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Radio Links for Highway Tunnels

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1 Introduction

The planned national highway system for Switzerland will include nearly 200 highway tunnels whose total length will be more than 200 km; i. e. about 10 % of the total highway length.

Figure 1 shows the number of national highway tunnels plotted as a function of length. Here it can be seen that roughly 50 of these tunnels are longer than 1 km and 100 are between 0.2 and 1 km long. The remaining tunnels are so short that at 80 km/h they are traversed in less than 10 seconds and are therefore of subordinate importance.

Without special measures, it is not possible to utilize mobile radios effectively or reliably. This is due to the high attenuation of the radio waves in the tunnel walls leading to communication break down within a short distance of the entrance.

Recently, various experiments have been carried out in railway and highway tunnels as well as in mine shafts. The most satisfactory radio link system tested so far utilizes a radiating coaxial cable and ordinary mobile radio equipment. Long tunnels require transmission subdivisions, this generating additional costs, particularly when multiple signals in different frequency bands are to be transmitted simultaneously. At the same time, complex intermodulation problems are generated.

Considerable literature on the subject of radiating cables has become available. However, nothing that will allow the detailed planning and implementation of such a system has as yet appeared.

Because of the complexity of the theoretical analysis of such a system it was decided that a careful empirical development would have to be untertaken.

Fortunately, *Huber + Suhner AG* in Herisau was interested in the development of radiating cables. As a result, a combined programme was worked out in which *Huber + Suhner AG* fabricated sample cables and the PTT carried out the electrical evaluations under real life conditions.

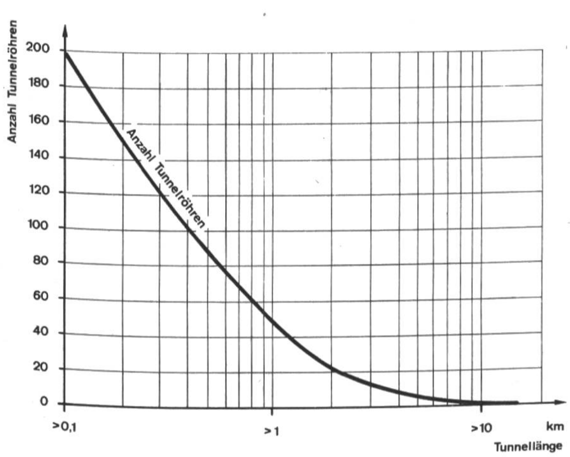

Fig. 1
Number and length of tunnels in the Swiss national highway network
Anzahl Tunnelröhren — Number of tunnels
Tunnellänge — Tunnel length

These efforts led finally to a cable design which is available today as a standard production item.

Based upon the gained information, experiences and the cable specifications it was possible to analyse the basic concepts for radio communication in tunnels, using low transmitter powers and inexpensive wideband amplifiers. These concepts were implemented in the 1.1 km long Baregg highway tunnel, near Baden. Four different radio services were tested: Vehicle identification/call, FM broadcast and mobile telephone in the 80 and 160 MHz bands. The final results fulfilled all expectations and complied with the predetermined specifications.

2 The Most Important Characteristics of Radiating Cables

The most important characteristics of radiating cables are attenuation and coupling loss. Both are influenced by the proximity of the tunnel walls. Reflections from the walls and interhole coupling along the radiating cable have profound effects on the coupling loss. As it can be seen in *figures 2* and *3,* the received signal has a strong fluctuating character, whose amplitude distribution approaches a *Rayleigh* distribution. Characteristics of commercially available cable are not readily comparable, and usually refer to cables measured in an uncluttered environment. Since we are primarily interested in providing radio communication for highway tunnels, the measurements and analysis would be more useful if carried out under the conditions prevailing in a typical tunnel.

The coupling loss is measured as the transmission loss between the transmitter end of the cable and a $\lambda/4$ monopole mobile receiver antenna, minus the corresponding cable attenuation *(fig. 4)*.

In this way, the maximum cable length between relay amplifiers can be determined

$$\iota_{max} = \frac{s-\beta}{\alpha}\,[\mathrm{km}]$$

where

ι Cable length in km
α Cable attenuation dB/km
β Coupling loss in dB
s System losses in dB

In order to extend to a maximum tue radiating range of the cable it is necessary in the design and mounting to keep the coupling- and cable loss as low as possible.

3 Investigation of Various Cable Types

The major difference between coaxial radiating cable and ordinary cable may be seen in the form of the outer conductor. Typically, the outer conductor carries a row

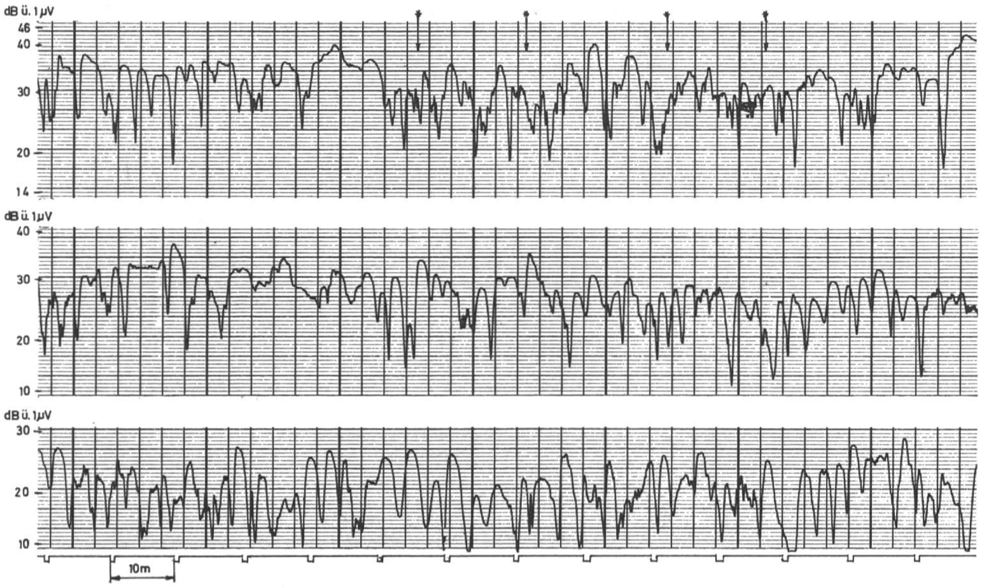

Fig. 2
Three typical examples of field strength measurements made in the Baregg north tunnel
Test frequency: 85 MHz; driving velocity: walking pace; recorder time constant: 0.25 s
The fast ripple designated by an asterisk (*) was generated by passing traffic

of holes along its length, or a continuous longitudinal slot.

