

REPORT 902-1

LEAKY-FEEDER SYSTEMS IN THE LAND MOBILE SERVICE

(Question 36/8)

(1982-1990)

1. Introduction

Leaky feeders are also referred to sometimes as 'radiating cables' but this term is inaccurate and should be avoided. The alternative expression 'leaky cable' is acceptable in specific regard to the feeders themselves, rather than the system, in the vast majority of cases where the feeder does in fact take the form of a cable rather than an open-wire transmission line.

A leaky feeder is a form of transmission line that enables radio communication to take place with or between mobile sets in its vicinity through its leakage fields, while substantially providing the linear range of the system through its internal propagation properties (Delogne, 1982; Martin, 1982).

Such systems are used in confined spaces, such as tunnels, mines or large buildings, where natural propagation is inadequate. They may be completely self-contained or extensions of conventional surface systems otherwise using free radiation: in the latter case the feeds for the underground coverage may either be taken 'off air' or share a base station with the surface antenna directly. Conversely, a primarily underground system may interface with a surface antenna to provide local cover, for example, of the precincts of a mine.

Leaky feeders may also be used on the surface, to confine radio coverage and thus improve spectrum efficiency.

The term 'leaky feeder' can also be taken to include a non-leaky cable with periodic discrete radiators or mode converters (Delogne and Liegeois, 1971).

2. Classification of leaky feeders

The following types of leaky feeder are commonly used:

- (a) bifilar lines;
- (b) continuously leaky coaxial cables;
- (c) coaxial cables with periodic apertures;
- (d) cables with mode converters.

Types (a) and (b) are intrinsically non-radiating in the sense that a cable of infinite length extending in free space can only carry waves guided by the structure. However, any discontinuity along the cable causes mode conversion and radiation.

In type (c), the periodic apertures are radiating discontinuities and act like elements of an antenna array. Maximum radiation is obtained in oblique directions determined basically by the ratio of the spatial interval to the wavelength.

In type (d) the mode converters or radiating elements are separate discontinuities acting in isolation.

2.1 Basic performance parameters

The performance of a leaky feeder system may be characterized by two parameters:

- longitudinal attenuation,
- coupling loss.

The longitudinal attenuation is governed primarily by the factors which apply to normal transmission lines, such as construction, conductor size and dielectric. Additionally there is a small loss component attributable to the leakage (or mode converters).

The coupling loss is, in general terms, the power loss between the feeder and a mobile antenna in its vicinity. For the commonly used coaxial types of leaky cable it is dependent on the degree of shielding in the feeder construction, the configuration of the shield or conductors and the permittivity of the dielectric. For a given cable construction it should also be noted that the coupling loss is also dependent upon:

- the environment in which the cable is mounted;
- the cable mounting position;
- the characteristics, position and orientation of the mobile antenna;
- the operating frequency.

The longitudinal attenuation of cables designed for a low coupling loss can increase substantially with close mounting of the cable to a wall, structure or other cables or with surface contamination, except for cables specifically designed to minimize this effect such as the triaxial (tri-coaxial) cables and inherently non-leaky cables using discrete mode converters. In the same process as the increase in attenuation the coupling loss is usually decreased (i.e. the received signal is increased locally).

For a given coupling loss, various types of cable are not necessarily subject to the same increase in attenuation by these effects of proximity and contamination. Bifilar lines are by far the most sensitive, followed by longitudinally slotted cables and lastly by the various types of cable with numerous small holes. Some braided types of cable are so insensitive to proximity effects that they may be run in normal hangers along with power cables, telephone lines and other such conductors without undue degradation of their performance in the VHF range.

2.2 Bifilar lines

Bifilar lines (nominally balanced) in general have a low coupling loss and a lower longitudinal attenuation for a given conductor size in comparison with coaxial cables. For these reasons they have generally the lowest cost of all leaky cables. However, they can be sensitive to mounting position and surface contamination at VHF and more especially at UHF.

