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## USER CAPACITIES OF PORTABLE HF CDMA NETWORKS WITH controlled transmitier powers

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## USER CAPACITIES OF PORTABLE HF CDMA NETWORKS WITH CONTROLLED TRANSMITTER POWERS

by
R. Skaug
(Radar and Communications Technology Branch)


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# USER CAPACITIES OF PORTABLE HF CDMA NETWORKS WITH CONTROLLED TRANSMITTER POWERS 

by

R. Skaug


#### Abstract

HF Radio Communication is an important candidate for solving a range of military communication problems. The development of portable data networks creates the need for simple approaches to the management of many limited resource stations. This report discusses simulation results on user capacities of networks using spread spectrum code-division multiple access and enforced control of the transmitter powers. The controlled power scheme is applied to both networks of groundwave links and skywave links.


## 1. INTRODUCTION

HF Radio communication is an important candidate for solving a range of military communication problems. However HF radios will increasingly become a part of or appendix to a communication network configuration, rather than form a dedicated circuit with only one information process at each end.

The use of portable HF radio sets seem to be the solution in a lot of tactical situations where the topography and/or distance prevent the use of line of sight frequencies. When the use of HF is to collect surveillance information from forward positioned sensors and patrols, a major issue becomes that of lowering the probability of intercept in order to lessen the dangers arising from direction finding, position finding and subsequent counter-measures of both electronic and physical kinds.

Various spread spectrum techniques have been developed to lower the detectability through either lowering the signal power density or transmitting the information in a pseudo-random manner across a wide frequency range. The latter technique known as frequency hopping does not lower the instantaneous power and is best suited in an environment of dense communication links where it becomes difficult for an interceptor to distinguish the hopping pattern in a crowded radio spectrum.

Spread spectrum techniques also allow for anti-jam features which must be incorporated in a communication system threatened by electronic countermeasures.

The degree to which a spread spectrum direct sequence system becomes "invisible" to the interceptor depends largely on the processing gain (PG) which it is possible to build into the system. However it also depends on the ability to match the instantaneous transmitter output power to that required for a certain transmitter-receiver pair and S/N ratio.

When the use of portable HF radio sets is to collect information from forward positioned sensors and observers, for example in a control and warning system, the information user might be a distant control center. In such a situation it is likely that the portable radio set will be used to report to a specific master station. The master station might be a sensor itself but with more radio/antenna equipment and more output power.

The employment of portable HF data sets in the above role creates the need for simple approaches to the management of many limited resource stations possibly slaved to a master station.

In recent years a lot of work has gone into the performance-analysis of a class of multiple-access techniques known as code division multiple access (CDMA) (1). Its advantages, compared to traditional time and frequency division multiple access techniques, are its lack of requirement for precise time or frequency coordination between the users in the system.

In spread spectrum multiple access systems, each user is assigned a particular code sequence which is modulated on the carrier along with the digital data. However, it is usually not possible to assign true orthogonal codes to the users, resulting in multiple user interference due to non-zero cross correlation effects. Much effort has gone into designing codes with good cross correlation properties (2). Nevertheless, in practice, with a processing gain constrained by hardware, the implementation of CDMA systems is complicated by the need to accommodate signals at unequal power levels. Usually it becomes impossible to operate a system under conditions of large "near-far" power differentials. Hence controlling the network stations output power is important for two reasons. It helps to solve any near far problem which may arise from operational aspects and it helps to lower the probability of intercept.

An empirical model of a CDMA HF tactical network has been developed. The model assumes a radio network operated in a master slave configuration where the multiple access problem relates to the master receiver. Bandwidth spreading and multiple access are achieved using Gold codes assigned to each slave.

All information generated at the individual slave sites is transmitted to the master site for further processing. Thus several communicators share a common carrier frequency and bandwidth in a code-division multiplexing scheme.

In the model the propagation modes possible are assumed either to be groundwave or skywave. The radio network tries to lower its detectability and to avoid any near-far problem by matching the individual transmitter's output power to the path length in question. Methods to assess capacities of networks of HF radio links based on probability of successful operation are developed. The model is based on requirements for meeting a specified signal to noise plus interference criterion.

