DIVERSITY RECEPTION

Diversity reception is a radio communication technique that improves system performance during periods of adverse propagation conditions by providing more than one transmission channel (or branch) to deliver the signal intelligence to a specified destination. Generally, the goal is to increase the transmission link availability sufficiently to meet prescribed system performance criteria and provide acceptable service. To take advantage of the multiple channels and increase the link performance, the capability must be provided either to select among the available signals, or else to combine the signals. (An approximate analogy is found in telephony, where many paths are generally available to the Public Switched Telephone Network to complete a call from one telephone to another, greatly increasing the probability of completing any given call.)

Usually, the objective in diversity reception is to reduce performance degradations caused by signal fading, such as multipath fading in mobile and terrestrial point-to-point systems, or signal attenuation caused by rainfall on the propagation path (rain attenuation) in earth-space (satellite) systems. Significant performance improvements can also be achieved with respect to other path impairments, such as unwanted signal depolarization (as encountered in dual-polarization frequency-reuse communication systems), angle-of-arrival variations, and cochannel interference. In many scenarios, link performance can of course be enhanced by simply increasing the transmitter power (assuming this approach is cost-effective), but this option is often precluded by regulations established to limit intersystem interference.

The propagation medium is presumed to cause occasional degradations in a single transmission channel that are sufficiently severe to justify the expense and complexity of implementing diversity reception. A sufficient understanding of the propagation environment is essential for designing effective diversity reception systems. For example, when multiple earth terminals are installed in earth-space telecommunication systems to reduce rain attenuation outages that would be experienced on a single path, the minimum site separation for the diversity terminals is dictated mainly by characteristics of the rain environment, although performance elements of the earth terminals, such as antenna gain and link fade margin, are also quite important.

For diversity reception to be effective, impairments on the separate channels are preferably independent, or at least sufficiently decorrelated that simultaneous severe signal degradations are rare. If the time-varying propagation effects on the individual channels are highly-correlated, the probability of simultaneous signal impairments is large, and the benefits offered by diversity reception will be small. (*Anticorrelation* of impairments is even more advantageous than zero correlation, but this condition is not generally attained.) If the propagation medium is spatially uniform or is not time-varying, there is little reason to use diversity. Diversity reception is not generally intended to counter slowly-varying macroscopic (bulk) changes in the propagation environment, as such changes tend to affect all available channels more-or-less equally. A general condition to be met in diversity systems is that the individual diversity signals should have similar mean received power levels (within 10 dB or so). Otherwise, the link performance is dominated by the strong signal(s), with little gain derived from the other channels.

Providing redundant transmission channels to deliver identical information can be expensive, and inevitably increases the equipment complexity. For example, diversity installations that employ spatially separated antennas must be connected by a communication link, such as a microwave link or optical cable, to allow combining of, or switching among, the signals from the diversity branches. In some installations, the diversity terminals may be separated by many kilometers. Furthermore, conditioning of the multiple signals is typically required to support selection or combining of the signals without losing information ("hitless switching"), and a decision criterion or algorithm must be devised to control any diversity operation. There must usually be an expectation of substantial performance benefits to justify implementation of diversity reception.

A well-designed diversity reception system can yield impressive enhancements in system performance during impaired propagation conditions. There are two standard measures used to quantify the benefits provided by diversity reception. One measure, *diversity gain,* specifies the reduction in single-path impairment level (signal fading in decibels, usually) achieved with diversity reception for a given operating time percentage (of the year or worst month). Diversity gain equals the decrease in signal-to-noise ratio, SNR (dB), that is required to meet a given performance criterion, relative to the SNR that would be required without diversity. The other measure, called *diversity improvement* (or diversity improvement factor or diversity advantage) is defined in the orthogonal sense as the ratio of the nondiversity and diversity probabilities of exceeding a specified impairment level. Both measures are used in this article.

APPLICATIONS OF DIVERSITY RECEPTION

Diversity reception has long been recognized as a viable impairment-mitigation technique in telecommunication systems (1,2), and applied in a variety of modes to practical systems (next section). Diversity reception has been used in high-frequency (HF) communications since the 1920s, when spaced receive antennas were found to yield partially decorrelated fading signals that could be used to improve path availability. Diversity operation is virtually mandatory in modern troposcatter communication systems, for which 4-channel (quadruple) diversity operation is common, implemented with dual spaced antennas at both ends of the link, each capable of cross-polarized reception or some other form of antenna-pattern diversity (3).

Vertical space diversity (often combined with angle diversity) improves the performance of terrestrial microwave links (4), and has been evaluated as a countermeasure against low-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

angle refractive fading on satellite links (5). Protection against severe frequency-selective (notch) fading is achieved by reserving an alternate frequency-diversity channel to protect several other channels that suffer notch fading (6). (In general, however, frequency diversity is considered wasteful of spectrum, and not recommended for many applications.) Space diversity using separated base-station antennas has proven valuable for mobile and cellular radio systems (7).

Site diversity reception is used on earth-satellite links at small path elevation angles to decrease the effects of severe low-angle fading (8), as well as to improve performance during rain impairments for high-reliability earth terminal installations (9). Antennas with small horizontal separations can be used to decorrelate tropospheric scintillation fading on earth–space paths (10). Since at frequencies above about 10 GHz, rain impairments are often severe for significant percentages of the time at many locations, site diversity may find wide application in earth–satellite systems at Ka-band (11), especially to protect feeder links that carry information from a central "hub" earth terminal to a satellite for eventual distribution to user terminals such as mobiles.

TYPES OF DIVERSITY RECEPTION

Several major classes of diversity reception are used in communication systems. These methods include *space, angle, polarization, antenna-pattern, field-component, frequency, time,* and *RAKE* diversity (see following subsections). Space diversity generically applies to methods that exploit the spatial characteristics of the propagating field and its interaction with the propagation environment. Frequency diversity requires access to an alternate, lesser-impaired frequency band to which communication traffic may be switched when the normal channel is impaired. Time diversity relies on retransmission of information that is received with inadequate unintelligibility, as in packet-switched communication systems whereby packets containing errors are identified at the destination and requested to be resent. In wideband systems that permit individual multipath components (echoes) within the delay-spread spectrum to be resolved, a RAKE diversity system, so named because it uses a comb of signal components that mimic the appearance of a garden rake, can combine the components to increase the signal power available to the receiver. Time diversity and RAKE diversity are generally used only for digital systems. (In general, diversity techniques are easier to implement in digital than in analog systems.)

Frequency diversity imposes a spectrum utilization penalty, since spare capacity must be reserved for access during adverse propagation conditions. Likewise, time diversity involves a penalty in information throughput, as some intelligence must be retransmitted, and overhead bits are required to identify information packets and control the diversity operation. For these reasons, these methods are often inefficient from the standpoint of spectrum utilization (12).

Space Diversity

Space diversity, probably the most common and easily visualized form of diversity, relies on the provision of two or more spatially separate propagation paths, typically by installing more than one receive antenna (or equivalently, more than one transmit antenna, then called *diversity transmission*) at one end of the link. Planning for the multiple paths is governed by the primary path impairment that the diversity configuration must overcome, such as rain attenuation, refractive fading on satellite paths at low elevation angles, or multipath fading on terrestrial line-of-sight links. Space diversity has been investigated in particular for application to the mobile-propagation environment. The benefits can be very large for the frequent and severe signal fading encountered while communicating with a terminal in motion.

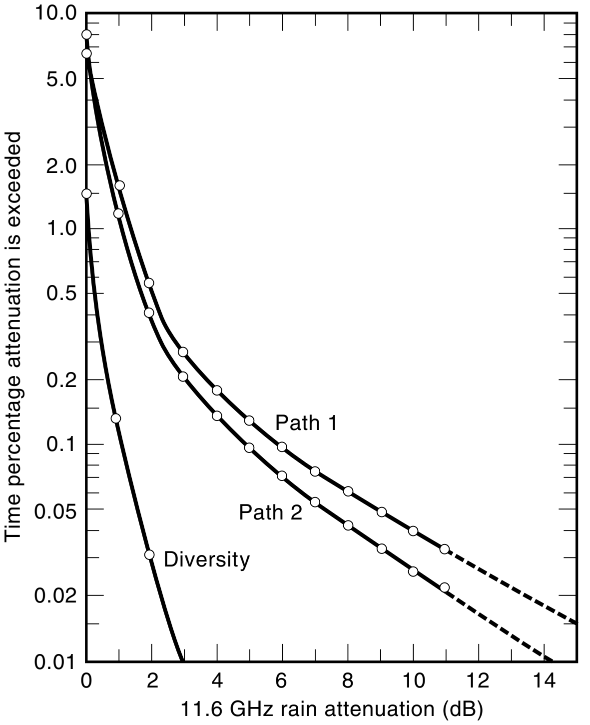

Figure 1. Annual statistics of 11.6 GHz rain attenuation for two earth–space paths, compared to diversity statistics obtained by always selecting the smaller single-path attenuation. (Copyright 1979 COMSAT Corp. All rights reserved by COMSAT Corp. Used by permission.)

