Power supply systems for cellular communications repeaters

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1. Summary

Cellular communications networks require the use of cellular repeaters (especially in mountainous areas) which are specifically designed to solve problems regarding insufficient coverage by the radio field in special situations. Thruway, railway and subway tunnels are some of the most common cases. Various repeater technologies such as leaky cables, antennas fed with coaxial cables and antennas fed with optical fibres are used, depending on the distances to be covered. A different type of power supply is used with each of these technologies. A central power cabinet is always included. This cabinet, which is generally installed on the road or railway bed, draws its power from public electric lines and must continuously supply the type of power required by the chosen repeater system. The cabinet may contain power supplies, batteries, or DC/AC or AC/DC converters. In certain cases, it is equipped with radio gear that provides communication with the nearest radio base station. The power supplied by the cabinet is drawn from its output line at intervals of 250-500 metres and furnished to the radio-frequency system. Radio-frequency signals (0.45 - 1.8 GHz) and certain supervisory signals (75 - 455 kHz) may be sent down the output line, whose resistance may vary from 2 to 20 ohms. In special situations such as railway tunnels, the currents induced by the transit of locomotives (which draw currents exceeding 5 kA) must be taken into consideration. The guidelines of project design include choice of voltages and type of current (continuous or alternating), degree of protection specified for the equipment, methods of handling ground potentials in the presence of surges that may cause malfunctions, and safety regulations. Diverse solutions are considered, and both currently operative systems and projects to be implemented in the future are presented for evaluation.

2. Cellular extension networks

In the procedure normally used for effecting radio transmissions between fixed stations and mobile stations, when the strength of the signal from the original station falls below minimum levels (as the mobile station moves from one point to another), the mobile station does not transfer the transmission in progress to another station without interruption. Now, thanks to the capability of transmitting data between fixed and mobile stations (and between the fixed stations themselves), a transmission can be transferred without interruption from a fixed station to an adjacent fixed station which is closer to the mobile station. The network of fixed stations created in this way is called a "cellular network", since each fixed station (called a "radio base station" or RBS) is the centre of a cell which is under the jurisdiction of that fixed station. Theoretically, this cell has a hexagonal shape.

2.1. Methods of radio-electric coverage used by TACS, GSM and DCS systems

In Europe, the best known cellular networks are called TACS, GSM and DCS. The first two operate at frequencies ranging from 870 to 960 MHz, while the third network (which has not yet been placed into full service) operates at a centre frequency of 1,800 MHz. GSM and DCS systems are completely digital, while the less recent TACS system operates with analogue modulation. The system is based on cells with a range of 1,000 to 5,000 metres. A radio base station (RBS) is located at the centre of these cells. Each base station has been assigned three groups of carriers operating at different frequencies, both along the direction extending from base station to mobile station (downlink) and in the opposite direction (uplink). Timed switching channels (TDMA) are the technology used for creating the uplink and the downlink. Naturally, the frequency groups used by the three cells surrounding a given cell are different from the frequencies used by that cell.

When a transmission is made by a mobile station on any group of frequencies in a cell, the communication channel to be used is determined by a special control channel. This communication channel remains active until the mobile station changes position. When the mobile station leaves the area which is exclusively serviced by the initial group of frequencies, it moves into a handover area (an area in which two frequency groups are simultaneously present). In this area, the strength of the original communications signal is reduced and the strength of the signal from one of the adjacent cells increases as the mobile station approaches that cell. In the case of TACS equipment, when the originating RBS senses that the signal is too weak, it orders the mobile station to switch to the channels of the adjacent cells until the base station controller (BSC) has identified the most suitable destination cell. Then, the transmission is totally transferred to the proper adjacent cell. In GSM and DCS systems, the mobile station, too, can perform the handover procedure when the received signal becomes too weak.

2.2. Limits of radio-electric coverage by RBS

Besides an insufficient number of cells, the following factors limit coverage by a cellular communications system:

- Road, railway and subway tunnels
- Buildings that are especially well-shielded
- Radio-electric shadow areas (city centres)
- Mountainous or hilly areas
- Zones without cells, where the coverage is necessarily limited

The situation involving tunnels is the most clear-cut case. The other cases can be resolved by increasing the density of the cells; however, this solution may not be advantageous because the radio-frequency signals may be reflected (especially in mountainous or shadow areas), which causes spurious handovers and probable losses of transmissions. Without a doubt, the most economical solution when frequencies are arranged by sector is to "illuminate" the shadow area with a repeater (cell extension system) that acquires radio-frequency signals from a radio base station and re-transmits them in a "dedicated, unaltered manner" into the shadow area, thus avoiding undesired handovers. Another problem to be considered during handovers is the speed at which the mobile station is moving. Since the search procedure for the mobile station is performed over 6 bands of carriers, it may require prolonged execution times. Measurements have revealed that such times may exceed 15 sec. in certain cases. At a speed of 150 kph, a vehicle travels at about 42 metres per second, which results in a distance of approximately 625 metres over the 15 second period. In a cell with a range of 2,000 metres, the field of possible handover does not exceed 500 metres. As a result, when the procedure is begun, the mobile station may be seen simultaneously in three bands of carriers belonging to three different RBS stations. It thus becomes impossible to determine the zone into which the signal should be transferred.

We shall discuss only the situations involving tunnels in the following paragraphs, since the cell extension technologies that are suited to solving such problems can easily be applied in a general way in these situations.