In highway tunnels, the only possible mounting of such a cable is directly on the tunnel walls. Efforts were concentrated on establishing which form of radiating openings would provide the most efficient operation.

To this end, the cable types shown in *figure 5* were investigated. Three samples of each type, 100 metres long, having different percentage of open surface were produced.

The mesurements were carried out in a small PTT owned tunnel. The cable under test was mounted at a height of 1.5 m. Cable attenuation and coupling loss were determined, in one case the radiating slots facing the wall, and in the other away from the wall.

The measurements showed that the cable with the spiral slot possessed an extremely high attenuation and the leaky braid model a high coupling loss. These were therefore excluded from further consideration. Even the sample with the spiral hole pattern was considered unacceptable in its performance in comparison with the manufacturing costs involved. The proximity effect of the tunnel walls was investigated on the remaining 3 cable types. It was found that the radiating slot size, orientation, and position relative to the wall had a measurable effect on the useful operational length of the cable.

The smaller the radiating hole, the smaller the cable attenuation, and the larger the coupling loss.

In an effort to increase for the same cable size the operational length of the radiating cable, the solid polyethylene dielectric was replaced with a polyethylene foam. The cable types with the longitudinal slot and the axial line of holes were treated in this manner and measured. At the same time the cable impedance was raised from 50 Ω to 75 Ω allowing to reduce considerably cost and weight per unit of length. Both these measures produced an increase in useful operational lenght by about 10 to 20 % when the cable was mounted directly against the wall. Both types showed more or less equal electrical performance when the fraction of radiating surface was optimized and for direct wall mounting. Orientation effects were equally small in both cable types.

The cable type with axial line of holes was further tested for adverse effects generated by the presence of

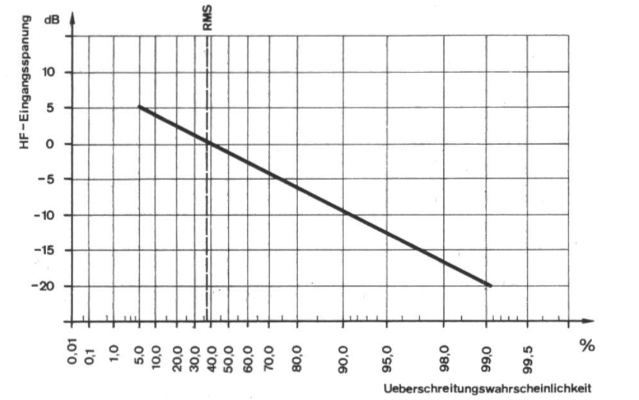

Fig. 3
Rayleigh distribution of field strength and coupling loss
HF-Eingangsspannung — RF input voltage
Ueberschreitungswahrscheinlichkeit — Probability of RF field strength exceeding ordinate value-%

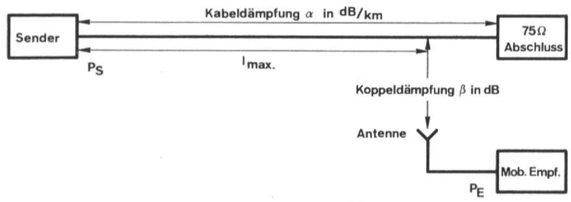

Fig. 4
Test set-up to determine the coupling loss
Sender — Transmitter
Kabeldämpfung α in dB/km — Cable attenuation α in dB/km
Abschluss — Termination
Koppeldämpfung β in dB — Coupling loss β in dB
Antenne — Antenna
Mob. Empf. — Mobile receiver

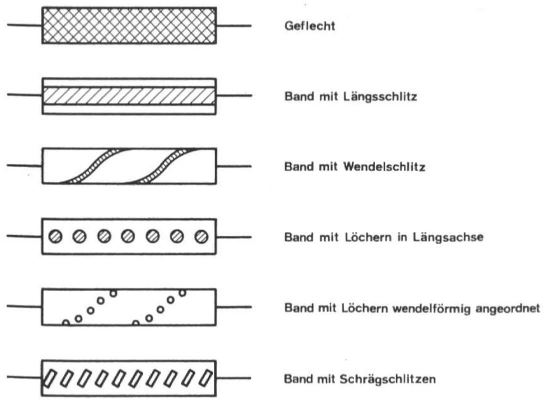

Fig. 5
Tested cable types
Geflecht – Braid
Band mit Längsschlitz – Outer conductor, longitudinal slot
Band mit Wendelschlitz – Helical slot
Band mit Löchern in Längsachse – Longitudinal line of holes
Band mit Löchern wendelförmig angeordnet – Helical line of holes
Band mit Schrägschlitzen – Longitudinal line of slanted slots

water and other pollutants. The materials tested are listed in *table I.* The results showed that the wetting or contaminating had practically no effect on the performance.

Table I. Cable Pollutants

Material	Electrical properties
Titanium dioxide powder	Good insulator, $\varepsilon_r \approx 100$
Aluminium powder	Good conductor, non-magnetic
Iron powder	Relatively good conductor, magnetic

Finally the frequency response of attenuation and coupling loss in the range 1 to 460 MHz was investigated on the same cable. The corresponding gain and conversion factors of the receiving antennas are listed in *table II.*

Figure 6 shows that the attenuation below 30 MHz is quite small and flat, but that the coupling loss is quite high and increases rapidly. In the higher frequency range, the coupling loss decreases only slightly but attenuation increases dominantly.