As the system performance evaluation depends on a set of variables, some statistically distributed, it becomes necessary as well as convenient to use computer modelling to determine performance sensitivity to input variables.

## 2. A REVIEW OF DETECTABILITY OF SPREAD-SPECTRUM SIGNALS AND THE NEAR-FAR PROBLEM

One of the attractive features of spread spectrum modulation is the concept of low detectability. Equation (1) describes the signal to noise ratio under which the spread spectrum receiver can operate assuming uniform noise power across the frequency band and implies that the receiver may operate at very low signal-to-noise ratio values,

$$
\begin{equation*}
S / N]_{S S}=\frac{1}{P G}[S / N]_{D} \tag{1}
\end{equation*}
$$

where $S / N]_{D}$ is that needed by a conventional receiver for the same message modulation and $P G$ is the processing gain.

In order to take full advantage of the low detectability feature, and thus nake it difficult to intercept the spread spectrum signal, it is important to keep the $\mathrm{S} / \mathrm{N}]_{\text {ss }}$ matched to the achievable processing gain and the $S / N]_{D}$ required. In practice, the processing gain is restricted by hardware. It thus becomes difficult and costly to maintain low detectability by increasing the processing gain to offset the use of unnecessary large output powers.

The simulated HF system is operated in a master-slave configuration. All information generated at the individual slave sites is transmitted to the master site for further processing. The slaves do not know their distances from the master and do not have the possibility of information exchange with other slaves except through the master station. Thus there is no overall timing between the slaves.

In the model we let slave station $M_{1}$ transmit the desired signal received with power $S$, at the master which is $d_{1} \mathrm{~km}$ away. Then another slave station $M_{2}$ at a distance $d_{2} \mathrm{~km}$ from the master may transmit a signal received with power $I$, which is interference to the slave $M_{1}$ - master link.

Let $C$ be the signal-to-interference ratio in $d B$ required at the antenna terminals of the master station receiver in order to produce an acceptable output. That is, the requirement for acceptable operation is defined as:

$$
\begin{equation*}
S-I \geq C \tag{2}
\end{equation*}
$$

The formulas for median received power is:

$$
\begin{equation*}
\mathrm{S}=\mathrm{P}_{\mathrm{M}_{1}}-\mathrm{L}_{1} \tag{3}
\end{equation*}
$$

and

$$
\begin{equation*}
\mathrm{I}=\mathrm{P}_{\mathrm{M}_{2}}-\mathrm{L}_{2} \tag{4}
\end{equation*}
$$

where $L_{i}$ denotes the median path loss for distances of $d_{i} k m$, and $P_{M_{i}}$ are the transmitter output powers for the i slave stations.

Substituting from (2) and (3) into (1) yields:

$$
\begin{equation*}
\left(P_{M_{1}}-L_{1}\right)-\left(P_{M_{2}}-L_{2}\right) \geq C \tag{5a}
\end{equation*}
$$

Thus:

$$
\begin{equation*}
\mathrm{L}_{2} \geq \mathrm{C}+\left(\mathrm{P}_{\mathrm{M}_{2}}-\mathrm{P}_{\mathrm{M}_{1}}\right)+\mathrm{L}_{1} \tag{5b}
\end{equation*}
$$

Equation (5b) is an explicit formula for the near-far problem, and will put restriction on where slave station $M_{2}$ can operate if the original system specification is to be met.

If the transmitter powers $\mathrm{P}_{\mathrm{M}_{1}}$ and $\mathrm{P}_{\mathrm{M}_{2}}$ remains constant while the value of $L_{2}$ is reduced, the inequality in expression (5a) may be violated. The use of power matching does however tend to reduce $\mathrm{P}_{\mathrm{M}_{2}}$ proportional to a reduction in $L_{2}$, thus keeping the difference $\left(P_{M_{2}}-L_{2}\right)$ constant. The value chosen for the factor $C$ will depend on the coding scheme used, which in practice relates indirectly to the processing gain of the system.