2.3. Solutions for extending coverage limits using cell extension systems

As was described above, the coverage limits of radio base stations can be extended by using cellular repeaters that re-transmit a band of carriers from the nearest radio base station into the area or environment to be served. The simplest method for reaching this goal is to use a radio reception/transmission antenna pointed toward the nearest radio base station, a bi-directional amplifier and a radiating element (for example, an antenna) whose spatial transmission characteristics (range, angle of aperture and angle of curvature) can be controlled sufficiently. Antennas are the radiating elements generally used when the areas to be covered are mostly straight. On the other hand, radiating cables (also called leaky cables) are used when the horizontal and vertical planes are curved. We shall now analyse these two cases separately.

2.3.1. Antenna-antenna systems

As can be seen in figure 1, an antenna-antenna type of cellular repeater system is made up of an RBS antenna, a radio-frequency amplifier and an RMA antenna.

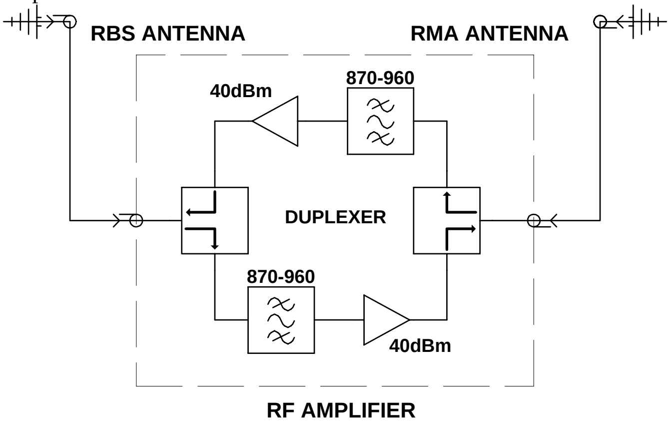

Fig. 1 - Antenna-antenna cellular repeater

The signal received by the RBS antenna (from the closest RBS, which is called the "donor RBS"), is amplified and sent to the RMA antenna, which is pointed toward the shadow area to be "illuminated". The signal from the mobile station, which is received by the RMA antenna, is treated in the same way and sent to the donor RBS. The characteristics of the three elements making up the system are as follows.

RBS antenna

The RBS antenna, which is rather simple in design, must provide good gain and good isolation from the signal radiated by the RMA antenna. It must also be directional enough so that it does not receive other bands from the donor RBS. This antenna is generally a Yagi with 4-5 directors.

RMA antenna

This antenna is more complex than the RBS antenna, since it must provide excellent gain and, in certain cases, a relatively acute angle of radiation, as well as circular polarisation of the electromagnetic field when used in tunnels. It, too, is generally a Yagi or a Helix-type antenna.

Amplifier

The bi-directional amplifier is a fundamental element in a cellular repeater system. It must offer excellent selectivity (the frequencies used in the TACS and GSM systems are adjacent to UHF television frequencies) and an excellent noise figure. Also, the duplexer must provide exceptional separation between the two sides. In many cases, a number of mobile telephone companies must be serviced in the same area. As a result, the amplifier must be able to selectively handle only certain channels received from the radio base stations located in that area. Finally, electric power consumption must be taken into consideration, since the level of consumption may limit (at least, from an economic standpoint) the use of a cellular repeater in certain cases.

2.3.2. Antenna-cable systems

In these systems (see figure 2), which are identical to the system described above as far as the RBS antenna and the bi-directional amplifier are concerned, the radiating element is not an antenna but a leaky cable.

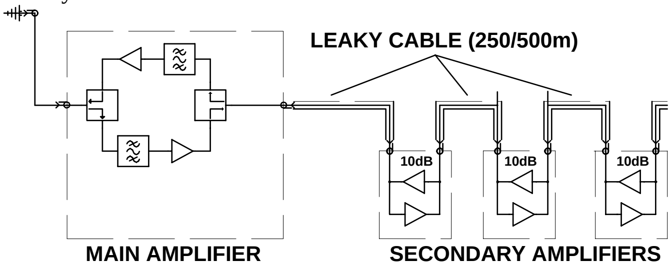

Fig. 2 - Antenna-cable cellular repeater

Antenna-cable systems are used when the area to be "illuminated" is very large (up to 10 km) and curved along both the horizontal and vertical axes. The additional elements in this system with respect to the antenna-antenna system are as follows.

Radiating cable

This special type of coaxial cable is equipped with slits along the external element (shield) which allow the radio-frequency signal to be emitted. The principal specifications for this cable are:

- External diameter	33 mm
- Typical impedance	50 Ω
- Losses at 1 GHz	< 40 dB/km
- Electrical resistance	< 2 Ω/km

Secondary amplifiers

As can be noted in the specifications for the cable, the signal loss at a frequency of 1 GHz is approximately 40 dB / km. For this reason, the signal received from the RBS side (and vice-versa) must be boosted at established distance intervals and with a gain equal to the loss inherent in the cable. Thus, the gain must be 10 dB if the amplifiers are located every 250 metres, 20 dB if they are placed every 500 metres, and so on. To obtain a uniform field and optimise energy consumption, only distance intervals of 250/500/750 metres, with gains of 10/20/30 dB respectively, are generally used. The amplifier must be rather selective in this case as well, even though no channel separation filter is required since the signal from the main amplifier is already filtered properly.