The foam cable with longitudinal line of holes was finally chosen for production. With the correct hole dimensions, this cable shows optimal performance independent of cable mounting and orientation with respect to the wall. These properties are not changed by the presence of water globules or pollutants on the cable jacket.

The basic electrical properties for this cable, designated as *S 17873-2,* are shown in figure 6. This cable type is available in various dimensions.

Noteworthy is the roughly inverse proportional behaviour of attenuation vs. cable size, whereas the coupling loss remains more or less constant.

4 Signal Strength and Signal to Interference Ratio (S/I)

Investigations with radiating coaxial cable have shown that the wall reflections cause large amplitude variations in the radiated field. At low RF levels, if the minima in the field are of sufficiently long duration, voice communication is either distorted or lost. On the other hand, short duration minima in the radiated field will only cause an increased of hissing noise. The net effect of these noise sources together with those of vehicle ignitions is to reduce intelligibility by only a small amount – sufficient however to be bothersome and undesirable.

As part of the requirements for a tunnel radio link, it was assumed that an «adequately» intelligible communication can be tolerated under extreme conditions. At all other times «good» quality with minor disturbances is specified. The subjective assessment of intelligibility or

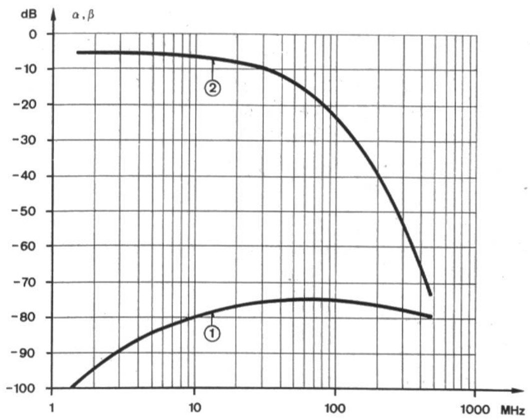

Fig. 6
Cable attenuation and coupling loss as a function of frequency (cable type S 17873-2)
① Coupling loss
② Cable attenuation

Table II. Mobile station antenna types

Frequency band in MHz	Type of antenna	Mounting of receiving antenna	*Factor K = $\frac{\text{Field strength}}{\text{Input voltage}}$	Gain over a $\lambda/2$-dipole
1	Telescopic antenna Hirschmann Auta 300 N	Front right in place of rear view mirror	11 m^{-1}	
30	Short monopole	Middle of car-roof	1 m^{-1}	
80	$\lambda/4$ monopole	Middle of car-roof	2 m^{-1}	0 dB
160	$\lambda/4$ monopole	Middle of car-roof	5.4 m^{-1}	–2.5 dB
460	$5/8\lambda$ monopole	Middle of car-roof	14.5 m^{-1}	–2 dB

* These factors were determined by measuring the received signal from 8 different directions (spaced 45°) around the car with a calibrated field strength meter

Table III. Signal strengths and signal to interference specifications in the tunnel

Radio Service		Specified signal level dB (µV)			Specified signal to interference in dB	
		Signal	Signal and noise	Signal + noise and impulse noise	Signal and unmodulated same channel interference (RF frequency shift: 300...1000 Hz)	Signal and unmodulated variable co-channel interference (RF frequency shift: 300...1000 Hz)
Voice radio 160 MHz (Mikrotel)	Quality level 3	2	4	11	23	20
	Quality level 4	18	18	25	36	36
FM radio broadcast (loudspeaker)	Quality level 3	5	9	10		
	Quality level 4	19	21	26		
Vehicle ident./call Call certainty 99 %		−4				

Noise = Frequency band restricted noise 90...360 Hz; volume 75 dB (A)

Impulse interference: Voice: level 51 dB (µV/MHz) on 50 Ω; Repetition frequency: 100 Hz; FM broadcast: level 55 dB (µV/MHz) on 50 Ω, repetition frequency: 100 Hz

Receiver sensitivity: Voice: 0.5 µV on 50 Ω for 20 dB signal to noise over telephone filter (deviation 3 kHz, modulation 1000 Hz); FM broadcast: 1 µV on 50 Ω for 20 dB signal to noise over music filter (deviation 22.5 kHz, modulation 1000 Hz); Vehicle ident./call: 0.3 µV for 90 % call certainty

quality according to the CCIR Report 358 corresponds to quality level 3 (= adequate) and 4 (= good) respectively.

To reduce the complexity of the measurements in the Baregg tunnel and keep the traffic limitations to a minimum, subjective hearing tests and system quality analysis were carried out in the laboratories by means of a multipath-signal generator, to establish the required signal strenght and S/I limits. Results are shown in *table III* for a vehicle speed of 80 km/h. The test set-up is shown in *figure 7.*

It this occasion the received signals of voice and FM broadcast were tape recorded and later compared to actual measurements in the Baregg tunnel. Good agreement was found between both measurements.

5 The Radiating Cable in the Baregg Highway Tunnel

For operational and safety reasons, the cable was mounted on the left (looking in the direction of travel) tunnel wall 4.5 m above ground. Newly developed mounting clips (Clic *E 16, Egli + Fischer AG,* Zurich) were used to support the cable at regular intervals of 1.5 metres.

The Baregg tunnel *(fig. 8)* possesses considerably larger section dimensions than those set up in the lab simulation. It was therefore expected that the coupling loss would increase correspondingly. However a control measurement carried out at 80 and 160 MHz in both lanes confirmed the previously measured values of figure 6.

For both frequencies an average of 76 dB *(fig. 9)* was determined for a vehicle speed of 40 and 80 km/h and in both traffic lanes. Further analysis of the data showed that neither traffic density, nor overtaking vehicles had any influence on the coupling loss.

Even the periodic cleaning of tunnel walls by rotating brushes and chemicals had no detrimental effects, electrically or physically, on the cable or the mountings.

6 Radio Service with Wideband Amplifiers

In most operational tunnel installations, the systems outlined in *figure 10a* have been adopted. Here the total system lenght is divided into sections. A two-way combiner/divider is introduced in the middle of each section. The receive/transmit signal must be coupled out of/into each section with the lowest possible losses in order to gain the longest possible section lenght. This is only possible with costly and space consuming filter circuits. A further problem exists in the fact that at each combiner junction there is a signal difference of 150 dB (T_x power = 10 watts, R_x power = 10^{-14} watts). The smallest non-linearity will therefore cause intermodulation products. For these reasons, this system concept is only applicable for short tunnel installations.

