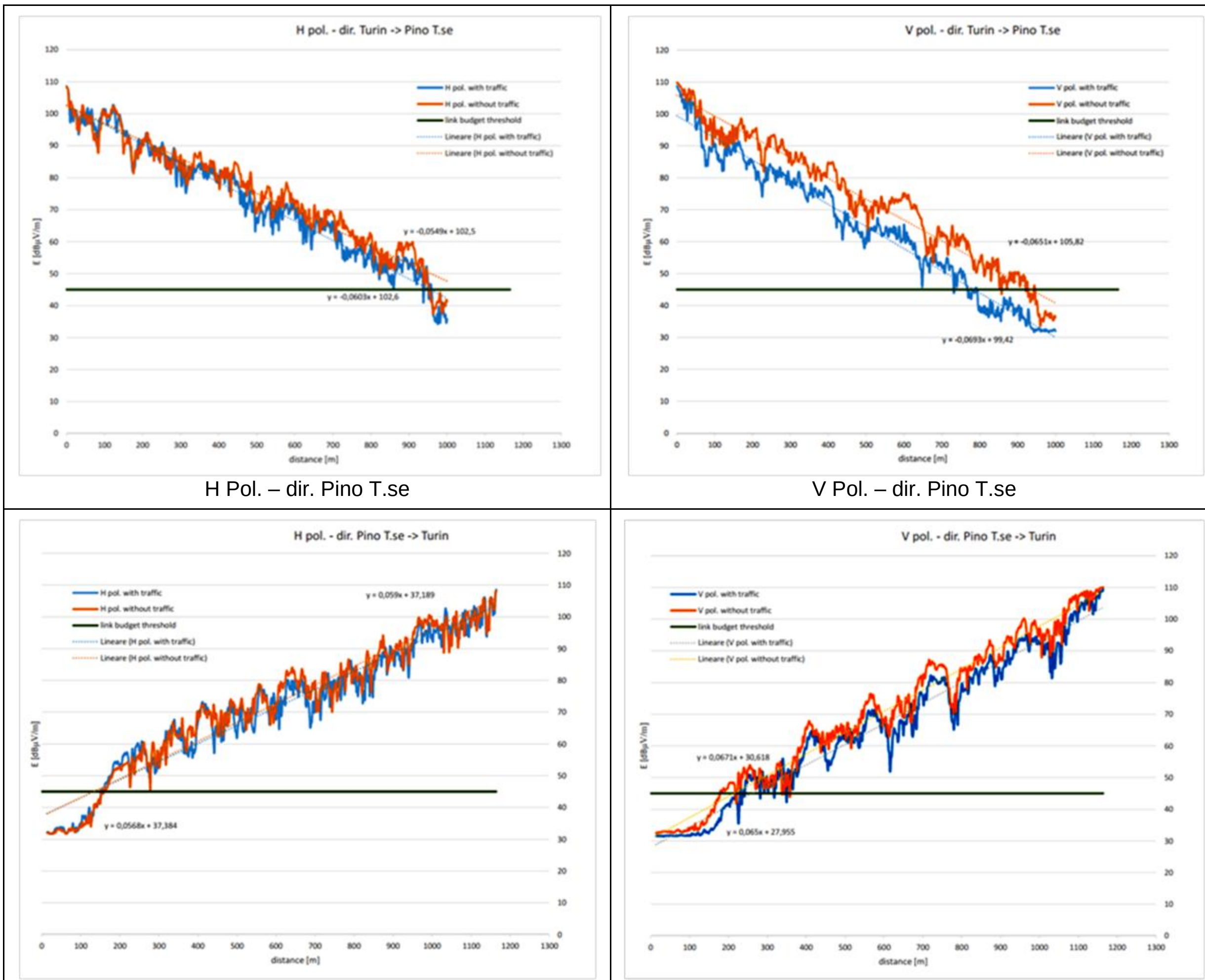
Pino Torinese tunnel

Further tests were run in the so-called "Traforo del Pino", a 1 km long tunnel along the SP10 road between Turin and Pino Torinese; as with the motorway tests, the RF transmissions were done with a 4 W signal by means of an antenna located 15 m outside the tunnel.

