FRONT END NOISE SOURCES
IN COMMERCIAL MICROWAVE RADIO RELAY SYSTEMS

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Abstract

Noise in long haul terrestrial microwave systems originates in several portions of the radio repeater, one major source being the receiver front end. A review of the circuits examined for this application in Bell System microwave facilities is given.

Introduction

Microwave radio systems for telephone, television and data services require high transmission performance, high reliability and economical cost. The Bell System has a vast network of microwave radio, encompassing over 4000 stations and over 45,000 transmitters and receivers which provide more than 1,200,000 one-way radio channel miles of broadband facilities. It is therefore important that high performance objectives be met when new repeater configurations are being designed or when modifications to existing systems are made.

During the last decade, a number of low noise input circuits have been developed, and while each can serve a useful function in specific applications, some of them cannot be used effectively in high capacity communication systems because of the severe requirements imposed upon certain characteristics. Those which have been considered but are not used include the tunnel diode amplifier, the parametric amplifier and the microwave transistor amplifier. Each of these is discussed and the shortcomings, as well as the virtues are mentioned.

Performance

Long haul microwave routes in the Bell System are engineered on the basis of 150 repeaters in tandem to cover a geographical distance of 4000 miles. These paths are not all the same length and it must be recognized in the design and operation of the receiver that short paths (low path losses) in some cases can result in overload of the early stages of the receiver while long paths result in low signal to noise ratios that make the receiver noise figure particularly important. The thermal noise of each repeater does not contribute an equal amount to the total system noise because of the different path losses of the hops. See Fig. 1.

The accumulation of small distortions in the repeater if added on a systematic basis, can lead to intolerable noise performance, totally unacceptable gain-frequency characteristics in the baseband or serious crosstalk between telephone customers. To achieve an acceptable design requires very precise control of all circuits in the repeater. The microwave systems used to date employ frequency modulation to minimize the requirements on amplitude linearity of the active devices. However, delay distortion and AM to PM conversion greatly affect the performance of an FM system.

The receiver front end can degrade the system performance if the noise figure is poor, if the beating oscillator for the down-converter contains FM noise or if there is AM to PM conversion in the electronic circuits. (Since the early IF stages play such an important part in the performance of the receiver, these will be lumped with the down-converter and all will be considered as a single unit.)

Crosstalk noise in the various telephone circuits at the output of the system can occur (1) within a single radio channel (2) between the various channels of a multi-channel system or (3) between separate systems operating in the same geographical area. The first can be caused by excessive delay distortion, the second by inadequate selectivity in the individual channels, and the third by insufficient antenna discrimination.

Before examining specific input circuits of microwave receivers, the environment at the front end should be examined. High capacity long haul analog systems use transmitter output devices capable of delivering modest amounts of power and directive, high gain antennas to minimize interference into and from adjacent systems. Therefore the received signal level is relatively high. A typical 4 GHz system might have the following characteristics:

1. Transmitter output power 5 watts (+37 dbm)
2. Waveguide and filter losses-typical 2.5 db
3. Antenna gain (per antenna) 39.5 db
4. Free-space path loss - 27 miles 137 db

A simple calculation of received signal power can be made from this data:

Transmitter power		+37 dbm
Transmitter waveguide loss	- 2.5 db	+34.5 dbm
Antenna gain (ERP)	+39.5 db	+74 dbm
Path loss-27 miles	-137 db	-63 dbm
Receiving Antenna Gain	+39.5 db	-23.5 dbm
Receiving Waveguide Loss	- 2.5 db	-26 dbm

If the hop length is only 15 miles instead of 27 miles, the signal level can be 5.1 db higher - that is -20.9 dbm. For certain types of input circuits, this signal power may be greater than can be accommodated without degradation of some important characteristic as will be shown in later sections. In such cases it may be necessary to insert an attenuator in the transmitter or receiver waveguide, thereby reducing the signal to noise ratio of the hop.

Microwave radio systems are subject to atmospheric fading, generally a multi-path type which at times can be highly selective. In high capacity systems which use frequency diversity, a 40 db fade in a channel results in a usable signal at the time the switching system requests a switch to the protection channel. Therefore the 4 GHz microwave circuits perform over a range of inputs from about -21 dbm to -66 dbm.

Silicon Diode Down Converter

When the TD-2 system was installed between New York and Chicago in 1950, a silicon point contact diode in a balanced down-converter was used in the input of the receiver. With a two-tube triode pre-amplifier, the repeater noise figure was then about 16 db. Later, a 3 stage pre-amplifier reduced the effective noise figure to about 12 db. Improvements in silicon point contact diodes have been made over the years and this device can yield an effective noise figure of about 10 db in the 4-11 GHz region. For the noise figure of the complete receiver to be close to the noise figure of the front end, the signal level at the input must be lower than the signal level at other points in the receiver for all operating conditions.