In the following we will investigate the system shown in *figure 10 b.* Here, the transmitters and receivers are located at opposite ends of the tunnel. Wideband equalized amplifiers are located at intervals through the tunnel, the equalizers compensating for the frequency dependent cable attenuation.

There are practical advantages to be gained with this technique; among them the saving of space.

The signal transmission problems associated with coaxial cables are already widely known. Therefore we will concentrate on some of the special qualities of radiating cable.

61 Positive Feedback into the Line Amplifiers

In contrast to other applications, a leaky radiating cable is utilized. The immediate question is: how large is the radiation coupling between the amplifier output/input terminals? To find an answer to this question, two cables were laid out on the ground. Output to input attenuation at a distance of a few mm was ≥86 dB and at 30 cm >100 dB. Since each amplifier has a maximum gain of 40 dB there is no possibility for self oscillation.

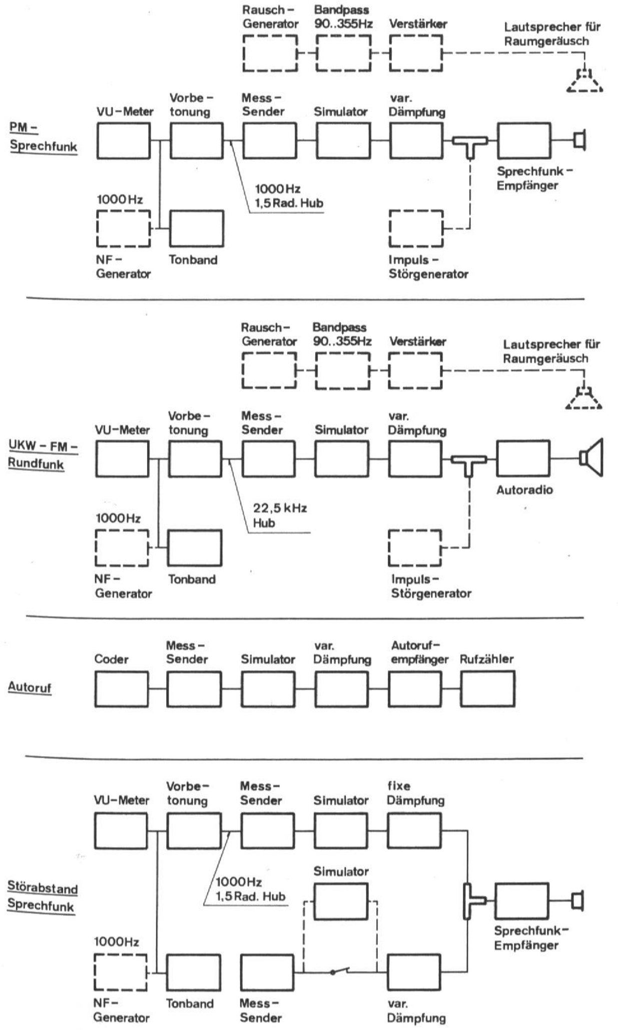

Fig. 7
Test set-up for the subjective determination of the specifications for signal levels and signal to interference ratio in connection with a multipath signal simulator
PM-Sprechfunk — PC voice radio
VU-Meter — VU-meter
Vorbetonung — Pre-emphasis
Rauschgenerator — Noise generator
Bandpass 90...355 Hz — Bandpass 90...355 Hz
Verstärker — Amplifier
Lautsprecher für Raumgeräusch — Loud-speaker for ambiant noise
Mess-Sender — Test transmitter
Simulator — Simulator
Variable Dämpfung — Variable attenuator
Sprechfunk-Empfänger — Voice radio receiver
1,5 Rad. Hub — 1,5 rad. deviation
NF-Generator — Low frequency generator
Tonband — Tape recorder
Impuls-Störgenerator — Impuls noise generator
UKW-FM-Rundfunk — FM broadcast
Autoradio — Car radio
Autoruf — Vehicle ident./call
Coder — Coder
Autorufempfänger — Vehicle ident./call receiver
Rufzähler — Call counter
Störabstand Sprechfunk — Signal to interference ratio for voice radio