## 3. SYSTEM PERFORMANCE CRITERIA

All slaves are assumed to communicate via a single channel at a common carrier frequency and data rate, $R_{S}=1 / T_{g}$ where $T_{s}$ is the duration of one symbol. All slaves have the same spreading code chip rate with $R_{c}=1 / T_{c}$ where $T_{c}$ is the chip time. However, it is considered possible for the codes to be some fraction of a chip out of synchronization with each other. (Please refer to Appendix A).

The master receiver attempting to extract a given signal (spreading code) from a composite of many signals, may accomplish this by the use of an
identification process extracting a countable number of samples from the received version of the signal during one symbol interval.

Performance estimates are based on the assumption that the master receiver does not destroy the time-phase separation of the slave signals, due to nearly orthogonal codes, during this process.

For the case of only one user the signal-to-noise ratio for the desired signal is given by

$$
\begin{equation*}
(\mathrm{S} / \mathrm{N})_{I}=\frac{\mathrm{P}_{\text {slave } / \mathrm{A}}}{\mathrm{~N}_{\text {master }}} \tag{6}
\end{equation*}
$$

where the subscript " 1 " implies one user, and $A$ is the path attenuation.
In the presence of several slave stations the effect on the desired master-slave link, is assumed to consist of other-user-interference which basically consists of the component in the power spectrum after correlation, occuring at zero frequency plus other possible spectral components occuring at frequencies within the final filter matched to the data rate. In the case of mutually noncoherently related slave signals, the power spectral densities will add. Thus the actual SNR at the front end of the master receiver will be:

$$
\begin{equation*}
(S /(N+I))_{m}=\frac{S}{N+\sum_{i=2}^{m} I} \tag{7}
\end{equation*}
$$

where $m$ represents the total number of users.
The effective SNR then becomes:

$$
\begin{equation*}
(S /(N+I))_{m}=\frac{S}{N+\sum_{i=2} \alpha_{i} S\left(\rho_{i}^{2}+T_{c} / T_{s}\right)} \tag{8}
\end{equation*}
$$

where $\alpha_{i}$ is the power ratio between the ith slave and the desired slave, $\rho_{i}$ represents the zero frequency component from the power spectrum after correlating the ith slave code and the desired slave code, and $\mathrm{T}_{c} / \mathrm{T}_{\mathrm{s}}$ expresses the effect of the system processing gain. When one period of the spreading code matches the data symbol interval, the only component in the power spectrum within the final filter matched to the data rate is the zero frequency component. However in the simulation results, the case where the data symbol interval may be slightly less than the sequence period is allowed for by setting $T_{c} / T_{s}=1 / p$ where $p$ is the period of the spreading sequence. The values of $\rho_{i}$ does however still take on the periodic values as discussed in section 4. This gives a somewhat higher other-user-interference level than for cases when $T_{c} / T_{s}$ can be set to zero. The effect of not having perfect chip synchronism due to the fact that the spreading codes will be independantly generated is left out in (8). Taking this into effect (8) can be rewritten as shown in Appendix A so that

$$
\begin{equation*}
(S /(N+I))_{m}=\frac{S}{N+\sum_{i=2}^{m} \alpha_{i} S\left[\left(\rho_{i}^{\prime}+\left(\rho_{i}^{\prime \prime}-\rho_{i}^{\prime}\right) t_{c}\right)^{2}+\left(2 t_{c}^{2}-2 t_{c}+1\right) T_{c} / T_{s}\right]} \tag{9}
\end{equation*}
$$

where $t_{c}$ is a fraction of $T_{c}$ and $\rho^{\prime}$ and $\rho^{\prime \prime}$ are the cross correlation between the ith code and the desired code for two consecutive chip shifts.

From equation (8) it becomes clear that the actual SNR is degraded from that expressed in (6) for a one to one link where the only interference is the sum of the thermal noise and the atmospheric noise.