If a bifilar cable is given a tight twist (e.g. several turns per wavelength) the balance is normally improved against proximity effects, thereby improving the longitudinal propagation, but in the same process the coupling loss may be increased by up to 15 dB (Martin, 1975).

2.3 Coaxial cables

2.3.1 Continuously leaky coaxial cables

This type (with either two or three coaxial conductors) includes the loosely braided cables, cables with continuous slots and cables with discrete apertures or slots separated by distances much smaller than the wavelength.

Since these coaxial cables have an imperfect outer conductor, part of the transmission-line energy travels outside the cable as a leakage field [Delogne and Safak, 1975; Fernandes, 1979].

Basic cable properties that (together with environmental factors) determine the coupling loss are (a) the internal propagation velocity and (b) the surface transfer impedance of the outer conductor. It is preferable to characterize cables by quoting these quantities, which can be measured in the laboratory, rather than an arbitrarily and artificially defined 'coupling loss'. Propagation velocity is determined by the internal dielectric constant, while surface transfer impedance is determined by the structure of the outer conductor and is increased, for example, by increasing the size or number of apertures.

Increase of surface transfer impedance results in a proportional increase in the coupled signal, and is normally accompanied also by an increase in longitudinal attenuation depending on the precise cable structure. The sensitivity of the longitudinal attenuation to mounting position also becomes more marked, but there is evidence that this is more a function of 'hole size' than of surface transfer impedance in itself, and so a large number of smaller holes is better than fewer large holes in this respect.

Increase of internal cable velocity (e.g. through the internal dielectric constant) increases the total energy in the leakage field, though this relationship is not linear and involves other parameters. The field close to the cable is actually reduced, but the spread of the field increases. The congestion radius, within which most of the power of the coaxial-mode leakage field is contained, is of the order of 60 cm at 100 MHz and varies in inverse ratio to the dielectric constant of the internal cable insulation. It is also directly proportional to wavelength.

The mechanism by which a mobile antenna outside the congestion radius is coupled to the coaxial mode is the diffraction of the coaxial-mode leakage fields by the inhomogeneities within the congestion radius; these are the inhomogeneities and irregularities in the environment, cable construction and suspension brackets and obstacles of all kinds. This diffraction is a random process: furthermore, in tunnels the resulting coupling loss does not significantly depend on the distance of the antenna from the cable; this is because the diffracted fields are carried by numerous waveguide modes.

2.3.2 Coaxial cables with periodic apertures

Coaxial cables having discrete apertures with dimensions and/or periodicity comparable with the wavelength are a source of radiation.

A coaxial cable with zig-zag slot arrays can be treated as an antenna array [Nakahara and Kurouchi, 1968] and the transmitted energy in the cable is little affected by the radiation from the slots. The radiating field propagates as a cylindrical wave.

Properly located zig-zag slots in coaxial cables improve radiation in the transverse direction and it is possible to manufacture cables with different coupling losses suitable for grading (§3.2.1).

2.4 Cables with mode converters, radiating devices or antennas

These are ordinary bifilar or coaxial lines fitted with devices to convert part of the energy carried by the line into guided modes propagating outside the line or into radiated spherical waves; the devices are installed with either regular or irregular spacing at points determined by the propagation conditions prevailing in the surrounding environment (Deryck, 1972; Delogne, 1973 and 1976).

A radiating device for coaxial cables can take the form of a slot cut around the circumference, forming a complete interruption of the outer conductor to which circuit elements are added so that only part of the power transported by the cable is radiated (Delogne and Liegeois, 1971).

The spacing of the mode converters or radiators may vary from 100 m to 1 km depending on the system input power, the position of the cable in the tunnel and the single-wire mode or tunnel-mode attenuation (whichever is predominant in the conditions). The conversion rate may be adjusted by a suitable choice of circuit components. A common rate is approximately 10%, which gives rise to an insertion loss of about 0.5 dB per converter (Delogne, 1982).