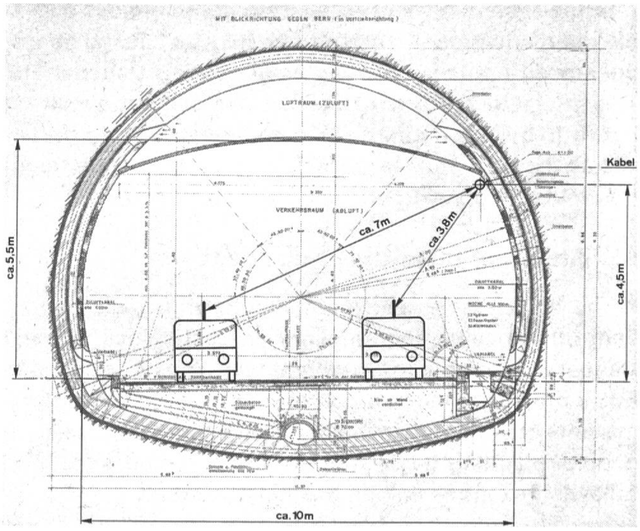

Fig. 8
Cross section of the tunnel
Kabel — Cable

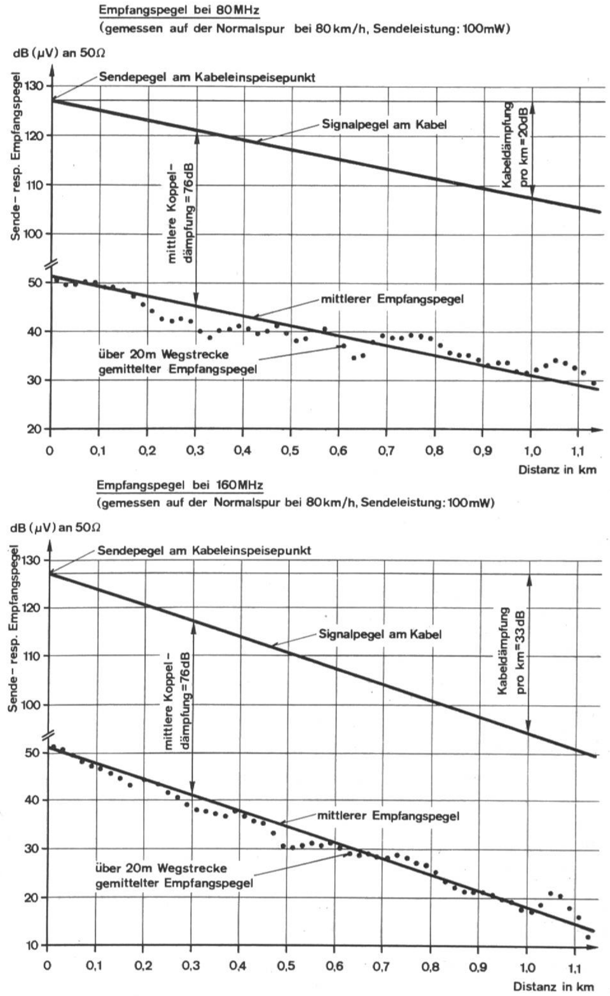

Fig. 9
Received signal level at 80 and 160 MHz
Empfangspegel bei 80 und 160 MHz (gemessen auf der Normalspur bei 80 km/h, Sendeleistung: 100 mW) — Received signal level at 80 and 160 MHz (measured at 80 km/h, T_x power = 100 mW)
Sendepegel am Kabeleinspeisepunkt — T_x level at the cable input
Sende- resp. Empfangspegel — T_x/R_x signal level
Mittlere Koppeldämpfung — Average coupling loss
Signalpegel am Kabel — Signal level on the cable
Mittlerer Empfangspegel — Average R_x level
Ueber 20 m Wegstrecke gemittelter Empfangspegel — R_x level averaged over measured every 20 m
Kabeldämpfung pro km — Cable attenuation per km
Distanz in km — Distance in km

62 The Received Signal in the Vicinity of an Amplifier

In the Baregg tunnel, a 35 dB wideband line amplifier was switched on between two cable sections, and the level of the RF signal was recorded. *Figure 11* shows the mean values of the level found, resulting from an averaging over 20 m intervalls. It may be seen that the signal begins to increase its level approximately 30 m ahead of the amplifier position.

In the system of figure 10a using commercially available radio equipment, interference may be caused by frequency differences between neighbouring transmitters. This problem does not occur in the system shown in figure 10 b. Only doppler shifts and delay times differences as the they appear in free space multipath propagation must be considered.

63 Amplifier Intervals, Cascadeability

The choice of amplifier interval is principally dependent on the cable and amplifier characteristics, highest frequency, number of channels and length of tunnel. Every project requires a compromise solution for transmission quality and reliability versus minimum cost. A general planning guide was therefore not possible. The following example will be examined instead.

The system contains 8 channels for PTT services and 3 extra channels for police and tunnel maintenance services *(tab. IV)*. Here it is assumed that all the channels are allocated in the frequency range most suitable for

Table IV. Channel allocations

	One-way Base — mobile	Simplex	Duplex	Frequency
National vehicle Telephone network (NATEL)			2	160-MHz-band
Telephone call (NATEL)	1			160-MHz-band
Vehicle ident./call	1			72.6 MHz
FM broadcast	1			87.6...104 MHz
Other services		3		80- or 160-MHz-band

coaxial radiating cable operation in tunnels (68 to 174 MHz). The 460 MHz mobile band may be considered for short tunnels, but becomes inefficient and unreliable for long tunnels, due to an increase in cable attenuation by at least a factor 2.

The *TRW model CA 2600* line amplifier developed for use in cable TV applications was considered the most economical. Maximum output power for 1 dB compression is approximately 1 Watt.

Because of the narrow (25 MHz) channel spacing, intermodulation products will, with high probability, fall between the useful channel frequencies. Within certain bounds, it is possible to ensure that this happens as for example in the National Vehicle Telephone Network (NATEL), where a choice of 12 channels is available. Here it is possible to reach greater dynamic range of the amplifier, as it is possible in cable TV systems. The most critical interference occurs when intermodulation products fall into a mobile to base station transmission channel. *Figure 12* shows the necessary interference protection as a function of amplifier output power per channel as well as the measured margin between signal and intermodulation signal up to the 5th order when both have equal power. The sum of the interference products of each amplifier determines the system quality. This means that the intermodulation interference protection per amplifier in a system containing 10 to 20 amplifiers must be better by 15 to 20 dB

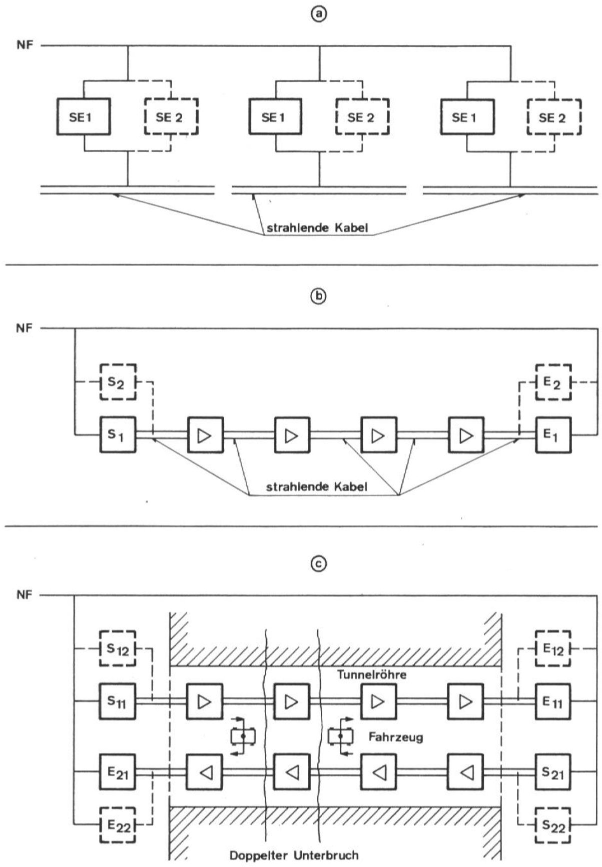

Fig. 10a...c
Block diagram for tunnel radio link
S Sender — Transmitter
E Empfänger — Receiver
SE Sender-Empfänger — Transceiver
NF Niederfrequente Sprech- und Rufsignale — Low frequency voice and call signals
Strahlende Kabel — Radiating cables
Tunnelröhre — Tunnel
Fahrzeug — Vehicle
Doppelter Unterbruch — Double failure

