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A New Approach to High-Capacity Digital Mobile Radio

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Space diversity (adaptive phased-array antennas) is an effective weapon against the cochannel interference encountered in cellular mobile radio systems. High-order diversity, and hence, strong interference suppression, can be achieved with modest hardware complexity by using time-division retransmission. With this technique, which is especially well-suited to digital modulation methods, the adaptive signal processing required for space diversity can be performed at just one end of the communication link, namely, the base station. At the other end (the mobile unit) only a single-element antenna is needed. Moreover, the use of coherent phase-shift keying in such a system allows simple RF *circuity, because the adaptive processing is done at baseband. In the context of cellular mobile radio, the combination of space diversity, time-division retransmission and 120-degree corner illumination of each cell can yield a reliable communication channel even in the presence of intercell interference, Rayleigh fading (both flat and frequency-selective), and shadow fading. The use of these techniques allows approximately 130 two-way channels per cell (at 32 kb/s each) to be accommodated in the 40-MHz bandwidth of the 850-MHz mobile radio band.*

I. INTRODUCTION

We present an outline for the design of a cellular digital mobile radio system suitable for telephone service in urban areas. This system serves two purposes: (*i*) it demonstrates that a digital system with a capacity comparable to that of existing analog designs[1,2] is a realistic possibility, and (*ii*) it provides a framework for taking advantage of future advances in digital signal processing, especially speech coding. In this paper, we assume that adequate speech quality can be achieved at 32 kb/s using adaptive-differential-pulse-code modulation

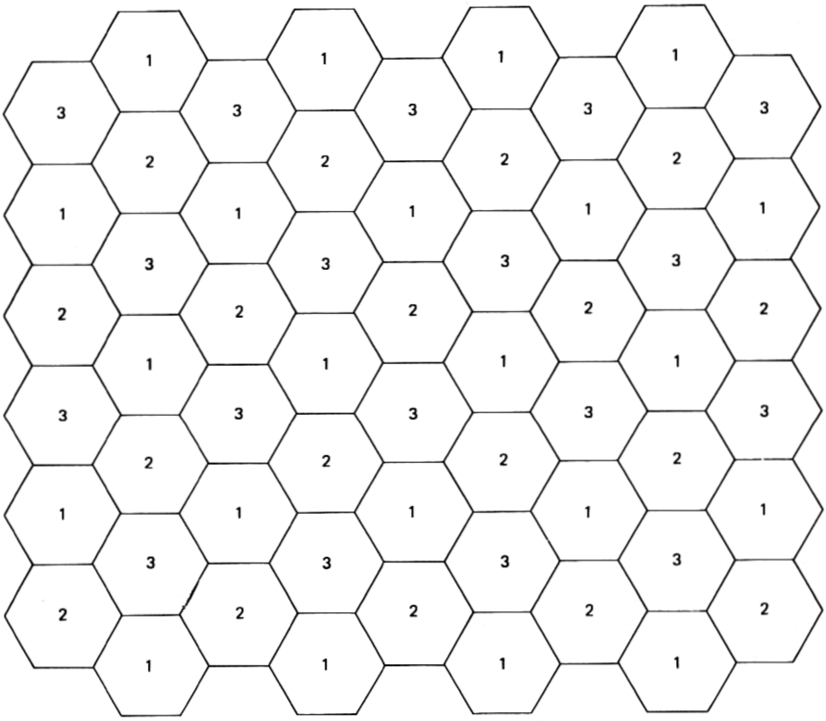


Fig. 1—A hexagonal-cell layout for a mobile radio system. The number in each cell refers to the channel set assigned to it.