Figure 7: "traforo del Pino" tunnel (SP10) with and without traffic

The measurement campaign was performed during the evening hours, in order to run tests both with and without traffic; unfortunately, as a result of maintenance work, trucks and other heavy motorcars were prohibited, thus preventing the analysis in the case of very dense traffic.

In this completely straight tunnel, excluding near field effects, the signal attenuation showed a linear behaviour (Figure 8), thus confirming the motorway (A1 campaign) results. Analogous conclusions can be found in [2].



H Pol. – dir. Pino T.se | V Pol. – dir. Pino T.se

H Pol. – dir. Torino | V Pol. – dir. Torino

Figure 8: field measurements in "traforo del Pino" tunnel

These tests confirmed other important results obtained in the A1 campaign. For example, fixing the polarization, it was verified that light traffic marginally increases the attenuation index (+0.5 dB, see Table 6), as in the Banzole measurements.

Table 6: degradation index inside the tunnel

	H Pol.	V Pol.
dir. Turin – Pino T.se with traffic	6 dB/100 m	7 dB/100 m
dir. Turin – Pino T.se without traffic	5.5 dB/100 m	6.5 dB/100 m

Furthermore, once again horizontal polarization was best, with a gain of about 1 dB over vertical polarization in terms of signal degradation (45 dBµV/m criteria).

Although the limit of 45 dBµV/m might indicate a coverage of 700/800 m, it was verified by subjective listening that both polarizations totally ensured complete tunnel coverage (1 km approx.)

Tunnel in the SS 589 road between Avigliana and Giaveno (Turin area)

Other field tests were performed in a tunnel connecting the cities of Giaveno and Avigliana in the Turin metropolitan area, along the SP 589 road.

The transmitter was placed outside the entrances (both sides). The tunnel is 1935 m long and, unlinke the “traforo del Pino” tunnel, has a significantly curved morphology.

Tables 7 and 8 summarize the results in terms of coverage, considering the usual limit of 45 dBµV/m and the subjective listening criteria, respectively. This tunnel measurement also confirmed that actual receivers are able to ensure reception beneath the threshold of 45 dBµV/m.

Table 7: signal coverage according to link budget calculation

	Pol. H	Pol. V
Tx @ Giaveno side, Avigliana dir.	300 m	250 m
Tx @ Giaveno side, Giaveno dir.	430 m	250 m
Tx @ Avigliana side, Avigliana dir.	400 m	220 m
Tx @ Avigliana side, Giaveno dir.	200 m	220 m

Table 8: coverage according to subjective tests

	Pol. H	Pol. V
Tx @ Giaveno side, Avigliana dir.	630 m	380 m
Tx @ Giaveno side, Giaveno dir.	930 m	430 m
Tx @ Avigliana side, Avigliana dir.	540 m	320 m
Tx @ Avigliana side, Giaveno dir.	290 m	290 m

Because of the curved shape of the tunnel, tests showed that propagation is more critical in this kind of structure; in addition, it was verified that signal degradation does not follow the usual linear behaviour achieved so far (Figure 9).