than the specified protection value. Figure 12 shows for short tunnels that the specified interference protection is achieved for a 17 dBm o/p power, when the station to mobile signal possesses no intermodulation products up to the 3rd order. For longer tunnels, depending on frequency, up to 5th order intermodulation products must be rejected. Furthermore, figure 12 shows that for a

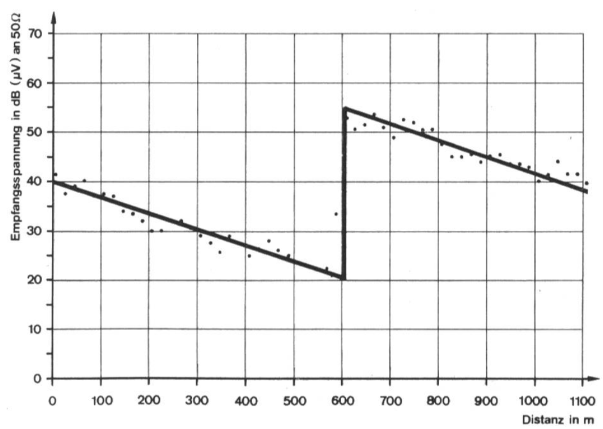

Fig. 11
Average received signal strength along a cable with line amplifier
Empfangsspannung in dB (µV) an 50 Ω — Received voltage in dB (µV) on 50 Ω
Distanz in m — Distance in metres

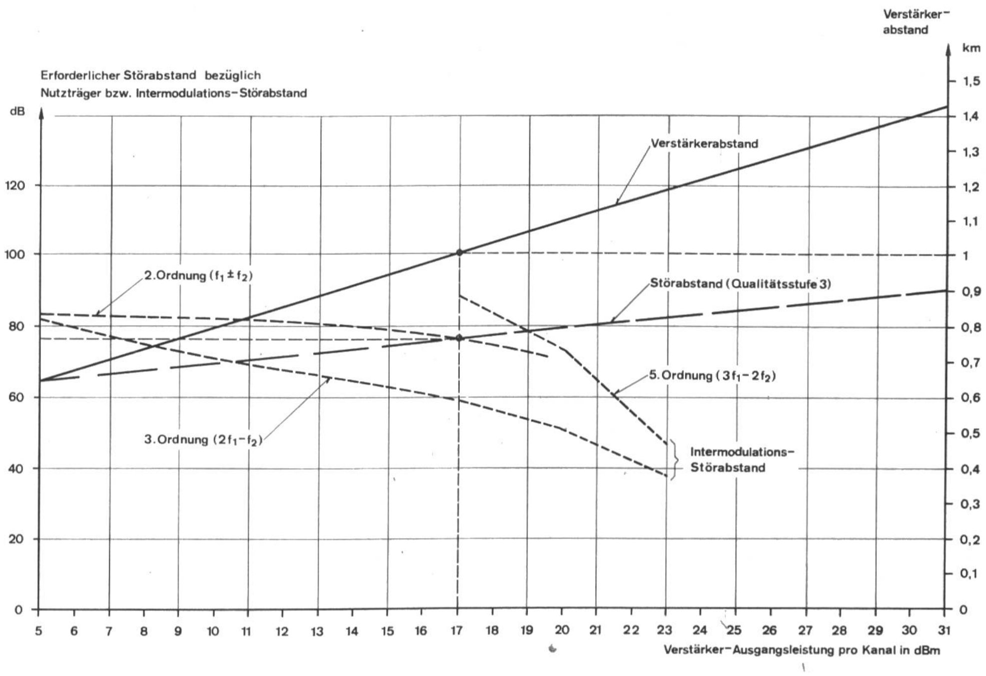

Fig. 12
Noise rejection and line amplifier spacing as a function of channel power

Frequency band: 160 MHz; cable attenuation: 33 dB/km; coupling loss: 76 dB; mobile power: 10 W. Average received signal: 15 dB (μV) on 50 Ω; co-channel S/I ratio = 23 dB
Erforderlicher Störabstand bezüglich Nutzträger bzw. Intermodulations-Störabstand — Specified signal to intermodulation noise ratio
Verstärkerabstand — Line amplifier spacing in the tunnel
2. Ordnung — 2nd order
3. Ordnung — 3rd order
5. Ordnung — 5th order
Störabstand (Qualitätsstufe 3) — Signal to noise ratio (quality level 3)
Intermodulations-Störabstand — Signal to intermodulation noise ratio
Verstärker-Ausgangsleistung pro Kanal in dBm — Line amplifier output power per channel in dBm

power of 17 dBm, the maximum line amplifier spacing is 1 km.

Figure 13 depicts the relative signal strenghts along the entire transmission line and at the input to the mobile receiver. For the case mobile to base station transmission, figure 13 also gives for the extremes conditions the corresponding minimum and maximum power levels. An 8-port passive combiner/divider (for instance a Anzac DS-309, with interport decoupling ≥30 dB and 10 dB of insertion loss) was assumed for the combining respectively subdivision of the transmitter and receiver signals. The main characteristics of such system are summarized in *table V.*

Due to low cable attenuation in the 80 MHz band and the greater NATEL receiver sensitivity, it was possible to reduce signal power by 10 dB. This assisted in reducing the system loading. For voice radio base station to mobile, a margin of 6 dB above the minimum for quality level 3 was attained. A similar level reduction for FM broadcast was not made due to the rather large variations of antenna gain and receiver sensitivities to be expected.