(ADPCM).* Over the next few years economical coders in the 10 to 16 kb/s range should become available.[5]

We consider a service area covered with hexagonal cells with radius (center-to-corner) typically one mile, as shown in Fig. 1.[6] A communication link between a base station and a mobile is established on an assigned channel (frequency band) chosen from the channel set available to that cell. To get high capacity, the same channel set may be re-used in several cells, provided they are widely enough separated so that the mutual cochannel interference is tolerable. The intervening cells, of course, must use different frequencies. To accomplish this, the total bandwidth used by the system is divided into several channel sets, each with an equal number of channels. Each cell is assigned one set (indicated by the numbers in the cells of Fig. 1) according to a plan that maximizes the distance between re-uses of any given set. The greater the number of channel sets, the greater the distance (and hence isolation) between cochannel cells. On the other hand, a large number

* In addition to ADPCM, adaptive-delta modulation at 40 kb/s is an attractive candidate for reduced-bit-rate voice transmission.[3,4]

of sets means relatively few channels per cell and, hence, low system capacity. We will see that one of the strengths of the system described below is that it requires the use of just three channel sets; analog systems use 7–15.[1,2]

In the following discussion, we use elementary models to characterize the phenomena which limit mobile radio communication. We then describe hardware for dealing with these phenomena, and calculate system performance. Our investigation is simplified by two assumptions:

(*i*) Cochannel interference is the sole source of additive signal degradation. (Thermal noise is negligible.)

(*ii*) The interference at any point in the system, being the incoherent sum of contributions from many interferers, is equivalent to stationary Gaussian noise. In effect, we are assuming that the shadow and Rayleigh fading (Section II) of the total interference is negligible compared with the fading of the signal.[7,8]

II. AVAILABLE SIGNAL-TO-INTERFERENCE RATIO

Mobile radio reception in urban areas is characterized by large fluctuations in received signal power P as a mobile travels along a street. This variability can be modeled as the product of three factors:[8]

$$P(\mathbf{r}) = |\mathbf{r}|^{-n} \cdot S(\mathbf{r}) \cdot R^2(\mathbf{r}), \tag{1}$$

where $\mathbf{r}$ is the position vector denoting the location of the mobile relative to the base station. The first factor on the right represents the general reduction in signal strength as a mobile recedes from the base station. In free space, of course, $n = 2$, but in an urban environment, n is in the range of 3 to 4.

The second factor, $S(\mathbf{r})$, represents shadow fading, which is primarily the result of blockage because of large objects, such as buildings and hills. Measurements of S in several cities indicate that it is approximately a log-normal random variable: values of S measured in dB display a normal distribution with mean value zero and standard deviation σ in the range of 6 to 10 dB.

The third factor in eq. 1 represents Rayleigh fading, a phenomenon caused by the random addition of signals arriving at an antenna via multiple paths. The amplitude of the received envelope, R, may be modeled as a random variable with a probability density function

$$p(R) = 2Rexp(-R^2). \tag{2}$$

The mean-squared value of R, corresponding to average signal power, is unity. In general, R varies with both vehicle location and signal frequency. For the time being, we neglect the frequency dependence.

A detailed view of a group of cells from Fig. 1 is shown in Fig. 2. To reduce cochannel interference, each cell is covered by three base stations located on alternate cell corners.[9] At any time, only one of these stations (usually the one receiving the strongest signal) serves a given mobile.

We estimate radio system performance by calculating worst-case signal-to-interference ratios (SIRs) for base-to-mobile (B→M) and mobile-to-base (M→B) transmission. The average SIR is defined to be the ratio of signal power to total interference power, based on an $|\mathbf{r}|^{-n}$ propagation law and averaged over shadow and Rayleigh fading. In the B→M direction, the worst-case SIR occurs when: (*i*) the desired mobile is in a cell corner between two base stations, and (*ii*) every cochannel cell is served by a base station whose antenna pattern covers this mobile. The resulting average SIRs for $n = 3$ and $n = 4$ propagation laws are

$$\left.\begin{array}{l}\text{SIR}(n = 3) \approx 8 \text{ dB} \\ \text{SIR}(n = 4) \approx 13.5 \text{ dB}\end{array}\right\} \text{B}\rightarrow\text{M}. \quad (3)$$