Mode converter systems have been constructed using a short section of continuously leaky cable inserted in the conventional 'non-leaky' cable. Such a section acts as a continuous network of circumferential slots.

3. Systems aspects

3.1 Basic system

A basic leaky feeder system for two-way communication comprises a base-station transmitter and receiver connected to a leaky cable which provides communication to conventional mobile stations, as shown in Fig. 1. By placing the base station at the centre of the cable the longitudinal range can be effectively doubled relative to an end-fed system.

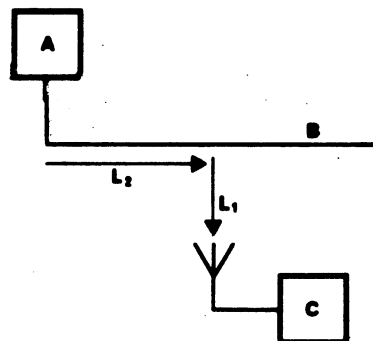


FIGURE 1 - Basic system

A: base station	L_1 : coupling loss
B: leaky cable	L_2 : cable insertion loss
C: mobile	

3.1.1 Communication range

The basic equation relating the parameters (in dB) of a leaky-feeder system is:

$$\text{SYSTEM LOSS} = \text{LINE LOSS} + \text{COUPLING LOSS}$$

where

SYSTEM LOSS is the ratio of the transmitter output power to the power at the receiver input terminal.

LINE LOSS is the longitudinal attenuation of the line between the base station and the point on the line nearest the mobile set;

COUPLING LOSS is the ratio of the power in the line at the point nearest the mobile set to the power at the antenna terminal of the mobile set.

In the case of centre-fed systems, the splitting loss of 3 dB has to be first subtracted from the system loss.

This relationship enables the approximate range of a simple leaky-feeder system to be predicted provided the basic parameters of the cable, radio sets and the particular environment are known. Typically, ranges of between 1 and 2 km are achievable.

Coupling losses as low as 30 dB have been recorded in favourable conditions (e.g. with bifilar lines in a poor state of balance), but more typical figures range from 60 to 90 dB. Short-distance variations of 20 dB, to a Rayleigh-type distribution, are common in tunnels and mines and result from multipath effects. To take these into account it is normally wise to work to a coupling loss figure of at least 90 dB for systems using a cable that is reasonably insensitive to mounting arrangements.

In the case of widely spaced discrete radiators or antennas rather than a continuously leaky cable the natural propagation of the tunnel has to be considered between radiators. Below cut-off frequency of the tunnel a different mechanism applies and the single-wire-mode propagation of the feeder has to be considered instead.

3.2 More complex systems

3.2.1 Graded cable

The basic range of a single base station may be extended by suitably grading the cable along its length, so that coupling loss reduces (at the expense of longitudinal attenuation or proximity effects) with distance from the base station, this technique has been used extensively in Japan. (Okada *et al.*, 1975).

3.2.2 Multiple base stations

The range of the basic system may be extended as required by deploying further base stations, which may be separately controlled or under common control with the first. Lack of synchronism between successive base transmitters gives rise to objectionable 'overlap' effects, but these may be minimized by leaving a gap between feeder extremities in the regions affected. The transmitters may instead be synchronized by passing a common crystal-frequency signal, already modulated, between them over the feeder itself.

If the base stations are to carry separate information, leaving a suitable gap between their feeder extremities will help the normal capture effect of the receivers to minimize the interference between the sections to a few tens of metres.

3.2.3 Use of repeaters

Line amplifiers or repeaters can be inserted at frequent intervals to compensate for line losses in the leaky feeder as shown in Fig. 2. Some system problems and complication in the design of the repeaters for two-way communication can be avoided by separating the base transmitter and receiver as shown in Fig. 3. Using these techniques the power radiated by the mobile or fed into the feeder can usually be less than 100 mW per channel (Martin and Haining, 1979).