The interesting question now becomes how much $S / N$ must be increased to maintain the performance to be achieved. The answer will obviously be dependant on the value of $i$, i.e. the number of users but also on $\alpha$, the power ratios between the users. The new value for $S / N$ required to meet the original system specification is obtain from (8) rearranging

$$
\begin{equation*}
S / N=\frac{S /(N+I)}{1-\left(1 /(N+I) \sum_{i=2}^{m} \alpha_{i} S\left(\rho_{i}^{2}+T_{c} / T_{s}\right)\right.} \tag{10}
\end{equation*}
$$

This increase in $S / N$ required to maintain performance in a multiple access system is hereafter named the code multiplexing power cost.

It is convenient and reasonable to assume the existance of a sharp signal to interference threshold above which the probability of successful operation (e.g. specified error rate) tends rapidly to unity and below which the probability tends rapidly to zero. A threshold value is therefore defined so that for ratios less than this value the link fails, while for ratios greater than this threshold the link operates normally. This simple approach is used in the network simulations to define the successful and unsuccessful operation of each slave-master link so that:-

$$
\begin{array}{ll}
\left(S^{i} /(N+I)\right)_{m} \geq R & \text { ith link successful } \\
\left(S^{i} /(N+I)\right)_{m}<R & \text { ith link unsuccessful }
\end{array}
$$

Conceptually power matching can be carried out by the master initiating the network by transmitting a call signal with known output power level.

The signal will be received by the slaves with a power level depending on the individual path losses. The slaves measures the received signal to noise ratio and compare this to a preset threshold value.

This threshold value, to be determined by the simulation, must in practice allow for other-user-interference which is a function of the number of stations in the network and the coding scheme used as shown by equation (9).

The slaves may now either assume that the atmospheric noise level is the same for master site and slave site, or due to different sources of manmade noise, obtain a value of the noise level at the master site encoded in the master call signal.

The slaves finally calculate the difference between the received signal to noise ratio and the preset threshold value and then use this value to adjust their output power.

Ideally, all slaves should now be received at the master with the same power level. However, it is assumed that the slaves are only able to adjust their output power in discrete steps and also measure the received signal to noise ratio with limited accuracy. This leaves $\alpha_{i} \neq 1$ in equation (9). In fact the computer simulation can determine the power cost as a function of power matching accuracy.

## 4. THE NETWORK SIMULATION

A computer program has been developed to simulate the HF CDMA network for analysis of the power matching technique(3). One program algorithm calculates the strength of the master probe signal measured at the slaves and computes slave transmission powers to match the path lengths. For this study two communications scenarios have been considered, networks based on HF groundwave and networks based on HF skywave.

A configuration of the network is obtained by specifying the number of stations and assigning to each station a distance from the master and a code sequence. The stations are assumed to be normally distributed at a specified mean distance from the master and with a specified standard deviation. The locations are generated randomly from a normal probability distribution. Since the properties of each slave-master link are of a statistical nature it is possible to randomly generate other specific configurations with the same properties. The above simulation procedure has been used to study each configuration for a number of statistical variations thus providing a statistical estimate of the network success.

A parameterization of path losses is required for the model. The parameterization of the groundwave path loss has been obtained by a straight line fit to the CCIR 10 MHz propagation curve (4). For the skywave case the path loss is considered to consist of the free space loss and the absorption of the ionosphere plus a parameter representing the fading of the signal. In the simulation model a value is drawn at random from a probability distribution to represent the fading at the time of measurement. The probability distributions of the fading that are available in the model are Rician distributions with a choice of specular component to scattered component power ratio of $10 \%, 50 \%, 70 \%$ and $90 \%$. The $10 \%$ specular component is practically identical to the familiar Rayleigh fading case. The distributions were generated by an analytic approximation to the $Q$ function based on a Taylor's series expansion (8).

Another important algorithm computes the signal strengths from the slaves measured at the master and the resulting other-user interference due to code cross correlation.

The assignment of the codes to the slave stations is in the simulation made from a cross correlation probability distribution generated by computing cross correlation values for all possible relative phase shifts of a preferred pair of m-sequences (5).