In the M→B direction, the worst case occurs when the desired mobile is in a cell corner between two base stations and the interfering mobiles are as close as possible to the base station being interfered with. The average SIRs in this case are

$$\left.\begin{array}{l}\text{SIR}(n = 3) \approx 7.5 \text{ dB} \\ \text{SIR}(n = 4) \approx 12.5 \text{ dB}\end{array}\right\} \text{M}\rightarrow\text{B}. \quad (4)$$

The corner-excited cells of Fig. 2 are effective in reducing the

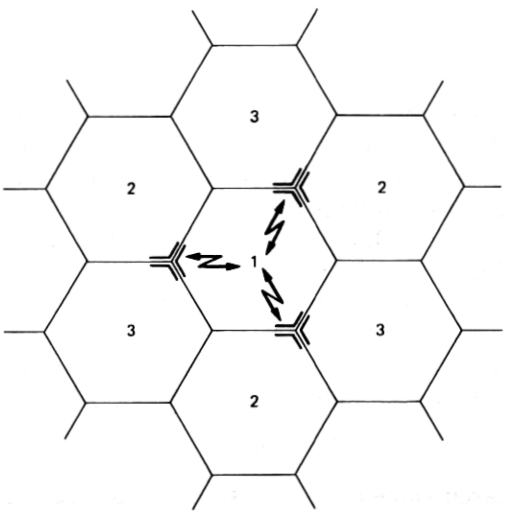


Fig. 2—Corner-excited cells. Each cell is served by three base stations equipped with 120-degree sectoral antennas.

performance degradation caused by shadow fading, because it is feasible to switch from one base station to another as shadowing conditions vary. Since the shadow fading on the paths to the three base stations is uncorrelated, the probability of a simultaneous outage on all three paths is far less than the probability of an outage on any one of them.[10] The performance of a corner-excited cell in the presence of shadow fading ($\sigma = 8$ dB) may be summarized as follows: over the entire area of the cell, the worst-case SIRs of eqs. 3 and 4 are exceeded at least 90 percent of the time. Stated differently, if a mobile communication system is able to operate satisfactorily with the SIRs of eqs. 3 and 4, then shadow fading will cause less than 10 percent of the cell area to have unsatisfactory service. (We consider 90 percent coverage to be a reasonable service objective.)[9] We, therefore, take the SIR values in eqs. 3 and 4 to be reasonable estimates of the available SIR in our radio system.

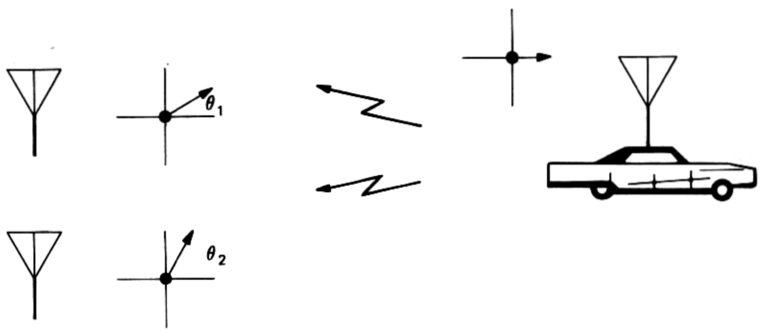
III. SPACE DIVERSITY

In a Rayleigh-fading environment the performance of conventional digital radio systems with SIR < 10 dB (eqs. 3 and 4) is very poor; binary coherent phase shift keying (CPSK), for example, has an error probability greater than 10^{-2}. The use of space diversity, however, greatly improves the situation and allows acceptable error rates ($\leq 10^{-3}$) to be attained.[7] In a space-diversity system, multiple antennas are used and the independently fading signals received on each branch are combined coherently. This process gives two benefits: it increases the output SIR because the signal contributions from the branches are added in phase, while the interference components are added randomly, and it smooths out the fluctuations in the output signal because all branches are unlikely to fade simultaneously. With binary CPSK and optimal (maximal-ratio) diversity,[7,11] the SIR at each branch required to achieve 10^{-3} error rate is 11, 7, and 4 dB for 2-, 3- and 4-branch systems, respectively. Comparing these values with eqs. 3 and 4, we see that 3-branch diversity is theoretically adequate for $n = 3$ propagation and 2-branch for $n = 4$. To allow reasonable margins for nonideal equipment, and also to simplify B→M transmission (See Section V), we will assume 4-branch diversity for $n = 3$, and 3-branch for $n = 4$.