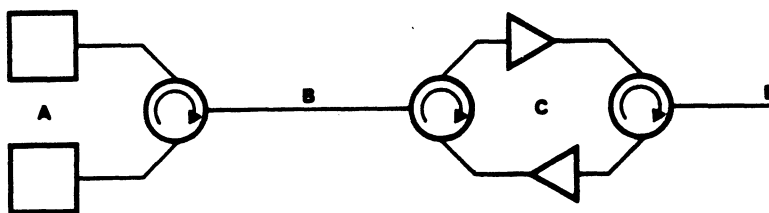


FIGURE 2 - *Extended system using two-way repeaters*

- A: base station transmitter and receiver
- B: leaky cable
- C: two-way repeaters

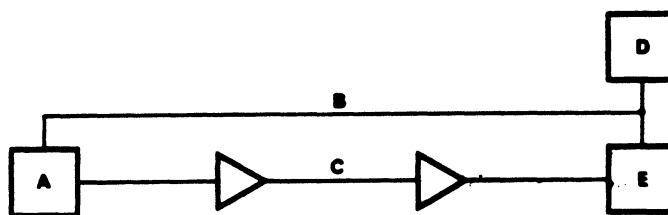


FIGURE 3 - *Daisy-chain system with one-way repeaters*

- A: base station transmitter
- B: audio line connection
- C: leaky cable with one-way repeaters
- D: control point
- E: base station receiver

The simple daisy-chain arrangement of Fig. 3 using one-way repeaters shares a disadvantage of the simple multiple-base-station systems in requiring a separate linking telephone line; it is also inconvenient to apply in a heavily branched form. Both these objections may be overcome by incorporating small line-powered frequency converters at the extremities of the system, in conjunction with a lower-frequency link signal carried over the same cable, allowing the base station itself to be re-united in one place (Martin, 1982).

There are many possible variations in the use of repeaters (Martin, 1982). The systems in general are characterized by a remarkable consistency of signal level and quality through the system. In the largest systems, noise generated by the repeaters may have to be taken into account in considering the transmission from mobile to base.

Repeatered systems are particularly economic in multi-channel operation, since the same repeaters can accommodate all channels providing suitable precautions are taken against intermodulation effects. When the number of channels exceeds about six it usually becomes worthwhile to duplicate the feeder and employ separate chains of repeaters for the two directions of communication. Such an arrangement can provide a useful measure of redundancy, for in the event of failure of one repeater chain the system can revert to simple daisy-chain operation with fewer channels or restricted operation.

3.3 Applications in mines and tunnels

3.3.1 Single-wire conductor link

An extremely rudimentary type of leaky feeder is a single-wire conductor insulated or spaced off from the wall of the tunnel. Its existence in a tunnel substantially modifies propagation because it gives rise to a quasi-TEM mode. This has no cut-off frequency and may therefore be used at low frequencies.

The attenuation of this single-wire mode depends in a complex way on the form and dimensions of the tunnel, the electrical parameters of the wall, and especially on the distance of the wire from the wall and the frequency. Acceptable attenuations are obtained below about 30 MHz. Such systems are confined to wholly underground use (Delogne, 1982).

3.3.2 Bifilar line

This type of leaky feeder has been in use for a long time in underground systems but has to be used with extreme care, especially with regard to mounting position and the possibility of surface contamination by grime or moisture. Generally, its characteristics in regard to longitudinal attenuation and coupling loss are most unstable. Such feeders, however, can be particularly useful in temporary or emergency applications.

3.3.3 Coaxial cables

All types of continuously leaky cables have been successfully used underground, but where severe moisture or difficult mounting conditions are encountered loosely braided cables have given the best results.

Coaxial cables with periodic apertures have been successfully used in railways and motorway tunnels (Suzuki *et al.*, 1980).