2.3.3. Antenna-optical fibre-antenna systems

This type of cellular repeater system is made up of an RBS antenna, a radio-frequency amplifier with a bi-directional laser-type converter, a connection using optical fibre technology and a number of secondary amplifiers with RMA antennas.

The signal received from the closest RBS (the donor RBS) by the RBS antenna is amplified and sent through an optical fibre system to secondary amplifiers which are each connected to their own RMA antenna. These amplifiers are located at distances of approximately 1,500 metres along the shadow area to be "illuminated". The signal received by the RMA antenna from the mobile station is treated in the same way and sent to the donor RBS. The characteristics of the elements making up the system are as follows.

RBS antenna

This antenna is identical to the equipment used in the systems described above.

Primary amplifier

This amplifier is identical to the unit used in the other systems described above, except for the fact that it is equipped with a bi-directional electro-optical transducer that converts the radio-frequency signal into an optical signal which is sent toward the zone to be "illuminated", and vice-versa in the opposite direction.

Optical fibre connection

This connection is made with either a glass optical fibre equipped with output-input branches, or a star-shaped bundle of optical fibres. The losses at a frequency of 1 GHz in a system of this kind do not exceed 3 dB/km.

Secondary amplifiers

As can be gathered from the specifications of the optical fibre connection, the losses at 1 GHz are only 3 dB/km. Thus, unlike the antenna-cable system, the signal does not have to be boosted in order to compensate for losses occurring during transfer. In this case, an amplifier is located at the end of the line to obtain a signal that is strong enough to pilot its antenna and thus assure the required minimum field strength in the shadow area. Naturally, the secondary amplifier is also equipped with a bi-directional optical transducer. To obtain a uniform field and optimise power consumption, only distance intervals of 1000/1500 metres are generally used.

2.4. Service reliability requirements

Technological developments in cellular systems have directly or indirectly enabled these types of telephone systems to be also used for services that are different from the specific purpose of private communications. A common case in this regard involves emergency calls for reporting road accidents and the use of cell phones by maintenance personnel working for electric, gas and water companies and the telecommunications companies themselves. Thus, the need for extending the cellular network into areas that are not currently served also derives from these considerations. For these motives - and naturally, for economic reasons - cellular extension systems must ensure that the relative service is sufficiently reliable. The following are the principal reasons why service may be unreliable when repeater systems are used.

- Unavailability of the signal from the donor radio base station
- Unavailability of channels due to saturation caused by inter-modulation of the carriers
- Malfunction of radio-frequency equipment
- Malfunction of power supply
- Malfunction of power line

Given the high MTBF values for electronic devices, the system reliability provided by cellular extension equipment depends on the number of malfunctions on the power supply line (the first two cases listed above have been excluded from this observation, since they are generally a function of the Erlang number which was used to determine the size of the system).

In order to obtain service reliability that reaches 99% of total operating time, the following estimates have been made. These estimates are a function of installation location, power lines, availability of power sources and the times required for service calls by electric company personnel:

Average time between malfunctions on power feed:	1500 hrs
Average repair time:	1 hr
Maximum repair time:	12 hrs

In view of the above estimates, in order to assure the desired level of service, the system must be equipped with a separate power source having an autonomy of at least 6 hours and an MTBF of at least 80,000 hours.

3. Power supplies for extension systems

Taking into consideration the possible solutions to limitations in radio-electric coverage and the possible environments where cellular extension systems are installed, one of the most important problems to be solved when such systems are installed regards the availability of electric power for the radio-frequency equipment. Often, cellular extension systems must be installed in existing tunnels which were not designed to meet the requirements of these systems. If renewable sources of electricity are excluded (because of their elevated cost, limited availability and the high power required), the only source which can be readily obtained in an entire geographic area is still conventional AC power from public power lines. A primary power station is installed near the primary radio-frequency equipment to furnish the correct voltage and ensure that the power is continuous enough for providing the required level of service. We shall now analyse the various problems which may arise.

3.1. Physical availability of electric power sources

Diverse solutions can be found in the various installation environments under consideration, depending on the presence of a public power line and on the type of radio-frequency system chosen.

3.1.1. Road and thruway tunnels

Existing AC power lines which have been installed for other uses may be available, depending on the length of the tunnel. These lines are most commonly used to power the illumination system in the tunnel. In general, this type of power line can be tapped at any point before it enters the tunnel. It is practically impossible to tap these lines inside the tunnel, since they are shut down from the illumination control panel under certain conditions of outdoor illumination. In particularly long tunnels, connections to the public power line can often be found at fixed distances from one another. These connections are used by maintenance personnel and in case of accident.

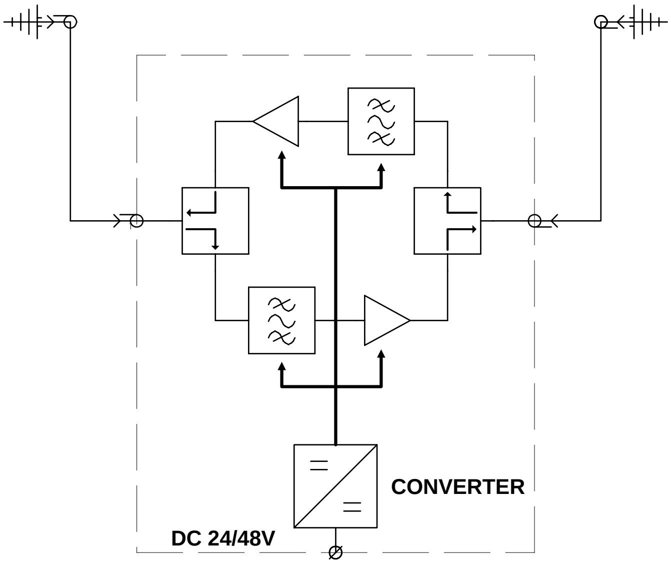

Fig. 3 - Antenna - antenna system: electric energy distribution

The following limitations must also be considered.