In terrestrial line-of-sight telecommunications, space diversity generally refers to the use of multiple antennas displaced vertically on a tower, mainly to overcome refractively-induced fading caused by unwanted multipath propagation on such links. Other examples include *path diversity* (access to adjacent microwave routes in terrestrial fixed telecommunications) and *site diversity* (deployment of multiple earth terminals in earth–space telecommunications), both generally used to reduce the effects of severe rainfall attenuation at frequencies above about 10 GHz.

Figure 1 shows 11.6 GHz cumulative rain attenuation distributions derived from measurements with two terminals separated by 35 km on propagation paths at an elevation angle of 18° (13). The curves labeled "Path 1" and "Path 2" are the rain attenuation distributions for the individual paths. The "Diversity" curve is the joint cumulative rain attenuation distribution obtained via computer simulation by always selecting the lesser-faded signal for each concurrent pair of rain attenuation samples:

$$A_J(t) = \min\{A_1(t), A_2(t)\} \tag{1}$$

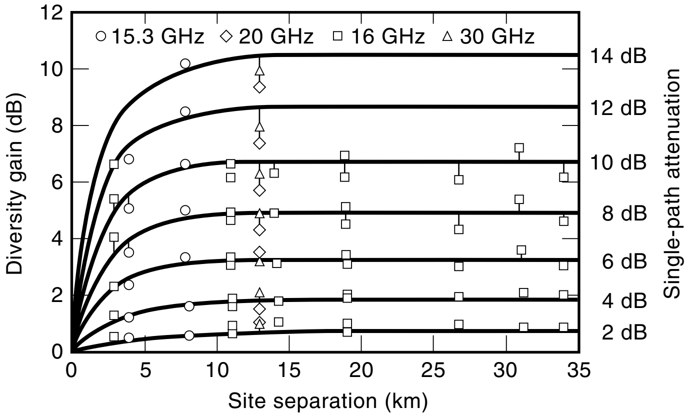

Figure 2. Measured Ka-band dual-site diversity gains (symbols) vs. site separation, along with curve fits (lines) parameterized in terms of single-path attenuation. (© 1976 IEEE.)

The increase in path availability achievable by (perfect) diversity switching is observed to be considerable, although independent fading statistics (equivalent to the product of the two single-path probability distributions) are almost never observed for dual diversity paths (14) because of mesoscale (widespread) rainfall effects. Practical diversity-switching systems are unlikely to achieve the degree of improvement indicated in Figure 1 since the switching algorithm would purposely be designed to avoid switching under conditions for which the resulting performance gain is not required to meet system performance objectives.

Space diversity gains are large during periods of heavy rainfall since it is highly probable that there is considerable spatial variability in the rain intensity. For terrestrial and earth–space links, separating diversity antennas by several kilometers greatly reduces the probability of simultaneous large fades on the different paths. Antenna separation is the dominant parameter, as illustrated in Figure 2 for several earth–space experiments at frequencies from 15 to 30 GHz (15). The majority of the available diversity gain is in fact achieved with separations smaller than 10 to 15 km. At temperate latitudes, diversity gains measured during the spring and summer (thunderstorm) seasons are generally significantly greater than those observed during the fall and winter (16).

The International Telecommunication Union (ITU) has compiled results of many earth–space site diversity experiments, mainly in the 10 GHz to 20 GHz range, to derive an average representation of *site diversity improvement* that gives the decrease in unavailable time percentage attained by dual-site diversity for a specified impairment level (17). The improvement is plotted in Figure 3 for site separations of 0 km (no improvement) up to 50 km. Results in this figure are approximate, since weaker influences such as frequency and path elevation angle are not explicitly taken into account. The figure indicates that performance gains achieved by increasing the site separation tapers off for separation greater than about 15–20 km. As an example, the curve for a separation of 30 km indicates that a single-path unavailability of $p_1 = 0.01\%$ (about one hour per year) can be reduced by two orders of magnitude (to $p_2 = 0.0001\%$) by the addition of a diversity terminal 30 km distant.

An empirical formula (18) has been derived to predict the dual-site diversity gain, G (dB), in terms of site separation D (km), frequency f (GHz), path elevation angle θ (deg), and the angle ψ (deg) between the path azimuth and the baseline between the two sites (defined so that $\psi \leq 90°$), as

$$G = a(1 - e^{-bD}) \cdot e^{-0.025f} \cdot (1 + 0.006\theta) \cdot (1 + 0.002\psi) \qquad (2)$$

where $a = 0.78A - 1.94(1 - e^{-0.11A})$ and $b = 0.59(1 - e^{-0.1A})$, and A (dB) is the single-path rain attenuation exceeded for a specified time percentage. Site separation is the dominant factor in this expression for site diversity gain. Three-site diversity has also been examined, but the additional gain achieved by adding a third terminal is generally marginal (16).

Another form of space diversity envisaged for earth-space communications is *orbital diversity,* in which multiple signal paths are established by providing access to two or more satellites that are within view of an earth terminal antenna. (The diversity antennas are in space, instead of on the ground.) Figure 4 shows attenuation time series measured during a fade event for an orbital diversity configuration using two satellites at frequencies of 19.8 GHz ("Satellite 1") and 18.7 GHz ("Satellite 2"), with a geostationary orbital angular separation of 32° (19). The peaks in attenuation on the two paths occur at different times, and the benefits of switching between the two paths in this event would have been substantial.

Orbital diversity requires that at least two satellites be available, and that spare capacity be reserved or that communication traffic be suitably prioritized so that higher-priority traffic may be switched upon demand. Since the diversity paths terminate at an earth station situated in that region of the atmosphere where rainfall occurs, the diversity gain may be small when the rain region surrounds the earth station.

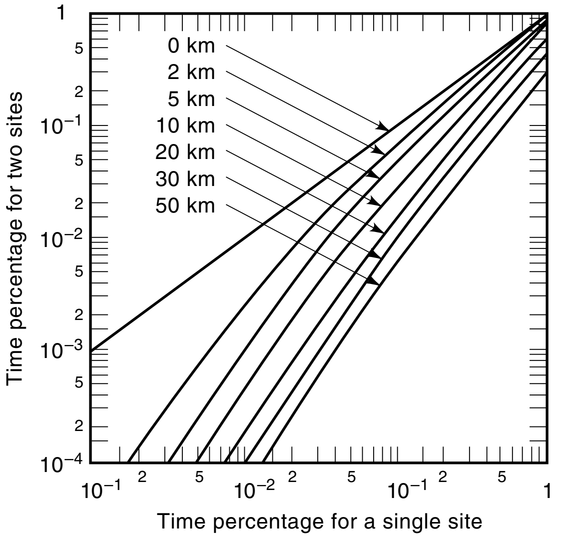

Figure 3. Relation between annual time percentages that a given earth–space path attenuation is exceeded single-path and dual-site diversity. (© ITU. Adapted from Recommendation ITU-R P.618-5. Used with permission of ITU. Author solely responsible for this presentation.)

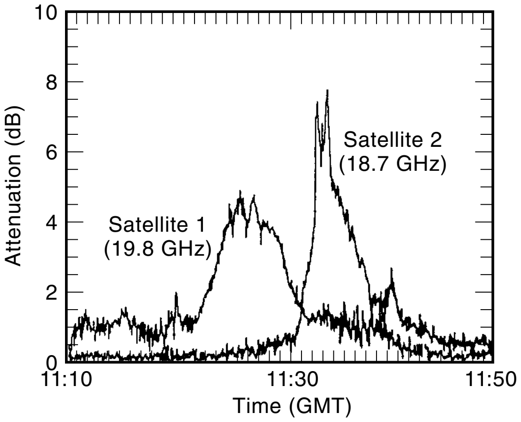

Figure 4. Concurrent 20 GHz path attenuation time series for two earth–space paths with geostationary orbital angular separation of 32°, demonstrating orbital diversity for rain attenuation. (© 1995 IEEE.)

Protection of large frequency bandwidths by transferring traffic from one satellite to another (and accommodating the corresponding network reconfiguration) appears difficult.