3.3.4 Cables with mode converters or radiators

Many installations have been made underground. No special care is needed in cable laying except for a few metres on either side of the radiating devices or mode converters. For the rest, any convenient way of running the cable may be used.

3.3.5 Transverse variation of the field in a tunnel

Since several modes are present in the tunnel when leaky cables are used above tunnel cut-off frequencies, a multipath situation arises. The median value of the field is approximately constant across the tunnel and the statistical variation of the field strength follows a Rayleigh law. With the twisted bifilar line or mode-converter system this variation of the field strength is reduced.

3.4 Applications in railways and motorways

Train radio systems are in use at 400 MHz using coaxial cables with periodic apertures installed alongside the track (Okada *et al.*, 1975).

Lateral measurements of the radiated field strength in an open area along a railway using this type of feeder has shown that coupling loss increases by approximately 3 dB per distance doubling. For other types of leaky cable in similar situations the coupling loss has been measured to increase by about 6 dB per distance doubling (Cree and Giles, 1975).

3.5 Applications in buildings

Leaky cables have been used to provide radio propagation within buildings. In some cases the base station working into the leaky feeder has also been connected to a normal radiating antenna to provide external coverage also. In some other cases the local base station itself has been replaced by an elevated antenna that interfaces the leaky-feeder system to a remote base station by taking off-air signals.

The principles described for tunnels are applicable to any confined spaces such as corridors, stairwells, lift-shafts and car-parking areas. But the large variety of shapes and dimensions of these spaces calls for some caution in system design and the need for empirical solutions is more common than in the case of simple tunnels.

4. Preferred frequency bands

Leaky-feeder systems have been used successfully over a wide range of frequencies, at least down to 3 MHz (Delogne, 1982) and as high as 800 MHz (Suzuki *et al.*, 1980).

Generally, economic factors favour the lower part of the VHF range, but other factors that may influence the choice are :

- the availability of channels for a particular scheme (especially if there is some surface cover involved);
- the size and configuration of a tunnel or building;
- if the system is intended as an extension of a conventional mobile radio system;
- the required linear (end-to-end) range;
- any required lateral range from the feeder down a side tunnel not itself equipped with feeder;
- the availability of suitable radio sets;
- the size of antenna on the personal sets.

Leaky cables tend to be more sensitive to mounting position and to surface contamination at the higher frequencies. Bifilar cables are affected the most in this way.

A factor that favours the higher frequencies is the possibility of employing tunnel propagation in suitable places to augment or extend the cover by feeder. Such extended range, however, will usually be dependent on the tunnel remaining unobstructed by vehicles.

In some situations the use of leaky feeders may be completely avoided by relying on such natural propagation at frequencies above the tunnel cut-off frequency (Emslie *et al.*, 1975; Delogne 1982). Again, however, blockage of the tunnel by vehicles between the base-station and mobile antennas can interfere with communication, to an extent depending on the tunnel and vehicle sizes.

5. Sharing with other services

Leaky-feeder systems used completely underground may operate in frequency bands allocated to other services without mutual interference, because the environment provides a high degree of shielding.

For surface application, systems may be designed to have a reduced overall path loss, such as with closely-spaced in-line repeaters (Martin and Haining, 1979). This enables the transmitter powers to be minimized and receivers to be desensitized, thus reducing the co-channel interference potential and susceptibility and facilitating sharing with other services.

In assessing an interference risk involving leaky feeders it should be noted that the interference sources (and susceptibilities) tend to be concentrated at the base station and repeaters, and at discontinuities such as the system extremities and sharp changes of direction.

In using a two-frequency channel within possible interference range of a conventional system it may be beneficial to transpose the frequencies, that is to use the base transmission frequency for mobile transmission and vice versa. This is because in a leaky-feeder system it is generally the mobile that has the greater interference potential and susceptibility rather than the base station as in conventional systems.

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