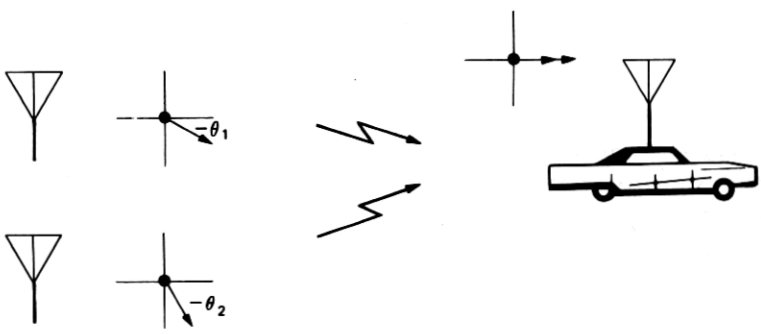
In conventional space diversity systems, arrays of multiple antennas are required at both the base station and mobile. However, a technique known as time-division retransmission[12] allows the advantages of space diversity to be obtained with an array only at the base station and just a single antenna at the mobile. In such a system, all the adaptive signal processing is done at the base station where its cost can be shared among many users. The equipment on the mobile is kept simple.

Communication with time-division retransmission requires time-sharing of a single channel by both directions of transmission. In the M→B direction, the antennas at the base station are cophased to achieve SIR enhancement; during B→M transmission, the excitation of each base station antenna is adjusted so that the separate contributions all arrive in phase at the mobile.

The operation of time-division retransmission can be understood from Fig. 3. Let the signals arriving at the base station be $\cos(\omega_c t + \theta_1)$ and $\cos(\omega_c t + \theta_2)$, where ω_c is the carrier frequency and θ_1 and θ_2 are phases measured relative to some arbitrary reference. If these signals are phase-shifted by $-\theta_1$ and $-\theta_2$, they will be brought to a common phase; simple addition at this point will be equivalent to coherent combining. For transmission back to the mobile, each antenna is excited using the conjugate (negative) of the received phase. These excitation phases exactly compensate for the different phase



(a)



(b)

Fig. 3—Time-division retransmission. (a) Signals received from the mobile are coherently combined at the base station. (b) Signals transmitted from the base station are phased so as to interfere constructively at the mobile.

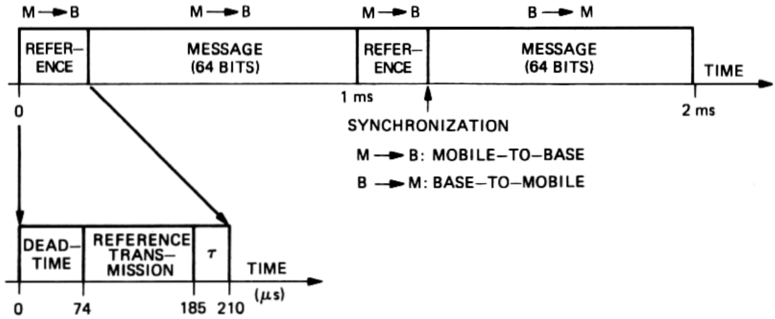


Fig. 4—A signaling frame for time-division retransmission. Both directions of transmission time-share a single channel.

delays experienced by the radiated signals, so that they all add up in phase at the mobile.

In addition to adjusting the phases of the base station antenna branches, the ideal combiner also adjusts their weights. For equal power Gaussian interference at each branch, the best net SIR is achieved with a maximal-ratio combiner, in which each branch contributes at its output a signal amplitude proportional to its received signal power.

From the foregoing description, it is apparent that there are two fundamental operations that must be performed by the base station receiver: identification of the desired signal, and coherent combination of the antenna branches. In Section IV, we describe hardware for implementing these functions.