Balanced down-converters in FM systems offer little over single-diode converters except for the amount of local oscillator energy transmitted back toward the antenna. An inexpensive circulator could serve the same function with a substantial cost saving.

Tunnel Diode Amplifiers

The tunnel diode amplifier, is simple in concept; it uses the negative resistance characteristic of a diode to provide the amplification. When it was first disclosed, high claims were made for its performance and low cost. At the time of its introduction, there was a belief that this device was the answer to the noise figure problem in radio relay systems and that it could be placed ahead of a conventional down-converter with little difficulty. Unfortunately, because the most desirable portion of the E-I characteristic is so limited, the tunnel diode amplifier is not generally suitable for high capacity long haul terrestrial microwave systems. It cannot handle the signal levels normally encountered. When the tunnel diode amplifier was tested in the input circuit of microwave receivers on an actual route in 1965, the noise performance of the system improved very little over that existing with the receiver down-converter alone. The tunnel diode amplifier should not be used if the received signal level exceeds about -32 dbm at the amplifier input, for even at this level the amplifier exhibited 1 db of compression. From the analysis of the example given earlier, the amplifier would not be used if the 4 GHz path loss was less than about 140 db. A tunnel diode would be useful on only 5% of the paths in the Bell System.

Parametric Amplifier

The 4 GHz TD-3 system development was undertaken in 1963 with an objective of better performance and higher circuit capacity than existed in TD-2 at that time. To achieve those objectives, the receiver noise figure had to be lower than TD-2 and initially, a parametric amplifier ahead of a silicon diode balanced down-converter was the configuration chosen.

This 4 GHz amplifier consisted of a pumped diode imbedded in a tuned circuit and connected to the transmission path by a three-port circulator. To simplify the repeater design, the pump source was the same as that for the down-converter. The actual pump frequency (about 11 GHz) was 3 times the Receiver B. O.

The gain-frequency characteristic requirements on the parametric amplifier over a 20 MHz bandwidth at 4 GHz was about $\pm$ .02 db. Experience and theoretical calculations have shown that this characteristic varies substantially with the level of the pump signal, particularly with fixed bias on the diode. To achieve the degree of flatness required over a 20 MHz band, self bias of the diode was necessary and the 11 GHz pump power to the diode had to be held to $\pm$.006 db. This very high degree of leveling in the pump circuit resulted in an expensive RF amplifier; one difficult to manufacture and difficult to maintain. While this design resulted in an effective repeater noise figure of 7.5 db, it was considered impractical for wide-scale use and was abandoned after an initial trial in about 40 repeaters.

Transistor Amplifiers

Transistor amplifiers are practical today up to at least 4 GHz. They are characterized primarily by moderately low noise figure and wide-band characteristics suitable for multi-channel systems. In 1966 Kurakowa and others published a paper[1] on a 4 GHz amplifier with an intrinsic noise figure of less than 7 dB and an average gain of 12.5 dB. This amplifier was intended for use in TD-2 ahead of the receiver down-converter. If used in each repeater, the cost of a transistor receiving amplifier would have been prohibitive and this approach was abandoned.

Consideration was given to the use of the amplifier in the waveguide common to a maximum of 6 RF channels. This would share the amplifier cost over a number of channels and provide improved performance on all channels. The linearity of Kurakowa's amplifier however was not adequate for 6 channels of about -29 dbm each and unsatisfactory intermodulation performance was experienced. Another drawback was that of reliability. The common amplifier will degrade all channels when it fails. Once it is installed in the waveguide to all receivers, the only way to gain access for test, servicing or replacement is to remove it from the waveguide by a "hot cut". This approach to noise figure reduction has not been used for TD-2 because of the above shortcomings.

The advancement in transistor technology since Kurakowa's original work has been considerable and the ability to design more linear transistors for high capacity coaxial and CATV applications has resulted in improved microwave transistors. Amplifiers available today have greatly improved intermodulation characteristics for the power levels normally used. If the amplifier can be designed to be "fail safe", that is, if the insertion loss of a failed amplifier is 15 db instead of a 15 db gain, the net effect would be that of a 30 db fade in one hop of a long system. This would not be a serious event if the frequency of occurrence was not great.

A reliable, low distortion common amplifier could be of use in high capacity systems if it were located outdoors at the base of the tower. There it would aid in overriding the waveguide losses from the tower to the equipment and in effect, improve the noise figure of the receiver. This could be as much as 2 db or more in some cases. Such an arrangement, while not presently used in the Bell System, may be reconsidered in the future.