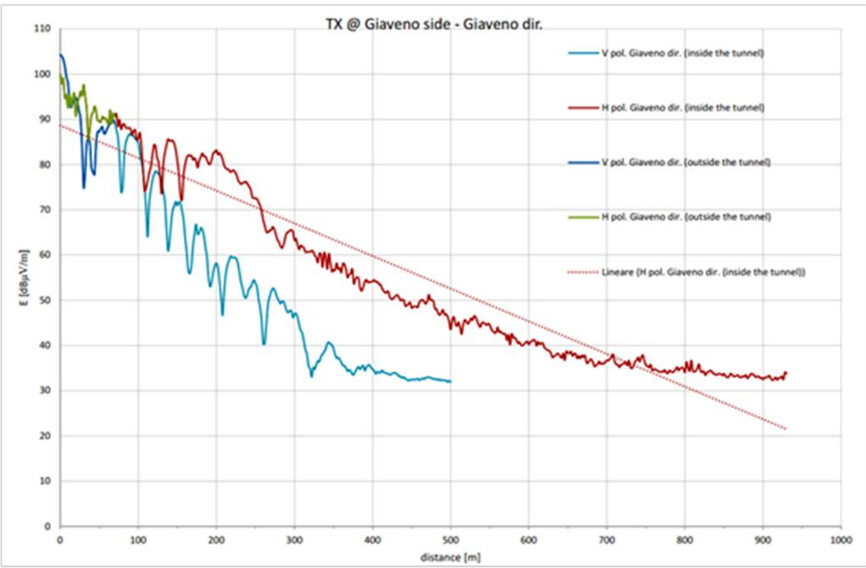


Figure 9: examples of bad linear approximation in presence of very curved tunnels

Turin-Aosta motorway (A5)

In the Aosta Valley the DAB+ service is actually on air with a SFN network between two TX systems in Col Courtil (25 W) and Saint Vincent – Salirod (40 W).

Table 9 summarizes the coverage results when receiving signals directly from HPHT transmitters. In the best cases, when the tunnel orientation is particularly favourable to HPHT signal penetration, the maximum tunnel coverage is about 100 - 180 m.

This confirmed the need for a complementary transmission system near or inside tunnels, to ensure the service continuity under mountains.

Table 9: A5 motorway, coverage from HPHT transmitters

	Penetration (2 TX - SFN network)	EM field at entrance [dBµV/m]	Margin [dB]	Penetration (Col Courtil only)	EM field at entrance [dBµV/m]	Margin [dB]
Montjovet tunnel dir. Entrèves (1339 m)	115 m	63	18	100 m	68	23
Montjovet tunnel dir. Torino (914 m)	N.A.	–	–	70 m	55*	10*
Petit monde tunnel dir. Entrèves (388 m)	40 m	49	4	35 m	58	13
Petit monde tunnel dir. Torino (834 m)	N.A.	–	–	180 m	53*	8*
Galleria Garin dir. Entrèves (357 m)	115 m	86	41	N.A.	–	–
Hône tunnel dir. Entrèves (717 m)	N.A.	–	–	57 m	53*	8*
Hône tunnel dir. Torino (795 m)	N.A.	–	–	17 m	50*	5*

*private network (not RAI)

COVERAGE CRITERIA AND RECEIVER BUDGET

Propagation tests in this document assume a threshold of about 45 dBµV/m as minimum mean field strength for satisfactory DAB+ reception (see link budget in Table 10) in accordance with [1].

As demonstrated during the test campaign, this threshold provides an additional margin of 13 dB over the threshold of a real DAB+ receiver, which still works down to about 32 dBµV/m. This 13 dB margin has been selected to guarantee a suitable location probability in tunnels and also corresponds to the margin which guarantees 99% location probability in an open-air HPHT transmission.

Table 10: link budget calculation in terms of potential coverage

Link Budget Parameters	Meas. units	Band III
Equivalent Noise Bandwidth B	[Hz]	1.536E+06
Rx Noise Figure F	[dB]	7.0
Required C/N (Rayleigh channel)	[dB]	13.5
Noise Power at the receiver	[dBW]	-135.1
Minimum input signal power	[dBW]	-121.6
Receiver Antenna gain	[dBi]	-0.1
Effective antenna opening	[dBm^2]	-7.6
Minimum power density	[dBW/m^2]	-114.0
Minimum equivalent field	[dBµV/m]	31.7
Absorption loss	[dB]	0.0
Margin in an open-air HPHT transmission		
Location probability (open-air)	%	99
Signal standard deviation	[dB]	5.5
Location Correction Factor (margin)	[dB]	12.8
Minimum mean power density	[dBW/m^2]	-90.2
Minimum mean field strength at 1.5 m	[dBµV/m]	**44.5**