IV. BASE STATION RECEIVER

The signaling frame for a 32-kb/s, 2-way voice channel is shown in Fig. 4. The basic cycle time of 2 ms consists of 2 message intervals, when speech is transmitted, and 2 reference intervals, during which the base station diversity combiner is updated. The 1-ms repetition period for reference transmission was chosen to be rapid enough to ensure that propagation conditions remain relatively constant during the message interval. (See Section VI.) To achieve 32 kb/s in each direction, 64 bits must be sent in each 790-μs message interval, implying a symbol rate of 81 kbaud. Depending on the details of pulse-shaping and filtering, this rate requires 80–120 kHz of bandwidth with binary phase shift keying (PSK) modulation. Thus, the number of channels per cell that can be served in the 40-MHz bandwidth of the 850-MHz mobile radio band is approximately 133 (40 MHz/3·100 kHz).

All the base stations are assumed to be synchronized at the instant indicated in Fig. 4. (A synchronization accuracy of ±1 μs can be achieved with pseudo-noise transponder techniques or direct time broadcast by satellite.[13,14]) A mobile establishes its timing from signals received from its base station; mobiles are not in synchronism with each other because of the distance-dependent propagation time across the cell.

The signal-processing circuitry for one branch of the base station receiver is shown in Fig. 5. We will see that when the demodulated signals from each branch are added as shown in the figure, the result is equivalent to maximal ratio combining. The operation of the receiver (somewhat oversimplified for the time being) is as follows. Within the

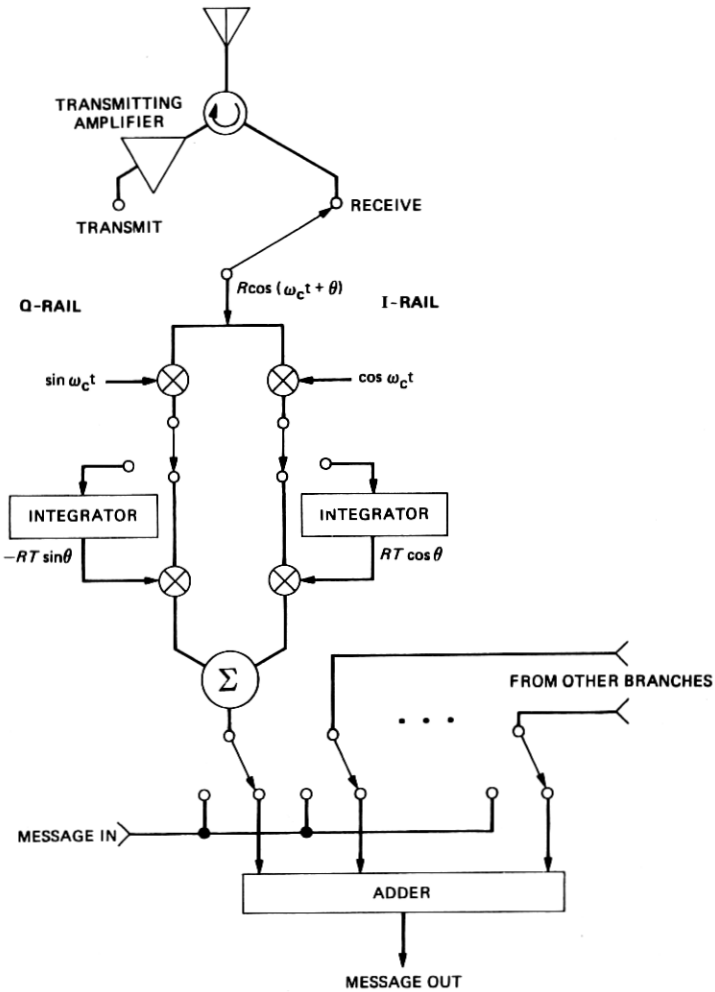


Fig. 5—Base station diversity receiver. The addition of the outputs from the several branches produces optimal (maximal-ratio) combining. The switches are in a position to receive the message-interval transmission from the mobile.