Angle Diversity

The general technique of configuring antennas to detect signals that have propagated along different paths, and which appear at the receive antenna with different directions of arrival, is called *angle diversity.* On terrestrial paths, vertically separated space diversity antennas may be mounted with slightly different pointing angles with respect to the normal line-of-sight direction to the transmit antenna to enhance reception during periods of angle-of-arrival variations caused by refractive structures near the earth surface. Vertical beam separation is preferable to horizontal separation in this application because variation in the refractive structure of the troposphere is more pronounced in the vertical direction. Another approach, used in troposcatter systems, is to employ a large antenna with several feeds configured to yield somewhat different pointing directions to create some degree of decorrelation among the corresponding propagation paths.

In troposcatter systems, the optimal vertical separation between the beams is about one antenna beamwidth, although the range of the optimum is rather broad (3). For terrestrial microwave paths, more complicated procedures are required to determine the diversity gain provided by angle diversity, which is related to the average angle of arrival as determined by the average value of the vertical refractivity gradient for the location of interest (4).

Polarization Diversity

For environments in which the polarization properties of a signal are altered during propagation, orthogonally-polarized transmission channels may become sufficiently decorrelated for *polarization diversity* to be effective. Polarization diversity is the reception of a signal on two mutually orthogonal polarizations, with or without transmission in the same two polarizations (20). If both polarizations are transmitted, a 3 dB penalty in transmit power per channel is imposed with respect to single-polarization transmission, as the power must be split between the channels. In contrast to the unwanted path-induced signal cross-polarization that afflicts dual-polarization frequency-reuse communication systems, signal depolarization is essential in polarization diversity systems. Several polarization-dependent reflections are usually required to depolarize the incident wave adequately.

Although the technique is limited to two diversity channels (one polarization and its orthogonal state), no additional frequency spectrum is needed, and a single dual-polarized antenna can be deployed instead of separate space diversity antennas, with positive cost and "real estate" consequences in mobile communication systems. The capability to receive both polarizations with adequate isolation between the channels must be incorporated into the receiver. Polarization diversity reception may be particularly beneficial for mobile handheld terminals, especially to compensate for the random orientations that such a terminal can assume in everyday use (21).

Antenna Pattern Diversity

Antenna pattern diversity, basically the same concept as angle diversity and polarization diversity, can introduce decorrelation among received signals by, in effect, sampling arriving wavefronts in different ways (6). This type of diversity can be accomplished by using adjacent antennas of different types, for example. Performance improvements with this method are primarily attributed to the sensitive dependence of frequency-selective (notch) fading on the amplitudes of the separate rays that destructively interfere to cause such fading, as observed in terrestrial microwave systems. With different antenna patterns, the probability of simultaneously experiencing the conditions for deep fades at both antennas is much reduced because the received signal amplitudes are less likely to be of almost equal magnitude, a condition for nearly complete destructive interference.

Field-Component Diversity

The electromagnetic fields of propagating signals are comprised of both electric and magnetic components which may be designated as E_z, H_x, and H_y, each of which contains the intelligence of the transmitted signal. In some environments, particularly mobile radio, these components are uncorrelated upon arrival at the receive antenna, but the powers in the field components obey the conservation relation (22)

$$|E_z^2| = |H_x^2| + |H_y^2| \tag{3}$$

If the individual components can be detected and combined, conditions for diversity reception are met and the average received signal power can be augmented by summing these components to achieve *field-component diversity.*

Three methods are envisaged to achieve the desired diversity action. *Incoherent combining* of the field components yields a resultant, R,

$$R = E_z + H_x + H_y \tag{4a}$$

Coherent combining of the components is equivalent to

$$R = |E_z| + |H_x| + |H_y| \tag{4b}$$

A third energy-diversity approach is given by (22)

$$R = |E_z|^2 + |H_x|^2 + |H_y|^2 \tag{4c}$$

which yields a resultant that is approximately constant with time. Special “energy-density” antennas have been designed for the implementation of field-component diversity (22).

Frequency Diversity

If the propagation characteristics of the medium depend significantly on the signal transmission frequency, then *frequency diversity,* the capability to select the transmission frequency to suit prevailing conditions, can be effective. In severe multipath fading on terrestrial line-of-site links, for example, the fading is often very frequency selective, such that deep but narrow notches appear in the receive channel (6). If provision can be made to switch the information contained in the channel experiencing the notch fading into a less impaired reserve channel, the probability of successfully transmitting the intelligence can be greatly increased.

The capability of frequency diversity to overcome severe multipath fading on digital terrestrial links is demonstrated by Figure 5, which displays bit-error rate (BER) data collected for “Channel 1” and “Channel 2” of a 6 GHz, 42.5 km digital radio link operating at 90 Mb/s during a 2.5 month period of active multipath fading (23). The center frequencies of the two channels were separated by 59 MHz. If a typical outage criterion of 10^{-3} BER is specified, the observed diversity improvement factor is about 45, an impressive enhancement in performance (approximately equivalent to the improvement expected for a vertical space-diversity separation of 10 m). The experimental data revealed that although power fading in the two channels was highly correlated, the multipath dispersion was decorrelated. The latter finding was presumed to account for the good performance of frequency diversity on this link.

In another form of frequency diversity envisaged to overcome deep fading associated with rain attenuation, use is made of the fact that the severity of rain attenuation increases rapidly with increasing frequency. If traffic on a high-frequency channel (say, at 14/12 or 30/20 GHz), where rain attenuation is severe, can be switched to a lower-frequency (such as 6/4 GHz), the probability of successful transmission is much enhanced. Frequency diversity requires that spectrum be made available at the diversity frequency to carry the information that would otherwise be lost in the impaired channel, and that the traffic either be satisfactorily prioritized or spare capacity held in reserve, to allow the transfer of protected channels to the alternate satellite when required. Diversity in this form might be used to protect smaller terminals of modest bandwidth capacity, such as Very Small Aperture Terminals (VSATs), by providing a small spare capacity on a satellite that can be accessed by terminals when experiencing propagation impairments. However, frequency diversity is less likely to be useful for large trunking earth stations, which generally continuously utilize all of the allocated frequency spectrum in a given band to support many communication links, and for which alternate provision will be expensive.

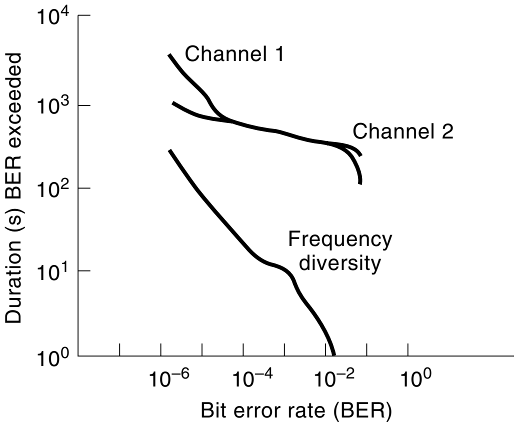

Figure 5. *Bit error rate* (BER) statistics measured at 6 GHz on 42.5 km link for two channels separated by 59 MHz, compared to BER statistics with one-for-one frequency diversity protection in severe frequency-selective fading environment. (© 1985 IEEE.)

Time Diversity

Time diversity refers to the exploitation of the time-varying nature of the signal impairments to retransmit information at suitable time intervals. A commonplace analogy is resending an unsuccessfully transmitted facsimile. Information should be retransmitted at time intervals somewhat greater than the reciprocal of the signal fading rate, to ensure adequate decorrelation between successive transmissions (1). If the fading conditions are quite variable, adaptive adjustment of the time interval may be necessary to attain efficient performance over the anticipated range of environmental situations.

In digital systems, such as packet-switched networks, the bit stream can be reconstituted from successfully received packets, possibly by interpolation between successfully-received packets or other sophisticated methods (24), allowing for powerful implementation possibilities. Overhead capacity must be provided both for network control and to identify and process the information bits, so increased spectrum and higher data rates may be needed to maintain sufficient information throughput. In time diversity systems, storage of the communication information is required at both the transmitter (to permit retransmission) and receiver (to support bit manipulation and message reconstruction), which constitutes an important disadvantage for many analog, real-time, and wideband applications.

RAKE Diversity

RAKE diversity is effective with wideband signals if the individual multipath components (echoes) can be separately identified and processed (1). RAKE diversity, also called multipath diversity or path-delay diversity, takes advantage of the existence of multipath components in its operation. It can be viewed either as a variation of frequency diversity (as in spread spectrum systems, where to reduce small-scale multipath effects the transmission signal is spread by several times the frequency width of the reciprocal of the delay spread) or time diversity (where the incremental time delays among components are used with a system time reference to identify and process the individual multipath components).