DAB+ mobile transmitter system

A complete DAB+ chain, including audio encoder, ensemble multiplexer and transmitter was installed into a special van equipped with a telescopic mast that is able to elevate the antenna up to 15 m. The DAB-ETI signal was generated by encoding an audio source provided by a CD player. The DAB+ transmitter supplied the power of 10 W and, due to the cable insertion loss, was able to feed the antenna with the power of 4 W. Figure 10 shows the functional block diagram and Figure 11 shows the equipment at the transmitter side.

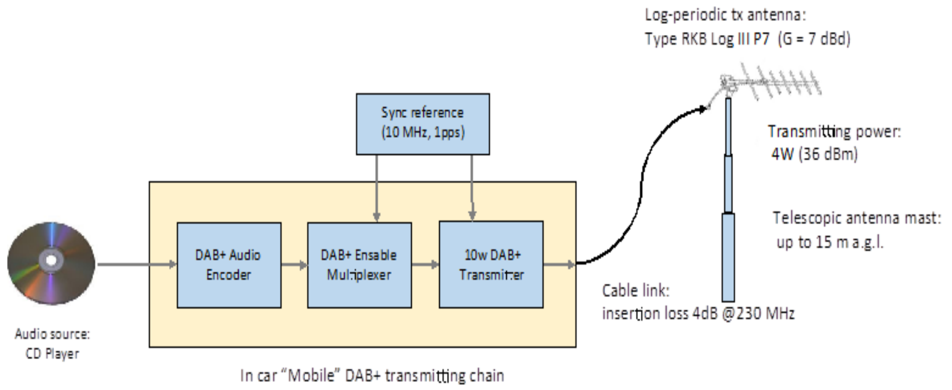


Figure 10: Functional block diagram of in car mobile transmitter

Figure 11: Equipment at transmitter side

The transmitting antenna was a log-periodic type RKB Log III P7 with a gain of 7 dBd (decibel gain relative to a dipole) at 230 MHz. The antenna radiation patterns and characteristics are shown in Figure 12.

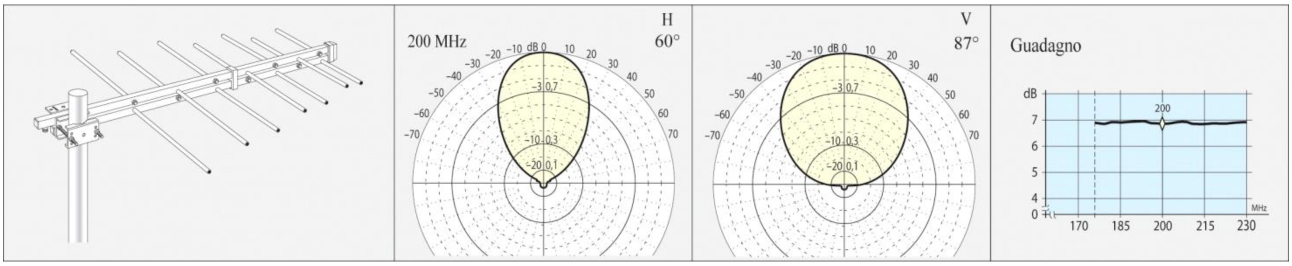


Figure 12: Log-periodic Antenna RKB Log III P7 characteristics

Signal variation: statistic analysis

Figures 3, 8, and 9 show that the received signal in tunnels is affected by two combined phenomena; the path-loss, which is the average signal attenuation between transmitter and receiver and the fading, due to low-delay multiple reflections.