reference transmission interval the carrier burst of duration T (111 μs in Fig. 4) received at an antenna has the form $R\cos(\omega_c t + \theta)$, where R is the Rayleigh amplitude and θ an unknown phase. (Both R and θ, though functions of time, are essentially constant during the reference interval.) After down-conversion the signals on the I and Q rails are $R\cos\theta$ and $-R\sin\theta$, respectively. These signals are integrated to produce reference coefficients $TR\cos\theta$ and $-TR\sin\theta$, which will be used for subsequent message demodulation. During message transmission to the base station, the kth message bit and accompanying interference may be written as

$$a_k R\cos(\omega_c t + \theta) + I_c\cos\omega_c t + I_s\sin\omega_c t,$$

where $a_k = \pm 1$ represents the transmitted bit, and I_c and I_s are Gaussian variables with zero mean and variance s^2. After down-conversion and multiplication by the previously determined reference coefficients, the I and Q signals become

$$a_k TR^2\cos^2\theta + I_c TR\cos\theta$$

and

$$a_k TR^2\sin^2\theta - I_s TR\sin\theta.$$

The sum of these terms gives a demodulated signal $a_k TR^2$ and a mean-square "noise" $T^2R^2s^2$, resulting in a s/n of R^2/s^2; this is precisely the performance that would have been achieved with conventional coherent demodulation. The output signals from all branches are in phase (independent of θ), and each has a magnitude proportional to R^2, the received signal power; thus, the simple addition of these outputs is equivalent to maximal-ratio combination. Observe that the adaptive signal processing is all performed at baseband, where it is amenable to digital implementation. Processing at RF is minimal.

The successful operation of the base station receiver requires a clean reference signal from the mobile, relatively uncontaminated by interference. The primary effect of such interference is to cause suboptimal combining of the various antenna branches, leading to reduced signal output power. This reduction is tolerable (less than a few tenths of a dB) for reference SIR greater than about 14 dB. However, if all mobiles were to transmit reference bursts at their carrier frequencies, the reference SIR (eq. 4) would be less than 14 dB and, hence, unacceptably low. This problem is solved using a frequency-offset reference transmission scheme based on the seven-cell cluster shown in Fig. 6. Each cell in a cluster is assigned an offset frequency, designated by the seven subscripts "a" through "g," which is a multiple (0, ± 1, ± 2, ± 3) of a low frequency $\Omega = 2\pi/T$, where T is the duration of the reference-signal transmission.

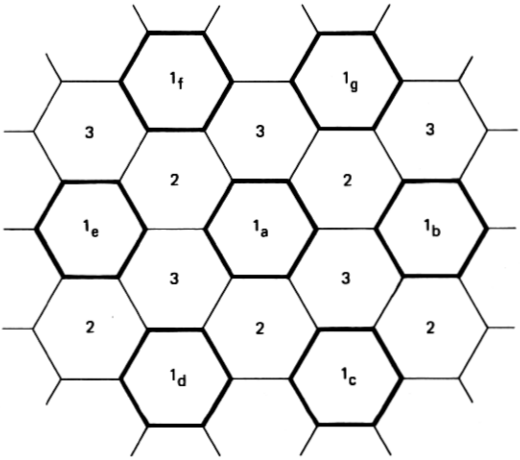


Fig. 6—A seven-cell cluster for offset-frequency reference transmission. The use of orthogonal reference signals allows interference from the first ring of interferers (subscripts "*b*" through "*g*") to be completely suppressed.

During the reference interval, the transmitting frequency of a mobile is shifted from the carrier frequency ω_c by the offset assigned to that cell. At the base station, the local oscillator is shifted by the same amount, and the reference coefficient is generated by the integrator as described earlier. We will show that the reference coefficient so obtained is the same as if no offset had been used at the mobile or base station, provided the fading on the M→B path is flat (nonfrequency-selective).