- An illumination system might not be present in relatively short tunnels.
- Independent power for the cellular extension system must be provided in case the illumination system malfunctions.

- The control circuits for the illumination system may be located at large distances from the entrance to the tunnel, which makes it impossible to use the existing power lines.

- The lines to the intermediate power connections in the tunnel are generally designed to supply a low level of power.

- The company which runs the cellular extension system prefers to register the energy costs for its system on its books in an independent manner.

3.1.2. Railway tunnels

Unlike road tunnels, railway tunnels are rarely equipped with existing power lines, either at the entrance or inside the tunnel. Illumination systems virtually do not exist in such tunnels. Also, in the few cases where a power line has been provided, it usually cannot be used because it belongs to the safety, signalling and traffic control system. In particularly long tunnels, a surveillance station with an electric power line may be located at the halfway point in the tunnel.

3.1.3. Subway tunnels

In this case, a power source is almost always available both at the subway station and inside the tunnel. Due to the short distances between stations, a power line up to 500 metres long can generally be installed, if necessary.

3.2. Type of electric power required by cellular extension systems

3.2.1. Antenna-antenna systems

In this type of system, which includes one or more receiving and transmitting antennas as well as a selective bi-directional amplifier, only one radio-frequency station is present. This station generally requires only one input voltage (24 or 48 VDC) and uses 200-400 W.

Primary radio-frequency unit

As can be seen on the figure 3, 24 or 48 VDC power is supplied to the operating components by a DC/DC converter installed in the radio-frequency unit. One of two solutions can be used to supply this voltage, depending on the degree of reliability desired for the cellular service and on the reliability of the AC power source.

- An AC/DC power supply used instead of the DC/DC converter
- A continuity system supplying DC power

The reliability of service provided by the first solution, which is sufficiently well-known, depends on the reliability of the AC power source. The second, less conventional solution consists of the following components.

- An AC/DC power supply acting as a battery charger
- A battery bank

In this case, the reliability of service does not depend on the reliability of the AC power source, since DC power can be supplied from the batteries if the AC power fails. Since a battery bank is used, the radio-frequency unit must be able to function over the wide range of voltages (generally, 48 VDC ± 20%) that are generated when the batteries are charged and discharged.

3.2.2. Antenna-cable systems

In this type of system - which is made up of one or more receiving antennas, a selective bi-directional amplifier located outside the tunnel (primary amplifier) and a series of selective bi-directional amplifiers located inside the tunnel (secondary amplifiers) - the primary amplifier is similar to the one used in antenna-antenna systems. However, the secondary amplifiers may use 5-50 W of power, and the input voltages required by their radio-frequency circuits may vary from 5 to 12 V.

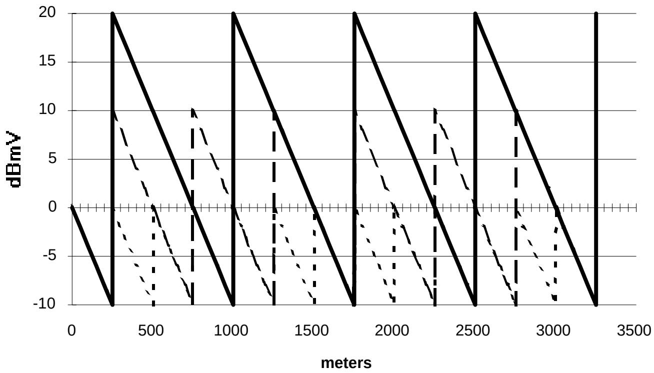

Fig. 4 - Secondary amplifiers RF levels

The significant differences in power drawn by these amplifiers depend on the distance intervals at which they are installed inside the tunnel.

As can be seen on the figure 4, where cases with amplification every 250/500/750 metres are shown, amplification with a gain of 10, 20 and 30 dB respectively is necessary in order to assure a minimum signal strength of -10 dBmV (threshold for guaranteeing a signal field that is strong enough to provide connection between the mobile station and the repeater). In terms of radio-frequency power, these gains are equivalent to approximately 1, 10 and 100 mW. Figure 5 depicts the radio-frequency power introduced into the line in the three configurations. The power drawn by each of the amplifiers is proportional to the values of radio-frequency power introduced into the line.

From the above discussion, it can be concluded that the best solution is to further reduce the distance between the amplifiers in order to reduce the power drawn by the entire system. This is impossible for the following reasons:

- The cost of the amplifiers is virtually the same regardless of gain. Thus, the total cost of the system would be too high.
- An overly large cascade of selective amplifiers causes a reduction in the passband of the amplifiers at the end of the line, which makes the amplifiers at the beginning of the line less selective. The final result is the risk of intermodulation distortion.
- Much of the power used by a secondary amplifier is drawn by its supervisory and control circuits, so that the total power drawn by the system increases proportionally as the number of secondary amplifiers increases.