In our analysis, the average path-loss was computed considering the "raw" measurement data set corresponding to 10 cm sampling spans, or about 12 samples per wavelength at 225 MHz. The DAB+ "null symbol" effect in some recorded data was removed before the analysis (see Figure 13). The fast-fading component was instead extracted by subtracting the power samples (dB) from the computed path loss (dB).

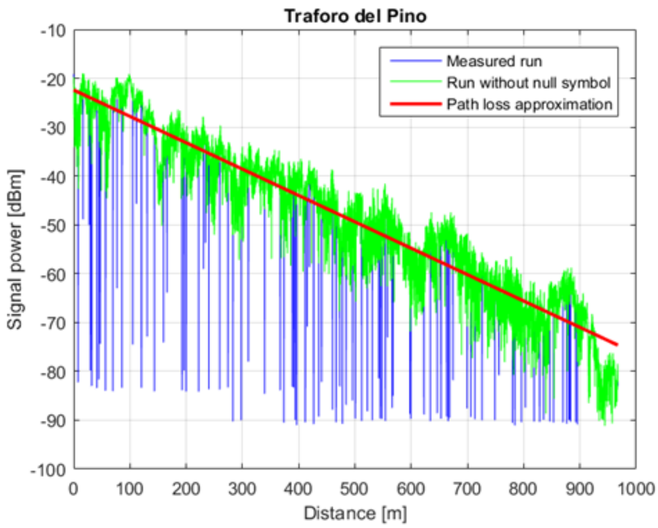


Figure 13: signal with and without null symbols

The result of such analysis applied to the measurement data sets without traffic in the "Traforo del Pino" (totally straight tunnel) is shown in Figure 13 (path-loss approximation) and Figure 14 (fading statistical distribution).

The results of the statistical analysis can be summarized as follows:

- The average (straight) tunnel path loss in far-field conditions (Figure 13) is about 5.5 dB/100 m (also see Table 6).

- The fading (dB) approaches a "quasi Normal" distribution (Figure 14, left), with μ ≈ 0 and standard deviation σ ≈ 4.8 dB. A location correction factor of 13.6 dB has been calculated on the measured samples in order to guarantee the coverage of 99% locations served (see Figure 14-right and Figure 15).

ITU-R P.1546-1 [1], used for planning the HPHT network, suggests the value of 13 dB for 99% location correction factor, corresponding to a standard deviation of σ = 5.5 dB. For simplicity and to provide an analogy between our results and the method described in [1], we decided to retain 13 dB as 99% correction location factor for tunnels, also.

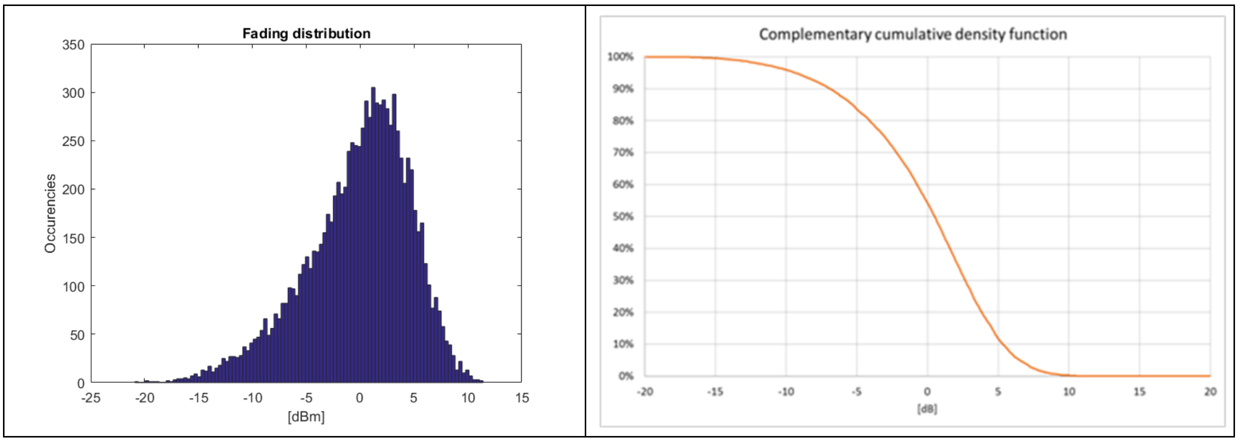


Figure 14: fading distribution (left) and cumulative density function (right)