The vehicle ident./call signal could possibly be reduced by 10 dB to further reduce system intermodulation interference.

In the case mobile to base station, a signal power margin of 26 dB was attained. However, amplifier generated noise has not been considered in the previous values. The noise figure of these amplifiers is 7 dB for the amplifiers used, which is about the value for the typical mobile equipment receiver used at the cascade end, leads for 20 amplifiers to a reduction of S/N of about 13 dB. Apart from spurious intermodulation, it is seen here that the mobile to base station link, even in long tunnels, will offer better quality than base station to mobile radio link.

It must be pointed out that the specifications of the base receiver with respect to selectivity, intermodulation, interchannel decoupling, can be quite conservative. Figure 13 indicates that within a given frequency band, signal variations of 53 dB can occur. Due to the separation of transmitter and receiver, no duplexers are necessary.

A 3 km long section of a radio link as just described was simulated in the laboratory, with 2 amplifiers, and with system characteristics as described in figure 13. The system consisted of 5 mobile, 1 FM broadcast station and 1 test transmitter. The frequencies and signal levels, monitored at the combiner terminals and amplifier outputs, are shown in *figure 14.* The available frequencies at the base station transmitters were free from intermodulation up to the 5th order. The experiment showed that all channels (including two extra mobile to base duplex channels) possessed a signal to interference ratio of >80 dB (limit of test receiver), relative to 124 dB (μV). Only the two transmitters in adjacent channel perturbed each other slightly through their self generated noises. Here the interference rejection was 76 dB and 74 dB respectively for both channels, which is more than satisfactory. The transmitters were also modulated and the quality of the radio link was evaluated at the system output. No reduction in quality could be observed even for the particularly critical AM vehicle ident./call.

At this point, a further interfering intermodulation effect needs to be considered. If several duplex channels are operated simultaneously, 3rd order intermodulation products due to the 4.6 MHz duplex intervals fall into the

Table V. Summary of the most important system characteristics

1 Service	2 Level at the o/p of the combiner (Base to mobile) dB (μV)	 mW	3 Minimum average amplifier output in dB (μV) (Mobile to base)	4 Necessary rejection in dB	5 Necessary rejection of co-channel interference w.r.t. 124 dB (μV) in dB	6 Minimum receiver signal in dB (μV)	7 Necessary receiver signal in dB (μV)	8 Margin of receiver signal in dB
Simplex voice radio 80 MHz								
Base to mobile	114	5		8	76	18	11 (4)	7 (14)
Mobile to base			71	23		41	2	39
Simplex voice radio 160 MHz								
Base to mobile	124	50		8	76	15	11 (4)	4 (11)
Mobile to base			71	23		28	2	26
Duplex voice radio 160 MHz (NATEL)								
Base to mobile	124	50		8	8	15	11 (4)	4 (11)
Mobile to base			71	23	76	28	2	26
Telephone call 160 MHz (NATEL)								
Base to mobile	114	5		8	18	5	0	5
Vehicle ident./call								
Base to mobile	114	5		8	18	18	−4	22
FM broadcast								
Base to mobile	124	50		20	20	28	10 (9)	18 (19)

The values in brackets do not take into account impulse noise

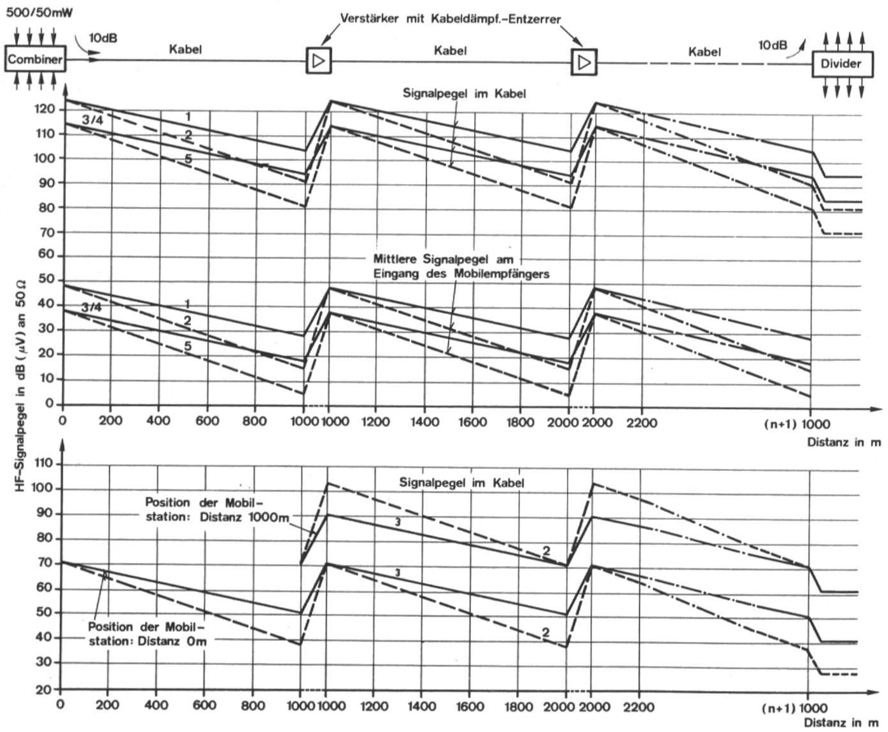

Fig. 13
Power budget

1 UKW-Rundfunk – FM broadcast
2 Sprechfunk 160-MHz-Band – Voice radio 160-MHz-band
3 Sprechfunk 80-MHz-Band – Voice radio 80-MHz-band
4 Autoruf – Vehicle ident./call
5 Ruf NATEL – Telephone call NATEL
Kabel – Cable
Verstärker mit Kabeldämpf.-Entzerrer – Amplifiers with cable attenuation equalizer
Signalpegel im Kabel – Signal level on cable
Mittlere Signalpegel am Eingang des Mobilempfängers – Average signal level at the input to the mobile receiver
Verbindung Fix → Mobil – Transmission base to mobile
HF-Signalpegel in dB (μV) an 50 Ω – RF signal level in dB (μV) on 50 Ω
Distanz in m – Distance in metres
Verbindung Mobil → Fix (Sendeleistung Mobil: 10 W) – Transmission mobile to base (T_x power: 10 W)
Position der Mobilstation: Distanz 0 m und 1000 m – Position of the mobile station: distance 0 m and 1000 m