In actual practice, it turns out that secondary amplifiers can be installed at distances of 250 and 500 metres.

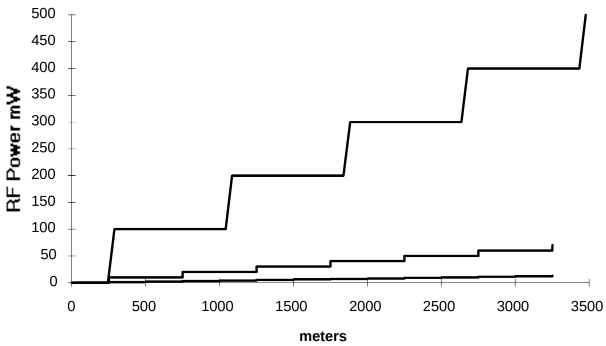

Fig. 5 - Injected RF power

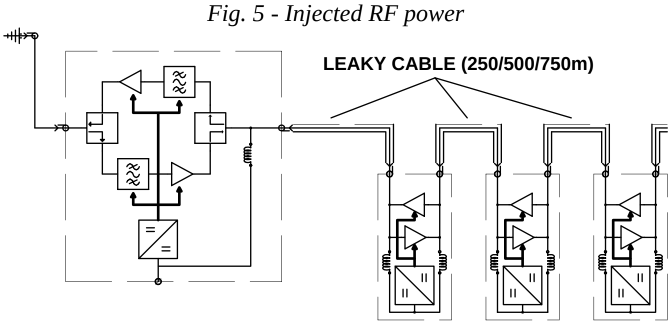

Fig. 6 - Antenna-cable remote powering

The following are possible methods for powering the secondary amplifiers.

- The use of power that is independent from the primary amplifier;
- The use of power that is connected in parallel with the primary amplifier;
- Powering the secondary amplifiers in series from the primary amplifier.

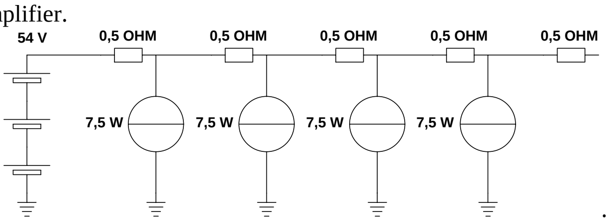

Fig. 7 - Remote powering schematic diagram

Except for the first case, power from the primary amplifier can be sent down the cable used for radio-frequency signal transmission or down a separate cable. In the systems dealt with in this paper, the former solution is used.

The use of power that is independent from the primary amplifier

In systems where a source of low-voltage alternating current is available (for example, in subway tunnels), the simplest solution is to include an AC/DC power supply together with the amplifier. Given the low power requirement involved, this power supply can be included in the same housing that contains the radio-frequency circuitry. This solution does not need further explanation because it is so simple.

The use of power connected in parallel with the primary amplifier

The architecture of secondary amplifiers is shown on the figure 6. A voltage of 60 V drawn from a 30-element lead-acid battery can be used to power this type of amplifier.

This voltage is connected in parallel with the coaxial cable through a decoupling inductance. Each secondary amplifier connected in line draws the power required for its operation (7.5W) from the input side of the line through a decoupling inductance. The same power travels through another inductance toward the output side of the line to feed the subsequent amplifiers. The schematic diagram for this system is shown on the figure 7. For simplicity's sake, the inductances have been omitted since they do not affect the electrical dynamics of the system.

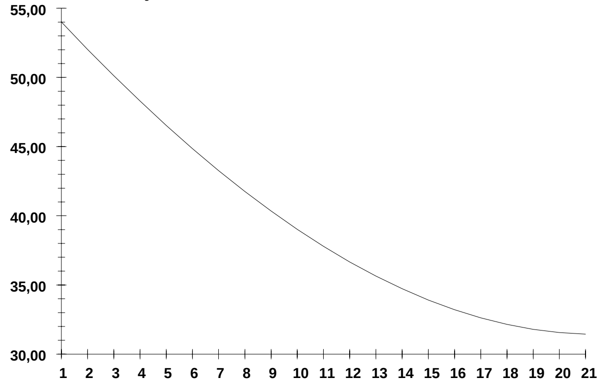

Fig. 8 - Amplifiers voltage
(trunk=250 m - Node power = 7,5 W - V = 54 V)

The battery voltage to be considered when calculating the voltage drop along the line is the minimum voltage measured at the end of the battery's discharge cycle (54 V).

The voltage diagram obtained along the line is shown in the figure 8. The relative function can be analytically expressed as a quadratic equation with constant coefficients. This equation has two solutions; one solution is discarded since it would indicate negative power consumption (supplied power).

In this system, the point of instability at the established voltage, power consumption and resistance is found exactly at the 22nd node, which is located at approximately 5,500 metres from the primary amplifier.

In order to extend the radio-frequency field to the degree required and in order to maintain a sufficiently wide security margin, it is necessary to work with the following parameters when determining a solution:

- Modification of the power drawn by the amplifiers
- Modification of the resistance in the sections of line between the amplifiers
- Modification of the voltage fed to the input side of the line

Due to current technological limitations, the first two parameters cannot be changed. As a result, the voltage must be increased, or at least it must be held stable when the batteries discharge in order to obtain curves with an inflection that is shifted at least 4-5 sections further down from the active sections on the line.