The actual assignment of the codes is made indirectly by constructing a square matrix of values drawn at random from the cross correlation distribution and subject to the symmetry constraint that element IJ equal element JI. The dimension of the matrix is the number of slave stations and each station is assigned one column with each element being the cross correlation between that station and each other station.

The simulation program has been written in FORTRAN IV and run on a PDP 11/60. For the groundwave case the results quoted are based on 100 variations of each configuration. For the skywave case results are obtained from 100 variations of the fading for each of 10 variations of the other configuration properties. This has required considerable computing time but is justified by the confidence levels that can be put on the results.

## 5. GROUNDWAVE

### 5.1 INTRODUCTION

Depending on the tactical situation and task, slaves may operate within a small or larger geographic area at different distances from the master. This is modelled on a computer which generates a random normal configuration of slave stations.

In the simulation no 1imitation on available power was assumed, and thus the curves extend to distances which may not reflect any physically realistic values for a deployed groundwave HF network. However, possible obtainable ranges for HF groundwave is not an issue to be raised here, and the curves are valid at all distances under the assumption of sufficient transmitter powers.

The path losses are obtained using approximations to ground wave propagation curves such as those given in CCIR report 112 (4). See Figure 1.

Operating at carrier frequencies other than 10 MHz used in this simulation, will give other path-loss values but does not change the performance criteria used to assess the power matching technique. It is assumed that a ground wave signal will not be subject to fading.

The values used to represent the atmospheric noise are fixed, median values. The statistical distribution of the individual noise values about the median value is not considered here, since it is always considered possible in a one to one link to supply sufficient power to ensure circuit operation for a given percentage of the time. All results are relative to this one-to-one link performance and median noise values are only needed in order to obtain typical transmitter powers and user capacities for CDMA.


Figure 1. Path loss curve for network of groundwave links

Using a value of $300^{\circ} \mathrm{K}$ as reference temperature, noise bandwidth of 100 Hz after processing and atmospheric noise level of 44 dB (6), results in total noise power of $\mathbf{- 1 4 0} \mathrm{dBW}$.

In the groundwave case, a network configuration is said to have a probability $P_{c}$ of successful operation if all the slaves are received with required SNR for $P_{c}$ of 100 trials. Since no variation in signal level with time is assumed, the 100 'irials only picture different possible configurations with the same number of stations, mean and standard deviation. Thus:

100

$$
\begin{aligned}
P_{c}=\frac{\sum_{u=1} A_{u}}{100} \quad A & =1 \text { for }\left(S^{i} /(N+I)\right) \geq R, \forall i \\
& =0 \text { else }
\end{aligned}
$$

Where $R$ is the success threshold for the ith link.

The results with power cost, number of users and $\alpha=\bar{\alpha}_{i}$ (the average power ratio between users) and geographic spread as parameters can be plotted on a co-ordinate system using "percentage of success of network" and "mean distance from slaves to master" as $\mathrm{x}-\mathrm{y}$ variables.
$\alpha$ is related to the step size in which the slaves are able to vary their power so that for_stations randomly distributed it represents the average case for which $\bar{\alpha}_{i}=1 / 2$ step size.

Thus in the simulation $\alpha_{i}$ contains only the effect of the discrete power level adjustments. Information on the added effect on $\alpha_{i}$ due to practical difficulties in calculating signal to noise ratio accurately, were obtained through an on-the-air experiment described in section 5.4.

### 5.2 BASIC SIMULATION RESULTS

The effect of $\alpha$ was considered to be somewhat different for two distinct cases. In one case the total other-user interference power is considerable less than the -140 dBW noise power. In the other case the total other-user m interference is comparable to the noise power. Replacing $\sum_{i=2} \alpha_{i}$ in equation (10) by $(\mathrm{m}-1) \alpha$ and then solving for number of users possible in the CDMA system gives


The factor $S /(N+I)$ in the denominator of the first part of the expression is just the threshold value designed for, and is a constant for a given performance. Thus the number of users will for a given threshold value depend on the value of $\alpha, S / N$ and the other-user-interference appearing inside the summing signs. If the other-user-interference is small compared to the noise, any increase in $S / N$, and thus slave output power, will increase the number of users for a given threshold and $\alpha$. However, when the otheruser interference is dominant the second expression in equation (11) is close to zero and the number of users is only determined by the threshold and the value of $\alpha$. The latter condition is usually called the bandwidth starved condition.