Schottky Diode Converter

The gallium arsenide Schottky diode makes an excellent down-converter since it has both low noise and low conversion loss. The fact that it is intrinsically a low resistance device leads to these properties but this also makes it more difficult to match into a waveguide structure. From a practical standpoint, the Schottky diode down-converter is an ideal circuit because of its relatively low noise figure and low cost. The down-converters used in the 4 and 6 GHz TD and TH systems have a conversion loss of about 4.5 dB, and when combined with a 2.5 dB NF preamplifier, the noise figure of the combined unit is about 7.0 dB. This leads to a repeater noise figure at 4-6 GHz of about 8 db.

The TD and TH systems use a Schottky diode down-converter. The local oscillator and the RF signal are injected into the same waveguide port by means of directional (complementary Band Pass-Band Reject) filters. The 70 MHz IF is taken out of the unit through a coaxial low pass filter. See Fig. 2

This down-converter provides the best performing and most economical input circuit of all of the circuits developed and tested so far. The unit uses a die-cast housing with full-size waveguide at the input and a step-transformer to match the standard guide to a section at one-tenth of standard height. A low-pass filter in the form of a waffle iron structure contains the harmonics of the microwave signal within the diode cavity.

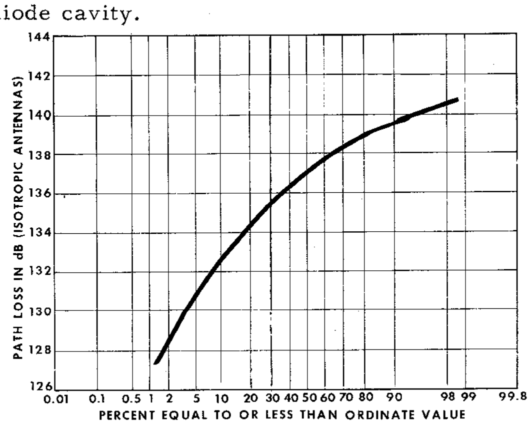

FIG. 1 DISTRIBUTION OF PATH LOSSES IN BELL SYSTEM MICROWAVE NETWORK(4GHz)

Care is taken to adjust the currents in the pre-IF amplifier stages for optimum noise figure and low AM to PM conversion. Best noise figure obtains when the transistor currents are low but if the currents are set too low, excessive AM to PM conversion takes place in the IF.

By the end of 1972 there will be more than 30,000 4 GHz and 6 GHz Schottky diode down-converters of the type shown in the TD-2, TD-3, TH-1 and TH-3 systems in the Bell System. To date virtually no trouble has been experienced with the design shown here.

Microwave Field Effect Transistor

Recent developments in the field effect transistor area have indicated certain interesting characteristics which may lead to low noise amplifiers for microwave systems. There is some encouragement for useful devices above 4 GHz which has been considered the upper limit of bipolar transistors. Some devices, in addition to having favorable low noise characteristics, may have appreciable power handling capabilities. This could lead the way to transmitter applications and the paralleling of a number of devices into a single amplifier structure. It is too early at this time to say what the success of the FET at microwave frequencies will be.

Conclusions

Input circuits for terrestrial microwave systems must have a relatively low noise figure, must be economical and essentially free of AM to PM conversion, and non-linear distortion. The minimum possible noise figure is not necessary since the antenna usually points to the horizon where it will be exposed to earth noise. Other noise sources, such as the FM noise from the receiving local oscillator, may set the noise threshold of the repeater. At the present time, considering all factors together, the Schottky diode modulator is the leader at frequencies between 4 and 18 GHz.

1 K. M. Eisele, R. S. Englebrecht, K. Kurakowa. Balanced Transistor Amplifier for Precision Wideband Microwave Applications. Intern. Conf. Solid State Circuits Dig. Tech. Papers. 8:18(1965)

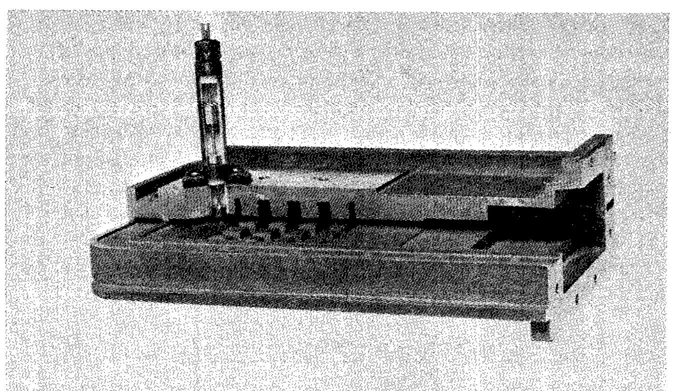

FIG. 2 - SCHOTTKY BARRIER DIODE DOWN CONVERTER