Since safety regulations limit the voltage on the feed line to a maximum value of 72 V, a DC/DC converter-stabiliser has been included. This unit applies a stabilised output voltage of 70 V to the starting end of the leaky cable. The architecture obtained in this way is shown on the figure 9. The voltage diagram obtained along the line under these conditions is also shown on the figure 10.

The function represented in the figure presents an inflection at the 29th section, which is located approximately 7,250 metres from the starting end of the leaky cable. The use of a DC/DC converter improves the system in the following ways:

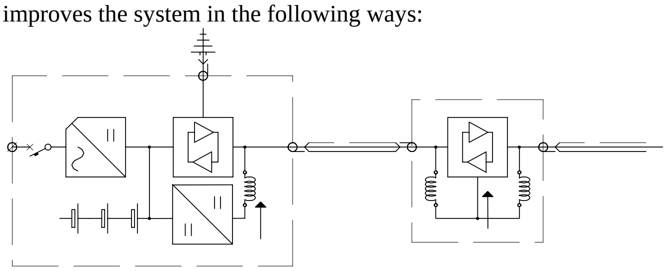

Fig. 9 - Remote powering with DC/DC converter-stabiliser

- The power drawn by the secondary system is reduced, since the amount of current circulating through the cable is reduced (even though the same amount of the power is drawn by each secondary amplifier), leading to a consequent reduction in RI^2 losses.

- The current drawn if a short-circuit occurs in the cable is limited by the regulator in the converter.

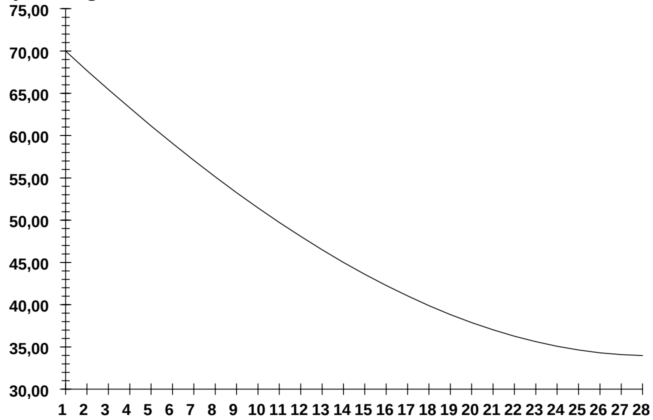

Fig. 10 - Amplifiers voltage (trunk = 250 m - V = 70 V)

- Increased short-circuit impedances make it easier to design the devices which protect against voltage surges.

In any case, for reasons having to do with operational security margins and system efficiency, it is not convenient to use this configuration over a distance of more than 5,000 metres. When this distance is exceeded, the voltage supplied to the secondary amplifiers drops so low that high currents are drawn, which has a negative effect on the functionality of the system.

By installing a single DC/DC converter-stabiliser ahead of the radio-frequency splitter (3dB RF splitter or Wilkinson splitter), the power feed system described above can also be used effectively in double tunnels equipped with a double leaky cable.

If sections of tunnel more than 5,000 metres long must be "illuminated", intermediate voltage stabilisation must be provided along the section through the use of one or more converters of the same type as the one used at the beginning of the cable.

The architecture thus obtained is depicted in the figure 11. If double voltage conversion is used along the line, the length of "illuminating" cable can be extended to an effective distance of up to 8,500 metres. The voltage diagram obtained along the line under these conditions is depicted in the diagram 12.

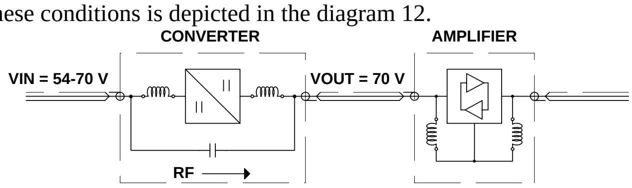

Fig. 11 - Remote powering with intermediate voltage stabilisation

As can be noted from the diagram, the inclusion of two converters along the line provides a choice of three curves with different input powers. A sufficient margin of system stability is nonetheless maintained. The inflection of the first curve is located at approximately the 8th section, the inflection of the second curve is at the 20th section, and that of the third curve is at the 38th section. By operating at the limit of system stability, it is theoretically possible to reach a length of around 12,000 metres. However, for reasons associated with efficiency, reliability and convenience, it is advisable to limit the system to no more than 35 operating sections having a total length of 8,750 meters.

In any event, it must be remembered that prevailing European regulations prescribe a maximum voltage of 120 V (including any AC ripple) for a "safe" DC power source. As a result, by increasing the feed voltage on the secondary amplifiers, it is easily possible extend the line to 15,000 metres.

Powering the secondary amplifiers in series from the primary amplifier

Another method for powering the secondary amplifiers is the so-called "in series" method. In this method, 60 V supplied by a bank of batteries is used to power a DC/DC converter that introduces (through an inductor) a direct current into the coaxial cable in a way that is similar to the method of power feed in parallel with the primary amplifier.

Converters installed in the secondary amplifiers (whose power feed lines are connected in series) transform this power into the proper voltage for the amplifier circuitry. The converters thus cause a voltage drop on the coaxial cable that is proportional to the transferred load.