RAKE diversity is considered applicable mainly for digital systems, which can support elegant information-processing techniques (25). A RAKE receiver should be matched to the signal received after distortion by the environment, instead of being matched to the transmitted signal. Therefore, channel adaptivity may be required if the propagation environment is quite variable.

DIVERSITY-RECEPTION PERFORMANCE ANALYSIS

Many investigations of diversity reception techniques have been undertaken to quantify and model the corresponding gain in channel performance to support reliable system design. Much of the analytical basis for diversity reception derives from studies related to communication with mobile terminals, for which the fading environment is generally quite severe. The motion of mobile terminals creates numerous opportunities for destructive interference to occur among multipath transmission components. Conditions for such interference can arise for every half wavelength of travel (perhaps every few centimeters). Methods to overcome such fading impairments are required. Diversity reception is a prominent impairment-mitigation method, and classic detailed treatments of diversity techniques are available (1,2).

METHODS FOR SELECTING OR COMBINING CHANNELS

A fundamental requirement in diversity reception is a reliable method for either switching among, or combining, the available transmission channels in order to enhance link performance. While various difficulties are encountered in practice, the basic concepts of switching and combining are amenable to theoretical analysis. In this section, the major classes of linear diversity selection and combining are analyzed. *Linear diversity combining* applies to implementations based on relatively straightforward linearly-weighted sums of the multiple received signals, the only method generally capable of distortionless reception in analog systems (1). Diversity signal processing schemes that are more-sophisticated can be envisioned for digital systems.

An obvious choice for diversity switching is simply always to select the "best" available signal, as defined using some criterion based on a quantity that can be measured or estimated (such as signal-to-noise ratio, bit error rate, signal-to-interference ratio) to enable the system to identify the best signal. This approach is called *selection diversity.* Each channel must have its own receiver or some other detection device to supply the information that permits selection of the best signal. A simpler form of diversity switching is *threshold selection,* in which the available signals are sampled in sequence until one is determined to be above some minimum acceptable threshold. That signal is then used for reception until it falls below the specified threshold, at which point the scanning process is repeated.

A more sophisticated approach is to combine the diversity signals to achieve overall augmentation in signal level available at the receiver. Common methods include *maximal ratio combining* and *equal gain combining,* which typically require that signals be suitably conditioned to ensure that they sum coherently. Other variations on these basic methods can be envisaged, depending on the signal conditioning and processing to be performed.

There are two general classes of diversity combining, called predetection and postdetection combining, depending on whether the diversity decisions take place before or after baseband detection. In *predetection combining,* the information required to make a decision regarding selection or combining of signals is acquired and applied prior to baseband detection, so the diversity operation can take place anywhere from the receive antenna down to the intermediate frequency (IF) input to the baseband receiver. *Postdetection combining* is implemented at baseband after the signal detection receiver, and typically implies that each diversity channel must be supplied with its own receiver.

Essentially identical diversity performance is typically obtained with well-implemented predetection or postdetection diversity combining for linear modulation formats. For nonlinear modulation techniques such as frequency modulation (FM), coherent predetection combining of diversity signals can in cases increase the signal resultant above the receiver signal detection threshold, even if the individual signals are below the detection threshold. Conversely, predetection switching can cause unwanted switching transients in the signal carrier, requiring some strategy to minimize the resulting degradation in receiver performance (2).

Selection Diversity. This subsection discusses the gain in performance achievable by selecting one channel from among M (=1, 2, . . .) available diversity channels (M-channel selection diversity), and summarizes the approach found in classic texts (1,2). In the severe fading environments often encountered in mobile radio systems, the signal fading signal is usually observed to obey Rayleigh fading statistics, which correspond to the sum of random multipath components in the absence of a direct line-of-sight (LOS) signal. When a direct LOS signal exists, as often is the case in microcellular and some other systems, Rician statistics (corresponding to the sum of a direct component and several random multipath components) are applicable.

If the electric field available to the receive antenna is assumed to be the summation of in-phase and quadrature terms, where each term is comprised of the N diversity components that arrive at the antenna, the in-phase and quadrature fields may be modeled as independent (uncorrelated) zero-mean Gaussian random processes (2). The in-phase and quadrature terms, designated as E_I and E_Q, each obey the standard normal distribution with probability density given by

$$p(x) = \frac{1}{\sqrt{2\pi b_0}} e^{-x^2/2b_0} \tag{5}$$

where x is either E_I or E_Q and b_0 is the mean power level. The envelope of these two components is the modulus (magnitude) of the electric field composed of the in-phase and quadrature terms:

$$r = \sqrt{E_I^2 + E_Q^2} \tag{6}$$

The probability density for the envelope, r, formed by the sum of many multipath components (without a direct LOS component) is the Rayleigh density function:

$$p(r) = \frac{r}{b_0} e^{-r^2/2b_0} \quad r \geq 0 \tag{7}$$

where the density is zero for $r < 0$.

If the signal in each diversity channel is assumed to obey the Rayleigh distribution, the signal envelope for the ith channel is given by Eq. (7), with r replaced by r_{i}. Over one RF cycle of the field (assumed sinusoidal), the instantaneous mean signal power in the ith channel is simply $r_{\mathrm{i}}^2/2$. The noise power in the ith channel may be designated as n_{i}^2. If each channel is assumed to contain the same mean noise power, this power is a constant, N, independent of the channel. The instantaneous signal-to-noise ratio (SNR) in the ith channel is thus simply the ratio of the local mean signal power and the mean noise power in each channel:

$$\gamma_{\mathrm{i}} = \mathrm{SNR}_{\mathrm{i}} = \frac{r_{\mathrm{i}}^2}{2N} \tag{8}$$

The *average* signal power in the ith channel is $b_0 = \langle r_i^2/2 \rangle$, so the *mean* value of the channel signal-to-noise ratio is $\Gamma = \langle SNR \rangle = b_0/N$. Replacement in Eq. (7) yields a representation for the probability density function of the envelope in terms of the SNR quantities γ_{i} and Γ:

$$p(\gamma_i) = \frac{1}{\Gamma} e^{-\gamma_i/\Gamma} \tag{9}$$

The probability that the SNR in the ith channel does not exceed a particular threshold value of interest, γ_{S}, where the subscript S indicates *selection* diversity, is obtained by integrating the probability density over the domain of interest:

$$P(\gamma_i \leq \gamma_S) = \int_0^{\gamma_S} p(\gamma_i) d\gamma_i = 1 - e^{-\gamma_S/\Gamma} \tag{10}$$

For M channels, the probability that the SNR values in all branches are all concurrently less than the threshold value γ_{t} is just the M-channel product:

$$P_M(\gamma_t) = (1 - e^{-\gamma_S/\Gamma})^M \tag{11}$$

The probability distribution given in Eq. (11) can be computed for various values of M to estimate the efficacy of M-branch diversity selection. For $M = 1$ (no diversity), the distribution is again the Rayleigh representation, which predicts an impairment level that increases at the rate of 10 dB per probability decade (a straight line on normal probability paper).

For example, at a probability level of 99.99%, the expected ratio of the local SNR to the average SNR is computed to be −40 dB, −30 dB at a probability level of 99.9%, etc., demonstrating the Rayleigh roll-off of 10 dB/decade. These fade depths illustrate the severe fading encountered in some mobile environments. With dual-channel diversity ($M = 2$), the multipath fading level predicted for 99.99% reduces from 40 dB to 20 dB, and the fade depth at 99% reduces from 20 dB to 10 dB, representing substantial improvements. Adding yet more diversity channels yields useful performance enhancements, but by far the largest diversity gain increment is achieved in going from $M = 1$ (no diversity) to $M = 2$ (dual diversity).

The mean SNR can be calculated by integrating γ_{S} over the probability density function for the range of allowable values (zero to infinity):

$$\langle \gamma_S \rangle = \int_0^{\infty} \gamma_S \left[\frac{d}{d\gamma_S} P_M(\gamma_S) \right] d\gamma_S = \Gamma \sum_{k=1}^{M} \frac{1}{k} \tag{12}$$

The mean decibel signal-to-noise ratio, 10 log[$\langle \gamma_S \rangle / \Gamma$] (dB), is plotted as curve (a) in Figure 6 to illustrate the gain in average output SNR obtained by selection diversity with an increasing number of channels (2). (The other curves in this figure are explained in the next two subsections.)