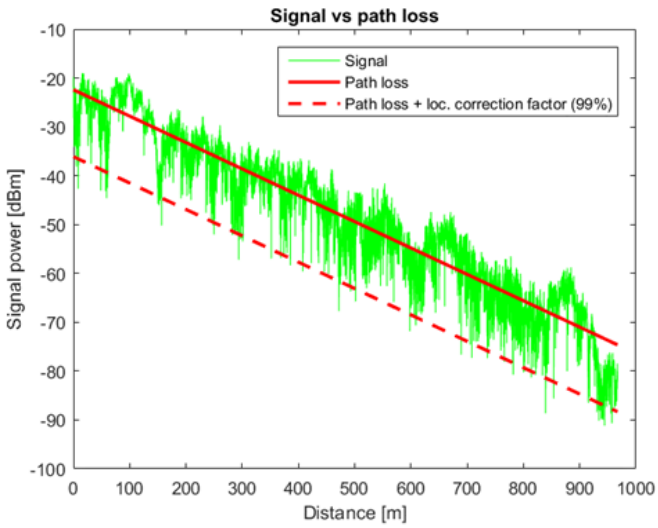


Figure 15: example of path loss with loc. correction factor

CONCLUSIONS

Based on Phase 1 and Phase 2 measurement campaigns, together with the additional tests performed in the Aosta Valley and in the Turin area, it is possible to conclude that tunnels are a non negligible bottleneck for DAB+ signal propagation around 200 MHz: in fact, in free space propagation conditions a 4 W signal transmission would ensure the DAB+ service coverage for several kilometres, while in tunnels the same signal can propagate for less than 1 km, also depending on traffic conditions.

The main aspects that emerged may be summarized as follows:

- "Direct radiation" via an antenna is an economically viable approach to extend DAB+ coverage inside tunnels, although the service quality is more traffic-dependent than the "radiating cable" approach, the savings on the network complexity and cost may be significant. Therefore, this last approach may be limited to very long or critical tunnels.
- The mimimum tunnel coverage achieved in our tests transmitting 4 W in presence of traffic is between 700 m (internal transmission from the entrance) down to 300 m (external transmission from a distance D <300 m from the entrance); transmitting from both sides of the tunnel would double such figures. Tunnels with such characteristics are the vast majority in the Italian motorways scenario.
- For very long tunnels (>1400 m), direct antenna transmission is not sufficient to ensure complete tunnel coverage: an internal signal retransmission is needed.
- Horizontal polarization should be used for transmissions to achieve the best performance, even with vertical receiving antennas.
- The minimum average field strength target of 45 dBµV/m can be used for planning in tunnels, offering a sufficient margin (around 13 dB) to guarantee a sufficient location probability for modern receivers (service threshold of about 32 dBµV/m). Such criteria are the same used for conventional open-air HPHT planning.
- Signal propagation is influenced by the tunnel morphology: in fact, the best propagation is achievable in straight tunnels. Sharp curves prevent propagation, thus internal signal repeaters may be necessary.
- Few cases of temporary service interruption have been detected in presence of heavy traffic conditions (for example when big trucks are running in parallel on all the lanes, blocking the line-of-sight between the transmitting and receiving antennas). A specific test campaign has been planned to analyse the statistics of those interruptions, in order to assess if reasonable quality of service targets may be fulfilled (e.g. >95% of time of good reception in the worst hour of the day).

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