The use of different reference frequencies by mobiles sharing the same channel allows the base station to select the desired signal and suppress the interference. In effect, the re-use factor for reference transmission is 21, even though it is only 3 for message transmission. The choice of $\Omega = 2\pi/T$ allows the various reference signals to be orthogonal; unwanted signals do not contribute to the integrator output. In the present system, $T \approx 111\ \mu s$ ($\Omega = 2\pi \cdot 9$kHz), which is a compromise between excessive bandwidth (T small) and excessive time allocated to reference transmission (T large).

The reference signal may be generated using a single-sideband modulator to shift the carrier frequency by the desired offset. To obtain offsets at the mobile and base station with the required phase relationship (see below), the offsets can be generated from the appropriate harmonic (9, 18, 27) of the 1-kHz reference clock which controls the timing of the reference bursts.

We now show that in a flat-fading environment, the reference coefficient is independent of the offset frequency. Flat fading means that the envelope delay (the derivative of phase with respect to frequency) is independent of frequency. Let the reference clock on the mobile be cos $\omega_r t$, and let its mth harmonic be used to generate the desired offset, so that the transmitted reference signal is $\cos(\omega_c t + m\omega_r t)$. The received signal (apart from a frequency-independent scale factor) is $\cos(\omega_c t + \theta + m\omega_r(t - t_d))$, where t_d is the envelope delay and θ is the unknown phase angle used in Section III. The base station reference clock, being locked to the envelope of the received signal, may be written $\cos \omega_r(t - t_d)$. The offset local oscillator is then $\cos(\omega_c t + m\omega_r(t - t_d))$. Down-conversion of the received reference signal by this local oscillator yields cos θ, independent of offset. We comment in Section VI on the degradation caused by non-flat fading.

Rejection of an interfering reference signal requires integration over its entire duration. Since interference comes from distant cells, some excess integration time must be allocated to cover the associated propagation delay. For a cell radius of 1 mile, 25 μs is adequate to allow complete integration of reference signals from the first ring of interferers in Fig. 6.

The reference scheme described above is implemented by dividing the 210-μs reference interval into three zones, as shown in Fig. 4:

(*i*) A dead time of 6 symbol intervals ($\approx$74 μs) following message transmission to let signals from distant cells "quiet down."*

(*ii*) Nine symbol periods ($\approx$111 μs) for actual reference transmission.

(*iii*) An excess integration time τ of 2 symbol periods ($\approx$25 μs).

The reference SIR in this scheme is 21 dB for $n = 3$ (inverse-cube propagation) and 28 dB for $n = 4$. These values are comfortably above the 14-dB requirement mentioned earlier.

V. BASE-TO-MOBILE TRANSMISSION

For transmission back to the mobile, the circuit shown in Fig. 5 is used with the signal flow along the rails reversed. The required phase conjugation is accomplished by inverting the sign of the Q-rail reference coefficient. This procedure gives the same SIR at the mobile as if all the transmitted power were radiated from a single antenna and maximal-ratio diversity (with the same number of branches as at the base station) were used at the mobile.[12]

The receiver on the mobile can be very simple if differential phase shift keying (DPSK) is used in the B$\rightarrow$M direction. The SIR requirements for this type of modulation, though greater than those of CPSK,[15] are met by the system. For inverse-cube propagation ($n = 3$) with 4-

* In some situations, e.g., a locale with hilly terrain, a longer dead time may be necessary in order to eliminate interference from distant cells.

branch diversity, the required SIR is 7 dB, 1 dB less than available (eq. 3). For $n = 4$ with 3 branches, the requirement is 9 dB, leaving a 4.5 dB margin.

VI. IMPAIRMENTS

In the preceding discussion, we considered some fundamental obstacles to mobile radio communication and proposed a system design to deal with them. As additional impairments are considered, a more refined design emerges. Two impairments that seem particularly important will be discussed very briefly in this section: the time dependence of the reference coefficients, and the error in these coefficients caused by frequency-selective fading.