A disadvantage of pure selection diversity is that each channel must be provided with a receiver, or at least some detection device that can identify the “best” signal at some stage of the detection process, which can be expensive to implement. In a variation called *scanning* or *threshold selection* diversity, available channels are scanned until an acceptable signal is found. The selected channel is used until the received signal falls below a specified threshold, where upon the scanning process is repeated until an acceptable signal is again obtained. This mode of operation is clearly nonoptimum, and can lead to rapid and unproductive switching when all diversity signals are below threshold.

A similar technique for two-channel diversity, called *switch and stay,* is to switch to the alternate channel when the received signal falls below threshold and stay at the new position, even if the signal is below threshold, until that signal is available and itself eventually goes below threshold. The signal, $R(t)$, resulting from such a process (2) is illustrated in Figure 7. If the individual envelopes $r_1(t)$ and $r_2(t)$ are assumed to be independent Rayleigh-fading time series, the probability density for each being above a specified fade threshold, A_{t}, is given by Eq. (7), with r replaced by A_{t}. By further assuming that the individual segments of each time

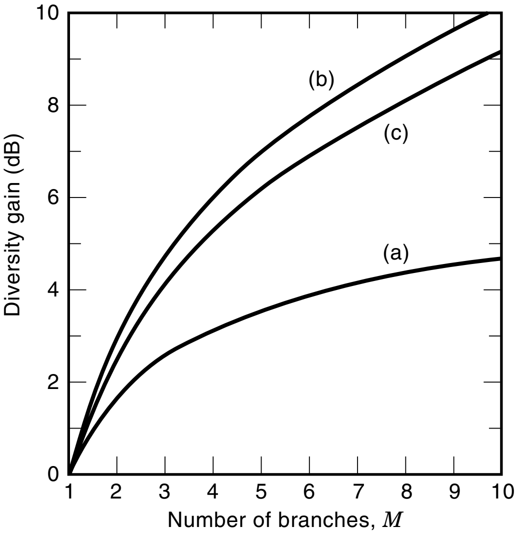

Figure 6. Predicted diversity gain in Rayleigh-fading environment with M diversity branches: (a) selection diversity; (b) maximal ratio combining; (c) equal gain combining. (© 1994 IEEE.)

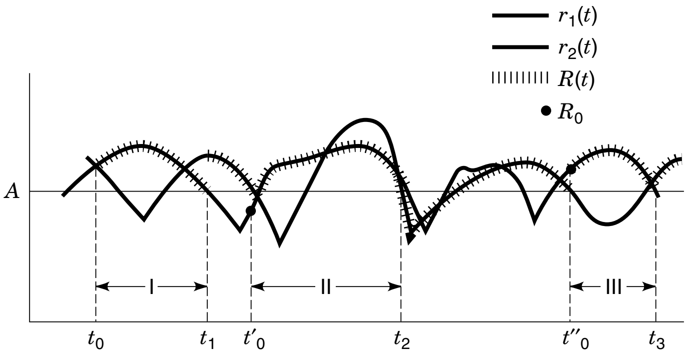

Figure 7. Signal envelope resulting from switching between two Rayleigh-fading envelopes with switch-and-stay technique: $r_1(t)$ and $r_2(t)$ are the two envelopes, $R(t)$ is the composite switch-and-stay envelope, and R_0 identifies the start of time segments defined by a signal switch. (© 1994 IEEE.)

series (portions prior to switching from, and portions subsequent to switching back to, either envelope) are uncorrelated, the density function of the composite (switched) carrier envelope, $R(t)$, can be established, as in the previous case for a single envelope. The composite probability density is found to be comprised of two Rayleigh densities with different weighting factors (2).

Maximal Ratio Combining. In *maximal ratio combining,* the signals are phased and coherently summed, instead of being selected one at a time. The complete scheme is to cophase the M channels, then apply weights, w_i, to the signals that are proportional to the SNR_i of the individual channels, and finally sum these signals. The resultant envelope, r, is the sum of the weighted envelopes r_i:

$$r = \sum_{i=1}^{M} w_i r_i \tag{13}$$

The channel noise contributions also scale in proportion to the corresponding weights, w_i. If the average noise powers (before weighting) are all assumed equal to N, the total noise power is

$$N_T = N \sum_{i=1}^{M} w_i^2 \tag{14}$$

In parallel with the analysis for selection diversity (but with a change of subscript to R to indicate ratio combining), the resultant SNR is $\gamma_R = r^2/2N_T$.

If the w_i are weighted proportionally to the instantaneous channel $\mathrm{SNR}_i = \gamma_i$, then

$$\gamma_R = \sum_{i=1}^{M} \gamma_i = \sum_{i=1}^{M} \frac{r_i^2}{2N} = \sum_{i=1}^{M} \frac{(r_I^2 + r_Q^2)}{2N} \tag{15}$$

As in Eq. (5), the in-phase and quadrature components obey zero-mean Gaussian probability densities with equal variances. The sum of the squares of independent standard normal variables, as given by the right-hand side of Eq. (15), is the chi-square distribution, with corresponding probability density function

$$p(\gamma_R) = \frac{\gamma_R^{M-1} e^{-\gamma_R/\Gamma}}{\Gamma^M (M-1)!}, \quad \gamma_\mathrm{R} \geq 0 \tag{16}$$

The cumulative distribution function, obtained by integrating Eq. (16) from zero to γ_R, is (2)

$$P_M(\gamma_R) = 1 - e^{-\gamma_R/\Gamma} \sum_{k=1}^{M} \frac{(\gamma_R/\Gamma)^{k-1}}{(k-1)!} \tag{17}$$

From Eq. (17), the diversity performance for maximal ratio combining is found to be somewhat better than that for selection diversity with the same number of diversity channels. Instead of the 10 dB diversity gain obtained with selection diversity at a time percentage of 99%, maximal ratio combining provides an 11.5 dB gain. Maximal ratio combining in fact provides the best performance that can be achieved with linear diversity combining techniques.

The average SNR, obtained in parallel with the first two terms on the left of Eq. (15), is

$$\langle \gamma_R \rangle = \sum_{i=1}^{M} \langle \gamma_i \rangle = \sum_{i=1}^{M} \Gamma = M\Gamma \tag{18}$$

The average SNR (dB) is plotted as curve (b) in Figure 6 to show the incremental diversity gain achieved by adding diversity branches to a maximal ratio combining system.

Equal Gain Combining. *Equal gain combining* is a simplified form of signal combining in which the weights are all constant and equal, and can be set so that $w_\mathrm{i} = 1$. From Eq. (13), the signal envelope of the combined signal is

$$r = \sum_{i=1}^{M} r_i \tag{19}$$

For equal noise power in all diversity channels, the corresponding output SNR is $\gamma_\mathrm{E} = r^2/2NM$, a sum of Rayleigh variables, for which there is no general solution for the probability distribution function. Solutions generated numerically reveal that the performance of equal gain combining is only slightly worse than maximal ratio combining (usually by less than 1 dB).

The general expression obtained for the average value of the output SNR is given by (2)

$$\langle \gamma_E \rangle = \Gamma \left[1 + (M-1)\frac{\pi}{4} \right] \tag{20}$$

where Γ is the mean channel SNR. The output SNR (dB) is shown as curve (c) in Figure 6 for comparison with the selection diversity and maximal ratio combining techniques. Maximal ratio combining provides the best performance, though it is not very superior to equal gain combining. Maximal ratio and equal gain combining are both better than selection diversity, but these performance gains are achieved with added system complexity and cost.

Operational Considerations in Diversity Systems

The performance gains estimated above for different types of diversity systems ignore several limitations that are confronted in practical applications. For example, impairments on the individual diversity channels may not be completely independent, and combining errors may introduce additional degradations in diversity system performance. Estimates of these degradations (1,2) are briefly illustrated here.

Imperfect Channel Decorrelation. Prior analyses implicitly assumed independence of fading among the diversity channels. In many environments, complete decorrelation is not achieved, and indeed is found to be unnecessary for successful diversity operation. General limits can immediately be placed on the behavior of the resulting statistical distributions: Complete independence of channel impairments yields results identical to analyses in the previous section, while complete correlation leads to Rayleigh fading statistics equivalent to a single channel without diversity. To investigate the effects of intermediate channel correlation, the complex correlation coefficient, ρ, between the diversity signals must be taken into account, where ρ^2 approximates the correlation function between signal envelopes (7).