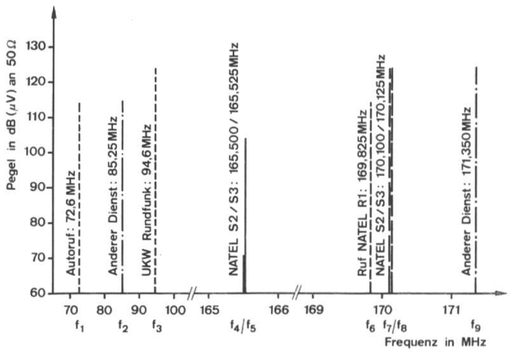

Fig. 14
Test system frequencies and levels
- - - - - One way base to mobile
—·—·— Simplex
— —— Duplex base-mobile
———— Duplex mobile-base
Pegel in dB (µV) an 50 Ω — Level in dB (µV) on 50 µ
Autoruf — Vehicle ident./call
Anderer Dienst — Other service
UKW-Rundfunk — FM broadcast
Ruf NATEL — Call NATEL
Frequenz in MHz — Frequency in MHz

mobile to base station channels. In this particular case, the product $f_5+f_7-f_8$ is identical with f_4 (or $f_5=f_4+f_8-f_7$). Since the signal of frequency f_5 varies as a function of time according to figure 2, a corresponding variation in the intermodulation level becomes evident. The amplitudes of the wanted and interfering signals in channel f_4 represent two uncorrelated varying signals of random level. Over short tunnel stretches, the level distribution approximates a Rayleigh distribution. The average channel level distribution shown in figure 14 occurs at any amplifier output when the interfering vehicle operating on f_5 finds itself immediately before the input of the line amplifier, and the receiving vehicle on channel f_4 near the output.

The average interference level can be determined from the 3rd order intermodulation protection curve of figure 12. For this extreme case, the average interference level is 51 dB (µV), and the difference between the average levels of useful and interferring signals is 20 dB. According to table 3 this still conforms to quality level 3. On the average, an interference protection (S/I) of 53 dB can be expected, whereby it must be noted that intermodulation products of the various line amplifiers are additive.

In summary, it is possible to provide a radio link along the maximum 16 km long national highway tunnels using the above described concepts. The most economical interval between amplifiers is 700 to 1000 meters. Despite of the generally small temperature variations inside of tunnels, probably ALC (Automatic Level Control) amplifier must be introduced at regular distances, in the case of long stretches where the total cable attenuation can reach several hundred of decibels.

64 Operating Reliability

The transmitters and receivers, due to their complexity, possess probably the smallest MTBF (Mean Time Between Failures) of the system. Even though the estimated MTBF of modern hybrid wideband amplifiers exceeds 10 years, any failure becomes very important. Failure of just 1 line amplifier causes a total system failure. Redundant parallel amplifiers should therefore be considered.

The public safety services such as police, ambulance and fire departments require reliable radio service at all times, even during catastrophes, particularly fires or an explosion. These requirements could be met with the system of figure 10c. The entire technical system is redundant in the opposite direction of transmission. Normally only 1 system is operational, whereby it is easily monitored by a pilot frequency fed at the beginning of the line and received at the other end (for instance a UHF-signal). In the event of failure, the system can be switched over to the parallel redundant circuit. In the event of a catastrophe, the radio link can be realized up to the failure point, by operating both redundant circuits. This however is only possible if the amplifier power supply itself stems from a «disaster proof» source and not through the cable as it often done. Another possibility would be to operate normally both systems simultaneously with different channels, restricting the transmission in case of perturbation to the most important services.

Cost analyses have shown that in longer tunnels the 1+1 redundant system is still considerably more economical than that of figure 10a.

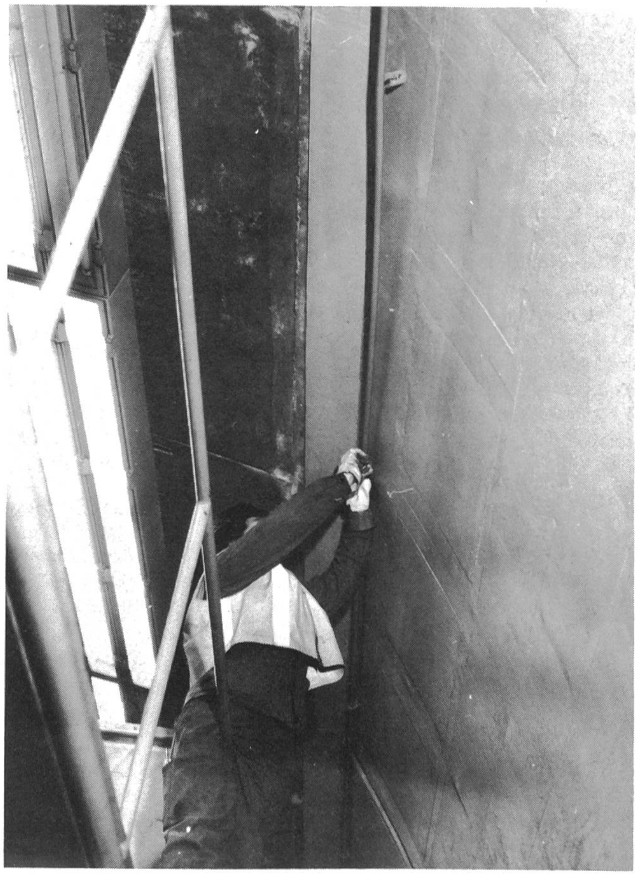

Fig. 15
Installation of a radiating cable in a highway tunnel