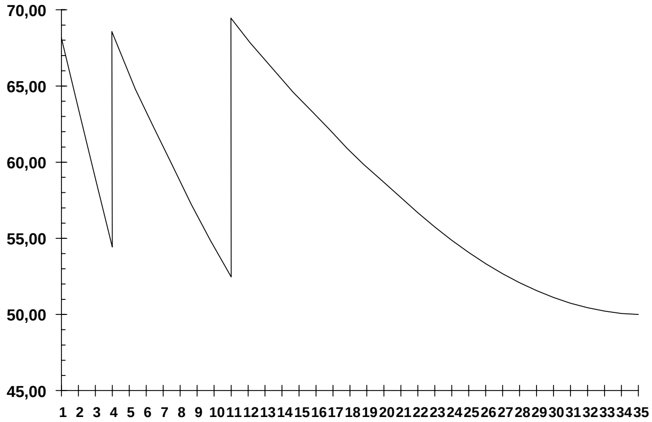

Fig. 12 - Amplifiers voltage with two stabilisations

Taking into consideration the resistance of the coaxial cable, the transferred load (approximately 7.5 W) and the maximum voltage allowed by safety regulations (72 V), it turns out that the optimum current for introduction into the cable is around 4 A and that the maximum number of amplifier units which can be powered in this way cannot exceed 15.

A comparison between parallel power feed and series power feed, as well as between direct current and alternating current

In order to correctly compare the various types of power feed, it is first necessary to consider the voltage limits imposed by European regulation EN 60439-1, which are:

- Class 0 systems: those with a nominal voltage which is less than or equal to 50 V if alternating current is used, or 120 V if direct current (not pulsating DC) is used.

- Class 1 systems: those with nominal voltage from 50 V to 1000 V if alternating current is used, or from 120 V to 1500 V if direct current is used.

In Italy, a law named D.P.R. 547 (1956) limits voltage in Class 0 systems to 72 V in the case of direct current, only.

When radio-frequency systems with external antennas are used, it is always convenient to connect one pole of the power feed line to the ground circuit, thus creating a PELV (Protective Extra Low Voltage) system whose low voltage classifies it as belonging to Class 0.

The use of a PELV system also eliminates the need to ground the isolated housings of the secondary amplifiers inside the tunnel for the purpose of providing effective protection against accidental indirect contact. However, it is important to remember that during the passage of a high-speed train drawing currents exceeding 5,000 A, the ground potentials along the track may in some cases assume potential differences of more than 2-3 V/m. Thus, when secondary amplifiers are placed at distances of 250 meters from one another, potential differences with respect to ground of 500 V may occur. When the housings of the secondary amplifiers are grounded, short-circuit loops are created in the shield on the coaxial cable, which causes harmfully high currents to circulate both through the amplifiers and through the cable itself.

The use of Class 0 systems is convenient and preferable, but the choice of parallel or "in series" power feed systems must be made. This choice fundamentally depends on the length of the section to be "illuminated". The limit of 15 units placed at distances of 250 metres from each other restricts the use of the "in series" system to tunnels whose length does not exceed 3,500 metres, while lengths exceeding 8,500 metres are possible with the parallel system.

On the other hand, the use of alternating current both in the parallel and the "in series" configurations is decidedly inconvenient, since safety regulations limit maximum voltage to 50 V. In any event, it must be considered that when alternating current is used in parallel systems, it is very simple to keep the voltage along the line virtually constant by including a step-up transformer in each secondary amplifier unit; the transformer both supplies power to the amplifier section and compensates for the voltage drop along the line, so that the voltage is kept constant.

In any event, in tunnels that are more than 8,500 metres long, it is indeed possible to use alternating current with a voltage exceeding 50 V, but only to power secondary amplifiers and only if the following conditions are met:

- The system will not belong to Class 0, but to Class 1. As a result, the secondary amplifier and coaxial cable must be properly protected against accidental contact, both direct and indirect.
- If the shield in the coaxial cable must be grounded (generally, on the outside of the tunnel), the system will no longer be considered PELV but TN-C.
- The voltage drop which is due to the circulating power feed on the shield must not exceed 50 V.
- Only specialized personnel may be allowed access to the secondary amplifiers.
- A differential safety switch must be installed so that all the amplifiers are shut down in case of accidental contact, whether direct or indirect.

Because this type of system is quite complex, it should be used only in very special cases. For example, a parallel direct current system can be used to "illuminate" tunnels up to 17,000 meters long by installing two primary amplifiers outside the tunnel (at both entrances), and two secondary systems with leaky cable, each secondary system having a maximum length that does not exceed 8,500 meters.

3.2.3. Antenna-optical fibre-antenna systems

In these systems, the radio-frequency signal is transported from the primary amplifier to the secondary amplifiers by an optical fibre. As a result, a metal conductor is not available for use by the power feed system as in antenna-cable systems. We shall now individually analyze the configurations of the primary and secondary amplifiers used in this type of system.

Primary amplifier

From the point of view of power feed, this primary amplifier is practically identical to the one used in antenna-antenna systems. The presence of the bi-directional electro-optical transducer does not have a significant effect on the operating voltage or the amount of power drawn.

Secondary amplifiers

The absence of a metal conductor for transporting the radio-frequency signal requires that a power line be provided between the primary amplifier and the secondary amplifiers, unless independent local power sources are available near the secondary amplifiers (as is the case in subway tunnels).