For selection diversity, analyzing more than two diversity channels is difficult, but for dual channels the probability distribution is found to be (1)

$$P_2(\gamma_S) = 1 - e^{-\gamma_S/\Gamma}[1 - Q(a,b) + Q(b,a)] \tag{21}$$

where $Q(a, b)$ is expressed in terms of the zeroth-order modified Bessel function, I_0, as

$$Q(a,b) = \int_b^\infty e^{-(a^2+x^2)/2} I_0(ax)x\,dx \tag{22}$$

with the parameters a and b given by

$$a = \sqrt{\frac{2\gamma_S}{\Gamma(1+|\rho|^2)}} \qquad b = \sqrt{\frac{2\gamma_S}{\Gamma(1-|\rho|^2)}} \tag{23}$$

Figure 8 displays the cumulative distribution functions computed with these expressions (2). The curve for $\rho^2 = 0$ corresponds to zero correlation, as in prior analyses, while for $\rho^2 = 1$, no diversity advantage is conferred by switching between the two channels. However, substantial diversity gain is achieved even when the correlation between the two signal envelopes approaches 0.8, attesting to the efficacy of diversity operation for this environment. Similar results are obtained for other modes of diversity combining.

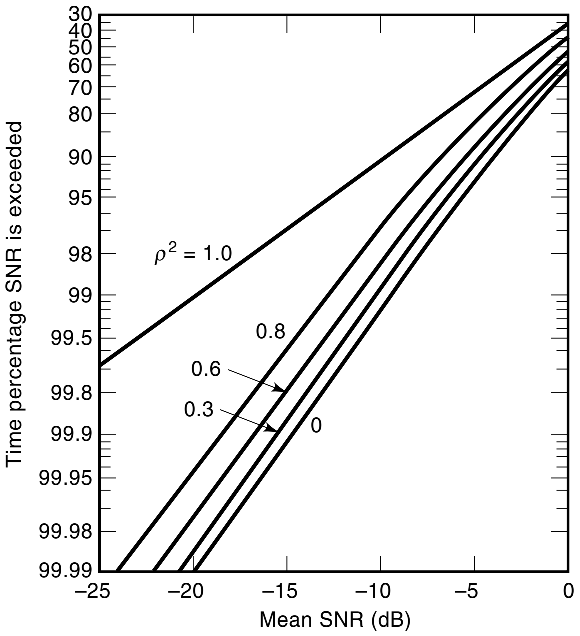

Figure 8. Rayleigh-fading statistics for 2-channel selection diversity assuming varying degrees of envelope correlation, ρ^2. Fade distributions are referenced to the SNR for a single (nondiversity) channel. (© 1994 IEEE.)

Switching and Combining Errors. No diversity switching or combining device is expected to operate perfectly, especially since randomly-fading signals supply much of the information used to control the switching or combining device. Errors introduced by imperfect operation degrade the performance of a diversity system. As already noted, a maximal ratio combiner must cophase and sum the diversity signals in proportion to the SNR in each channel, necessitating SNR estimates for each channel. In some systems, a continuous-wave pilot signal is transmitted adjacent to the communication band to supply reference amplitude and phase information to assist in the control of the combiner. Degradations resulting from imperfect correlation between a pilot signal to control operation of a maximal ratio combiner and the signals themselves are summarized here to indicate the magnitude of the anticipated errors.

The output of an M-channel maximal ratio combiner that relies on a pilot for the reference control information is found to have the probability density (2)

$$\begin{aligned} p_M(\lambda_R) = \frac{1}{\Gamma}(1-\rho^2)^{M-1} e^{-\gamma_R/\Gamma} \sum_{n=0}^{M-1} \binom{M-1}{n} \\ \times \left[\frac{\gamma_R \rho^2}{\Gamma(1-\rho^2)}\right]^n \frac{1}{n!} \end{aligned} \tag{24}$$

The first term after the summation is the binomial distribution, and ρ is the correlation coefficient between the pilot and the adjacent signal channel. (Note that here correlation is desirable, unlike the case for envelope correlation.) The first moment (mean) of γ_R is obtained by integrating with respect to the probability density in Eq. (24):

$$\langle \gamma_R \rangle = \int_0^\infty \gamma_R p_M(\gamma_R) d\gamma_R = \Gamma[1 + (M-1)\rho^2] \tag{25}$$

and is equivalent to the mean SNR. The probability distribution obtained by integrating over the density function is

$$\begin{aligned} P_M(\gamma_R) &= \int_0^{\gamma_R} p_M(x)\,dx \\ &= 1 - e^{-\gamma_R/\Gamma} \sum_{n=0}^{M-1} \binom{M-1}{n} \rho^{2n}(1-\rho^2)^{M-n-1} \sum_{k=0}^{n} \frac{(\gamma_R/\Gamma)^k}{k!} \end{aligned} \tag{26}$$

which represents the statistics of the combiner output signal.

If the correlation between the pilot and channel signal is perfect ($\rho^2 = 1$), representing perfect operation of the diversity combiner, Eqs. (26) and (25) respectively give

$$P_M(\gamma_R) = 1 - e^{-\gamma_R/\Gamma} \sum_{k=0}^{M-1} \frac{(\gamma_R/\Gamma)^k}{k!} \quad \langle \gamma_R \rangle = M\Gamma \tag{27}$$

which are equivalent to Eqs. (17) and (18), respectively. If there is no correlation between the pilot and channel signal ($\rho^2 = 0$), the resulting expressions are

$$P_M(\gamma_R) = 1 - e^{-\gamma_R/\Gamma} \quad \langle \gamma_R \rangle = \Gamma \tag{28}$$

showing that diversity operation provides no benefit for this case.

To illustrate the impact of such errors on the overall performance of a maximal ratio combiner, Figure 9 displays fading statistics for 4-channel operation with varying degrees of correlation (2). The performance penalty imposed by combiner-control errors is considerable, especially in the critical deep-fading portion of the distribution (for example, compare curves for $\rho^2 = 1.0$ and $\rho^2 = 0.75$). From Eq. (25), however, the degradation in *mean* received signal power is modest. If the correlation coefficient ρ^2 decreases from 1 to 0.5, for instance, the mean SNR for the 4-channel combiner decreases from 4 Γ to 2.5 Γ, a loss of only 2.0 dB.

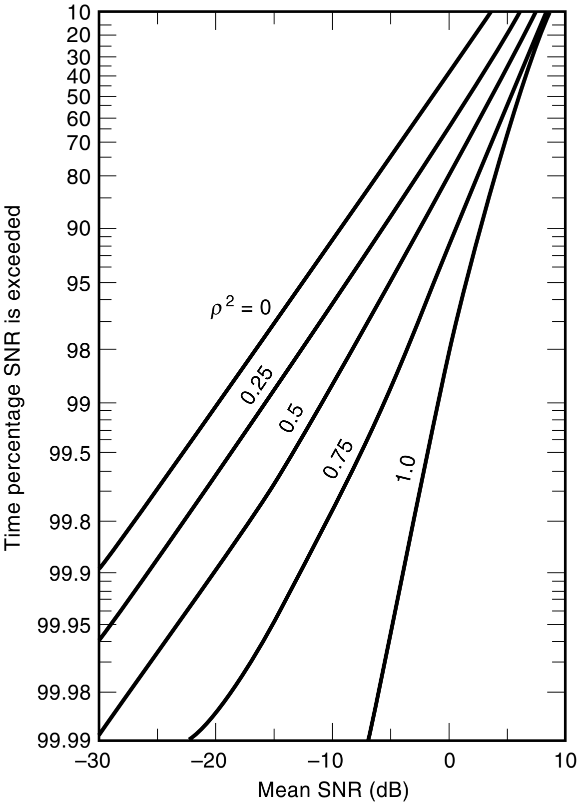

Figure 9. Rayleigh-fading statistics for 4-channel maximal ratio diversity combining with combiner errors (specified by ρ^2) between reference pilot and channel signal. Fade distributions are referenced to the SNR for a single (nondiversity) channel. (© 1994 IEEE.)

Other System Considerations. Even if diversity operation offers substantial improvement in overall circuit availability, other practical constraints may need to be taken into account. For example, site diversity significantly improves availability for earth–satellite paths subject to rain attenuation, as verified in Fig. 3. However, in large earth stations that utilize wide bandwidths to serve many users, potential outages related to switching among available diversity signals is a severe problem to be avoided. Therefore, the entire receive band for the diversity channel must be conditioned and synchronized with the main-station signal to support switching among channels with no loss of information.

However, on the uplink to the satellite, such synchronization is extremely difficult due to variations in radio path length (such as caused by satellite motion) between the earth stations and the satellite. Therefore, uplink site diversity is much less viable than downlink site diversity, except possibly in packet-switched applications where lost packets can be recovered. A potential compromise solution for this case is to protect the downlink path with site diversity, but implement transmitter power control (27) to increase the availability of the uplink path.