(*i*) *Time Dependence.* The reference coefficients, since they are determined at 1-ms intervals, do not precisely correspond to the propagation conditions existing during message transmission. The consequent system degradation may be estimated by modeling the reference coefficients as samples of a narrow-band Gaussian process with sample-to-sample correlation of $\rho(\tau) = J_0(\omega_c v\tau/c)$, where J_0 is the zero-order Bessel function, v is the vehicle speed and τ is the sampling interval.[16] The greatest error occurs at the end of a message interval when the reference coefficient is 1-ms "old"; the mean-squared fractional error between the "true" and "available" coefficients is $E^2 = 2(1 - \rho(\tau))$. At a carrier frequency of 850 MHz and a vehicle speed of 55 mph, $E^2 \approx 0.1$. This degradation is equivalent to an SIR during reference transmission of ~10 dB, which is unacceptably low. (See Section IV.) The problem can be largely eliminated by using a simple two-point linear predictor to estimate the reference coefficient during message transmission.[17] In this case, the mean-squared fractional error is $E^2 \approx (\omega_c v\tau/c)^4/8 \approx .005$, corresponding to an effective reference SIR of 23 dB.

(*ii*) *Frequency-Selective Fading.* When frequency-selective fading is significant, the envelope delay is no longer independent of frequency. This leads to errors in the reference coefficients determined by the frequency-offset technique (Section IV). The mean-squared error associated with this degradation is $E^2 \approx (\Delta\omega)^2 \cdot \mu_2$, where $\Delta\omega$ is the frequency offset and μ_2 is the second central moment of the path-delay distribution.[18] Let us assume that the multipath characteristics on the three links between the mobile and the corner base stations are statistically independent. In a typical urban location, the probability of finding $\sqrt{\mu_2} > 2\ \mu s$ on any link is ~0.2, so the probability of finding $\sqrt{\mu_2} > 2\ \mu s$ on all three links is less than 1 percent. (In effect, we are using base-station diversity to combat frequency-selective fading in much the same way that it is used against shadow fading. Since the outages caused by these phenomena are small and nearly uncorrelated,[19] the net system outage will be approximately the sum of the two, or 11 percent.) We, therefore, use 2 μs as a reasonable value for $\sqrt{\mu_2}$, and find a mean-squared reference error due to frequency-selective fading of $E^2 \approx (2\pi \cdot 27\ kHz \cdot 2\ \mu s)^2 \approx 0.1$, which is not acceptable. A large improvement is obtained when reference transmissions are made alternately on two frequencies, one above and one below the carrier; interpolation can then be used to estimate the desired reference coefficient. The mean-squared error depends on the product of the two frequency offsets, so the best pairings are (+27, −9), (+18, −18), (+9, −27), where the numbers denote offset frequencies in kHz. The resulting error is $E^2 \approx \frac{1}{4}(2\pi \cdot 18\ \text{kHz})^4 \cdot \mu_4$, where μ_4 is the fourth central moment of the path-delay distribution. For an exponential distribution $\mu_4 = 9\mu_2^2$, so $E^2 \approx .006$, corresponding to a reference SIR of 22 dB.[20]

The errors caused by time dependence of the reference coefficients and frequency-selective fading degrade the reference SIR computed in Section IV. Since these errors arise from independent sources, they add incoherently, and result in net reference SIR's of 17 dB and 19 dB for the $n = 3$ and $n = 4$ cases, respectively. These values are safely above the 14-dB requirement mentioned in Section IV.

VII. SUMMARY

In the preceding discussion, we developed an outline for a high-capacity cellular digital mobile radio system. To mitigate the effects of shadow fading, the plan uses three-corner excitation of each cell. Rayleigh fading and cochannel interference are combatted using space diversity; an array of 3 or 4 elements provides adequate performance. Time-division retransmission is an attractive way to implement space diversity on two-way channels; it allows all the adaptive signal processing to be performed at the base station. Moreover, the use of CPSK modulation permits this processing to be done at baseband, thereby minimizing the complexity of the RF hardware. To provide clean reference signals for the base-station diversity combiner, a frequency-offset transmission scheme is used. The impairments associated with this technique, though not negligible, are acceptably small.

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