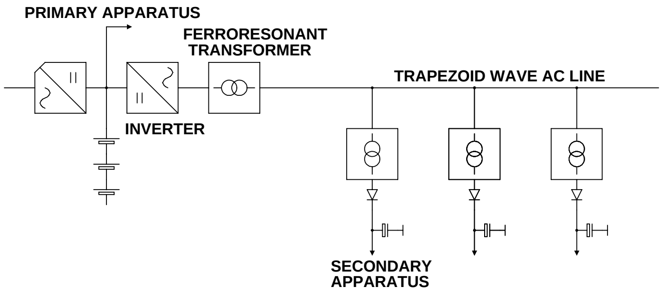

Fig. 13 - AC trapezoidal remote powering

The high power (around 100 W) drawn by secondary amplifiers placed at a distances of 1,000 meters does not allow operation at voltages that would qualify the system for Class 0 status, which also excludes the use of PELV circuits. The most convenient scheme turns out to be the one depicted in figure 13.

This scheme is composed of the following elements:

- A rectifier and 60 V battery, as in the systems previously described.
- An MOS inverter, which transforms direct current from the battery into current with an unstabilised square wave having a frequency of 50 or 60 Hz.
- A ferro-resonant transformer/voltage stabiliser with output voltage of 230 VAC @ 50-60 Hz, trapezoidal.
- A power feed line, integrated together with the optical fibre cable, having a cross-sectional area of 10 mm^2 and resistance of 3.4 Ω/km.
- A transformer/rectifier for powering the secondary amplifiers.

The use of a ferro-resonant transformer/voltage stabiliser with trapezoidal output current provides the following advantages:

- Excellent isolation from the primary amplifier is obtained, so that any interference on the power feed line is not propagated toward the battery.
- A stable voltage is generated by the power supplies in the secondary amplifiers, even if the battery voltage varies.
- The trapezoidal waveform significantly facilitates the design of the power rectifiers in the secondary amplifiers.

The alternating current used to feed the power line also makes it simple to include an intermediate voltage booster which permits the usable distance to be extended to more than 20 km, an advantage that was seen in the antenna-cable systems powered from a parallel line.

3.3. Ambient conditions of installation

Before examining ambient conditions of installation, it is first necessary to distinguish between the following cases:

- Primary amplifiers installed at railway or road tunnels
- Secondary amplifiers installed in railway or road tunnels
- Primary and secondary amplifiers installed in subway tunnels

Primary amplifiers for railway or road tunnels are normally housed in insulated shelters made of metal or cement. The internal volume of the shelter varies between 5 and 8 m^3. Considering the power dissipated by the radio-frequency equipment and the primary power supply (approximately 700 W), and considering the maximum outdoor temperature (which in temperate climates does not normally exceed 40°C), it is sufficient to provide a forced ventilation system that can maintain shelter temperature at 45 °C. With regard to low temperatures, the power dissipated by the equipment is sufficient to maintain an internal temperature of -5 °C when the outdoor temperature is -20 °C. When the equipment is first turned on at low temperatures, the power dissipated by the isolation transformer on the battery charger is sufficient to heat the inside of the shelter to -10 °C in less than 6 hours. In this situation, the amplifiers need only be protected against accidental direct contact and against drops of moisture dripping from the ceiling in the shelter; an IP31 level of protection is generally sufficient.

Secondary amplifiers installed in railway or road tunnels are subjected to smaller variations in temperature (-10 °C to +35 °C), although greater protection against the penetration of rain and dust must be provided; an IP65 level of protection is generally sufficient.

The primary and secondary amplifiers installed in subway tunnels operate under less severe conditions as far as temperature (+10 to +35°C) and protection against rain and dust are concerned; an IP44 level of protection is generally sufficient.

4. Conclusions

In this paper, a number of possible solutions for powering cellular extension systems were analyzed. The fact that these systems are used in special environments such as railway, road and subway tunnels requires that each installation be carefully evaluated in terms of choice of radio-frequency equipment and determination of the most suitable power feed system.

During the design of various projects of this kind, the authors were able to analyze cases of installation in subway tunnels and street tunnels and, last but not least, along the recently designed Naples-Reggio Calabria leg of the railway system running along the Tyrrhenian ridge in Italy. This railway system is more than 500 kilometres long and has over 100 tunnels of various lengths and configurations. The project involves the use of antenna-antenna systems, antenna-cable systems and antenna-optical fibre-antenna systems. The longest tunnel examined is 15,300 metres long. In this tunnel, two antenna-cable systems are used. Each system is equipped with 31 secondary amplifiers, and the systems are powered from the eastern and western entrances, respectively.

Bibliography

[1] T. Klemenschits, "Wave propagation in road tunnels - The method of image antennas" COST 231 TD (95)/33

[2] Parkhomenko, "Electrical properties of rocks" Plenum Press N.Y.

[3] Tarter, "Solid-State power conversion handbook" John Wiley & Sons, Inc. N.Y.

[4] M. Da Ros, E. Dallago, E. Bassi, "Low and medium voltage static converters: standards and specifications" Università di Pavia - Corso di aggiornamento 20/23 Giugno 1994

[5] F. Rossi, "Radiopropagazione in galleria nelle bande 450 MHz e GSM" Università degli studi di Bologna - Tesi di laurea Anno Accademico 1997 / 1998

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