Figure 10 shows a 14/11 GHz earth-space site diversity configuration (28), planned for the two sites represented in Fig. 1. In this system, the entire downlink receive band (500 MHz) from the secondary station is transported to the main station by the microwave *Diversity Interconnect Link* (DIL), buffered and synchronized with the main station receive signal, and made available at the diversity switch. (Signal combining of the diversity signals is unlikely to be considered for this wideband application because of the difficulty in matching phase variations across the two 500 MHz receive bands.) Signal regeneration (demodulation and remodulation) is implemented in the DIL, not only to support frequency conversion, but also to preserve the quality of the transmissions. In this design, the uplink signal is also made available at both transmit sites, but this capability mainly increases the reliability of the overall system by enabling a redundant uplink signal transmission capability.

RECENT DEVELOPMENTS

Despite the rather well-developed state of diversity reception concepts, the field remains quite active. Many recent developments are related to new service offerings such as *nongeostationary* (NGSO) satellite systems, digital cellular systems and indoor mobile systems, and systems that often must operate in severe propagation environments.

One novel consumer application is the installation of space-diversity antennas in some automobiles to mitigate reflection multipath fading and improve urban FM radio reception (29). Antenna diversity has also been demonstrated for vehicular reception of mobile-satellite transmissions. For reception at 1.5 GHz with a single terminal fade threshold of 10 dB, space diversity reception using two antennas separated by 3 m provided a diversity gain (fade reduction) of 4 dB when the major cause of fading was shadowing and blockage by roadside trees (30).

Because of the importance of preserving links supporting multiple users, site diversity is beginning to be implemented to protect feederlink earth stations in some mobile-satellite

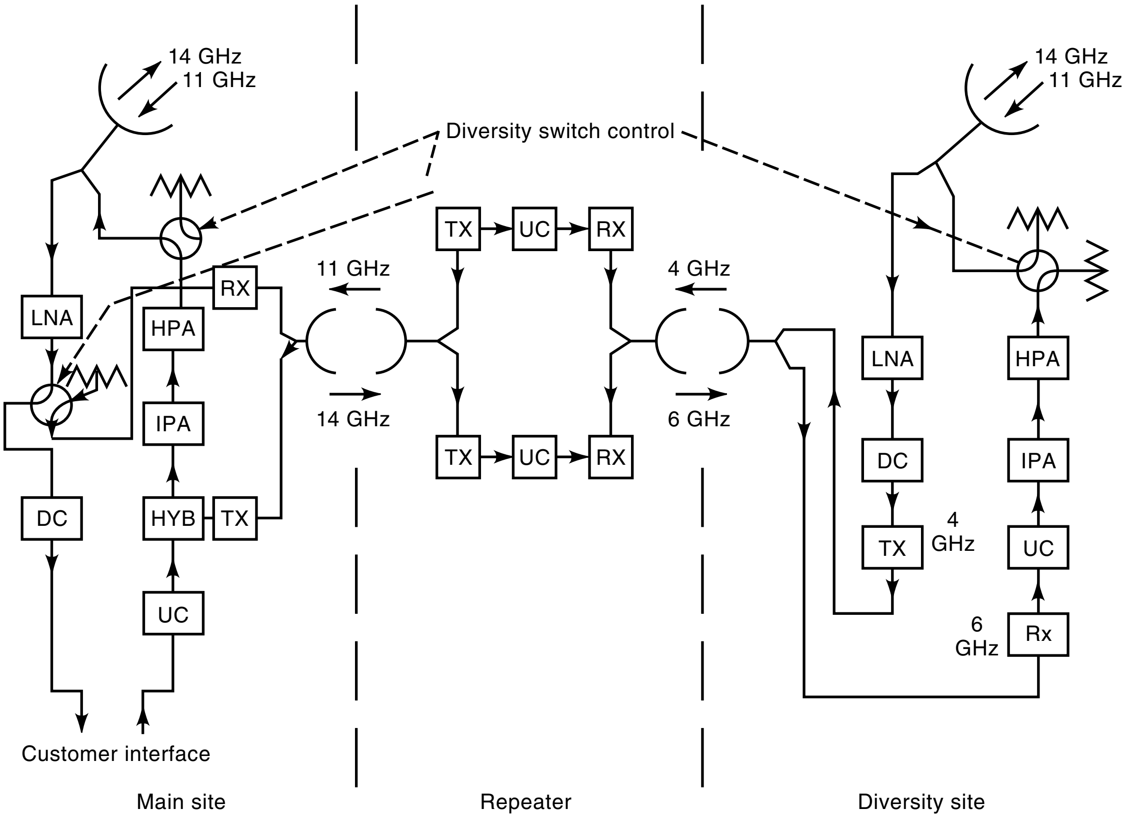

Figure 10. Configuration for 14/11 GHz earth–space site diversity, including microwave link that interconnects the main and diversity stations to support selection diversity (TX/RX = transmit/receive; IPA/HPA = intermediate/high-power amplifier; LNA = low-noise amplifier; UC/DC = up/down converter; HYB = hybrid). (Copyright 1979 COMSAT Corp. All rights reserved by COMSAT Corp. Used by permission.)

systems (9). A novel proposed application of site diversity, called *wide area diversity,* is to protect many VSAT terminals connected to a metropolitan area network by switching traffic among the VSATs as required to counteract impairments on the separate earth-space paths (31).

Recently the orbital-diversity concept has been investigated for narrowband VSAT systems, where a small reserve capacity can be made available on an alternate satellite as protection for several VSAT links. This application does not require the difficult switching of wideband signals between satellites. Interestingly, early experimental tests (32) indicate that the diversity gain in snow events was superior to that for rain events, but rain will likely represent the more important impairment.

Yet another variation of orbital diversity (also called path or satellite diversity in this context) is planned for some NGSO satellite configurations, such as *low earth orbit* (LEO) constellations, intended to communicate with ground-based terminals (especially handheld terminals). The primary path impairments are shadowing and blockage by terrain and surface objects (trees, buildings, etc.) as the NGSO satellites change position with respect to a user terminal. In such constellations, more than one satellite may often be potentially accessible from a given location on the earth, providing the capability to switch among the separate, independently-fading paths to create a diversity configuration (33).

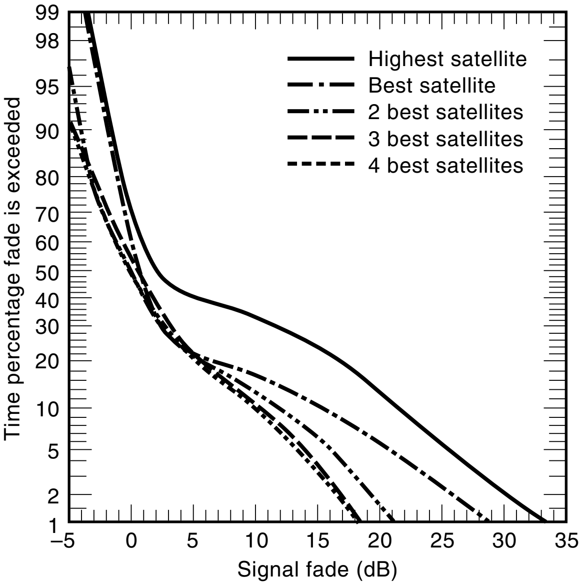

Figure 11. Urban shadowing/blockage fading statistics simulated for NGSO satellite constellation. “Highest” satellite is the one with greatest elevation angle; “best” satellite is the one with least-faded path; other curves assume coherent combining of signals from 2, 3, or 4 satellite paths, respectively. (© 1997 IEEE.)

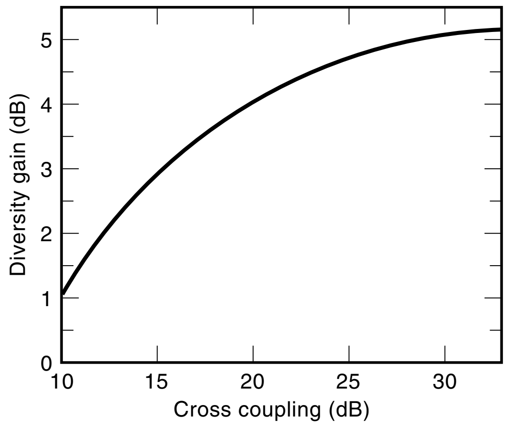

Figure 12. Polarization diversity gain (90% probability level) as a function of antenna *cross-polarization discrimination* (XPD), simulated for worst-case fading with selection diversity in urban environment. (© 1997 Horizon House Publications, Inc. Used by permission.)

There will be many instances when at least one of the satellite paths is free of obstruction. If the most favorable path can be selected as required, or the multiple signals can be combined, path performance is enhanced. Figure 11 shows the cumulative fading distributions estimated by simulating the path availability achieved by equal-gain combining of available signals from multiple satellites for an urban shadowing/blockage environment (33). The substantial benefits of path diversity for this environment are apparent. In such systems using path diversity, the RAKE receiver technique may be implemented, not only to overcome shadowing and blockage impairments, but also to enable smooth handoff among the available satellite beams (34), which might be required every few minutes in LEO systems, since satellite motion is rapid with respect to earth-based terminals.

Polarization diversity has found renewed interest in mobile telephony as a means to improve performance while avoiding the need for additional spectrum or a second space-diversity antenna, especially for handheld terminals (35) in which the antenna orientation is quite variable. In a study of polarization-diversity reception based on measurements in an urban area (36), the achievable diversity gain was related to the cross-polarization discrimination, *XPD,* of the received signals. Figure 12 shows diversity-gain results at the 90% probability level for selection combining with worst-case reception (assuming the two signals arrive 180° out of phase), referenced to the +45° branch of two linearly-polarized elements oriented at ±45°. The results indicate that the diversity gain achievable with polarization diversity in this application is only a dB or so less than typical space diversity gains achieved with antenna separations of the order of 20 wavelengths. In this environment, better performance was obtained with linear polarizations oriented at ±45° than for vertical and horizontal polarizations, as the former maintained more nearly equal mean signal levels in the two diversity channels.

Additional diversity reception applications will inevitably arise in response to future developments in telecommunication systems and technology.

BIBLIOGRAPHY

1. M. Schwartz, W. R. Bennett, and S. Stein, *Communication Systems and Techniques* (in particular chaps. 10 and 11), Piscataway, NJ: IEEE Press, 1996.
2. W. C. Jakes (ed.), *Microwave Mobile Communications,* Piscataway, NJ: IEEE Press, 1994.
3. G. Roda, *Troposcatter Radio Links,* Norwood, MA: Artech House, 1988.
4. Recommendation ITU-R P.530-7, Propagation data and prediction methods required for the design of terrestrial line-of-sight systems, International Telecommunication Union, Geneva: *ITU-R Recommendations 1997 P Series, Part 2:* 271–295, 1998.
5. D. L. Bryant and J. E. Allnutt, Use of closely-spaced height diversity antennas to alleviate the effects of low angle non-absorptive fading on satellite slant paths, *Electron. Lett.,* **26**: 480–481, 1990.
6. S. H. Lin, T. C. Lee, and M. F. Gardina, Diversity protections for digital radio—summary of ten-year experiments and studies, *IEEE Commun. Magazine,* **26** (2): 51–64, 1988.
7. R. G. Vaughan and J. Bach Andersen, Antenna diversity in mobile communications, *IEEE Trans. Veh. Technol.,* **VT-36**: 149–172, 1988.
8. V. Mimis and A. Smalley, Low elevation angle site diversity satellite communications for the Canadian arctic, *Conf. Record, IEEE Int. Conf. Commun.,* Philadelphia, **2**: 4A.4.1–4A.4.5, 1982.
9. C. Kittiver and E. Sigler, Propagation considerations in the American Mobile Satellite System design, *Proc. 17th NASA Propag. Experimenters Meeting,* Pasadena, CA: JPL Publ., **93–21**: 171–181, 1993.
10. J. C. Cardosa, A. Safaai-Jazi, and W. L. Stutzman, Microscale diversity in satellite communications, *IEEE Trans. Antennas Propag.,* **41**: 801–804, 1993.
11. A. Bosisio et al., Analysis and application of short-distance site diversity techniques for 20/30 GHz communication links, *Conf. Record, IEEE Global Telecommun. Conf.* : Singapore, **1**: 749–753, 1995.
12. D. C. Cox, Universal digital portable radio communications, *Proc. IEEE,* **75**: 436–477, 1987.
13. D. V. Rogers and G. Hyde, Diversity measurements of 11.6-GHz rain attenuation at Etam and Lenox, West Virginia, *COMSAT Tech. Rev.,* **9**: 243–254, 1979.
14. D. V. Rogers, Diversity and single-site radiometric measurements of 12-GHz rain attenuation in different climates, *IEE Conf. Publ., No. 195,* Part 2: 118–123, 1981.
15. D. B. Hodge, An empirical relationship for path diversity gain, *IEEE Trans. Antennas Propag.,* **AP-24**: 250–251, 1976.
16. J. Goldhirsh et al., Three-site space-diversity experiment at 20 GHz using ACTS in the eastern United States, *Proc. IEEE,* **85**: 970–980, 1997.
17. Recommendation ITU-R P.618-5, Propagation data and prediction methods required for the design of earth-space telecommunication systems, International Telecommunication Union, Geneva: *ITU-R Recommendations 1997 P Series, Part 2:* 305–323, 1998.
18. D. B. Hodge, An improved model for diversity gain on earth–space propagation paths, *Radio Sci.,* **17**: 1393–1399, 1982.
19. E. Matricciani and M. Mauri, Italsat-Olympus 20-GHz orbital diversity experiment at Spino d'Adda, *IEEE Trans. Antennas Propag.,* **43**: 105–108, 1995.
20. R. G. Vaughan, Polarization diversity in mobile communications, *IEEE Trans. Veh. Technol.,* **39**: 177–186, 1990.
21. P. C. F. Eggers, J. Toftgård, and A. M. Opera, Antenna systems for base station diversity in urban small and micro cells, *IEEE J. Sel. Areas Commun.,* **11**: 1046–1057, 1993.

22. W. C. Y. Lee, *Mobile Communications Engineering,* New York: McGraw-Hill, 1982.
23. P. L. Dirner and S. H. Lin, Measured frequency diversity improvement for digital radio, *IEEE Trans. Commun.,* **COM-33**: 106–109, 1985.
24. W. C. Wong et al., Time diversity with adaptive error detection to combat Rayleigh fading in digital mobile radio, *IEEE Trans. Commun.,* **COM-31**: 378–387, 1983.
25. G. J. R. Povey, P. M. Grant, and R. D. Pringle, A decision-directed spread-spectrum RAKE receiver for fast-fading mobile channels, *IEEE Trans. Veh. Technol.,* **45**: 491–502, 1996.
26. A. Mehrotra, *Cellular Radio Performance Engineering,* Norwood, MA: Artech House, 1994.
27. J. E. Allnutt, *Satellite-to-Ground Radiowave Propagation* (Sect. 7.5.2), London, UK: Peter Peregrinus, 1989.
28. L. F. Gray and M. P. Brown, Transmission planning for the first U.S. Standard C (14/11 GHz) INTELSAT earth station, *COMSAT Tech. Rev.,* **9**: 61–90, 1979.
29. H. K. Lindenmeier, Antennas on land vehicles for improved communications, *NATO AGARD Lecture Series,* No. 165: 7-1–7-19, 1989.
30. W. J. Vogel, J. Goldhirsh, and Y. Hase, Land-mobile satellite fade measurements in Australia, *J. Spacecraft Rockets,* **29**: 123–128, 1992.
31. K. Hobson, R. Heron, and T. Spracklen, Wide area diversity and wide area networks, *Proc. Olympus Utilization Conf.,* European Space Agency Publ. **WPP-60**: 227–232, 1993.
32. T. Hatsuda et al., Comparison of multiple satellites diversity characteristics between rain and snow attenuations for 14/12 GHz band, *Digest, IEEE Antennas Propag. Soc. Int. Symp.,* Montréal, **4**: 2556–2559, 1997.
33. R. Akturan and W. J. Vogel, Path diversity for LEO satellite-PCS in the urban environment, *IEEE Trans. Antennas Propag.,* **45**: 1107–1116, 1997.
34. J. Schindall, Concept and implementation of the Globalstar mobile satellite system, *Proc. 4th Int. Mobile Satellite Conf.,* Ottawa, Canada, A11–A16, 1995.
35. F. Lotse et al., Base station polarization diversity reception in macrocellular systems at 1800 MHz, *Proc. IEEE 46th Veh. Tech. Conf.,* Atlanta, **3**: 1643–1646, 1996.
36. C. Beckman and U. Wahlberg, Antenna systems for polarization diversity, *Microwave J.,* **40** (5): 330–334, 1997.

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