## Case 1: Performance Limited by Power-Matching Accuracy and Thermal Plus Atmospheric Noise

The plot shown in Figure 2 shows the performance for ten and twenty stations with a geographic spread given by a 10 km standard deviation using $1 \mathrm{~dB}, 3 \mathrm{~dB}$ and 10 dB power step sizes as well as no power matching at all. The curves are all plotted from simulations where the power cost was 1 dB for the ten stations cases and $1.5 \mathrm{~dB}-1.85 \mathrm{~dB}$ for the twenty station cases. For the cases of no power matching the power cost has no meaning. The total


Figure 2. Simulation results showing degree of success of network with 10 and 20 stations
power of all interference is found to vary between -150 dBW and -142.5 dBW and thus is smaller than the -140 dBW noise floor.

For the cases of ten and twenty stations using a step-size of 1 dB and 3 dB , the percentage of network success comes very close to $100 \%$ for all mean distances from the master. The use of 10 dB power steps does however introduce significant performance degradation, worsening with increasing number of users. The degradation is seen to be most severe at the shorter distances. The reasons for this can be found by examining the path loss curve shown in Figure 1. With two slaves a fixed distance apart, the differential path loss will depend on the mean distance from the master.

Thus a geographic spread around a mean far away from the master introduces much less change in individual path losses than the same geographic spread at a mean distance close to the master. This of course means that there is less need for power matching at longer mean distances, since most of the slaves will tend to be affected by comparable path losses.

This fact also shows up when one compares the case of 10 stations with 10 dB power matching steps with no power matching at all. The improvement at larger mean distances is limited but the improvement is drastic at shorter distances. The same general trend also applies for the case of twenty stations with 10 dB power matching steps compared to no power matching. However in this case the overall performance is further reduced from the 1 dB power matching case.

The reason for the poorer performance using the 10 dB power step size obviously emerges from the fact that stations at nearly the same distance may use transmitter powers 10 dB apart, one being just below the other just above a power step.

The power cost of 1 dB ( $1.5-1.85 \mathrm{~dB}$ ) will move stations one power step up if they are less than $1 \mathrm{~dB}(1.5-1.85 \mathrm{~dB}$ ) below the power step. However, with a step size of 10 dB it becomes reasonable to expect improved performance if the power cost is increased so as to move stations in the upper half of the 10 dB step to the step above. This will depend on the actual geographic spread and such an optimization process is likely to be less valuable in a tactical network situation. Any transmitter power increase will generally improve performance in this situation where the noise is still dominating the total noise plus interference figure. The result of increased power cost is shown in Figure 3. For the 10 station case and the 20 station case a performance nearly matching the performance of a network using 1 dB power steps is achieved, increasing the power cost by 2 dB and 8.15 dB respectively.


Figure 3. Simulation results showing achievable performance using coarse power control but large transmitter powers

The penalty for improved performance using 10 dB power step sizes is thus a large increase in transmitter power for the slaves.

To show the general change of performance as the geogrpahic spread increases, the standard deviation is increased to 20 km . Figure 4 shows the results of a simulation with 10 and 20 stations, the only change from previously discussed cases being that of a standard deviation of 20 km .

Again the performance drops for the 10 dB power step size situations and the now power matching case, the case of no power matching practically dropping to no success at any mean distance. In addition the curves for the 10 dB power step size no longer show the same distinct poorer performance for shorter mean distances, the reason obviously being that with a large geographic spread, larger mean distances may very well have several stations close to the master introducing the effect of the distant dependant incremental path loss curve shown in Figure 1. This will thus tend to even out the performance for all mean distances.

Once again the performance for the 10 dB power step sizes can be improved by increasing the power cost as shown in Figure 5.


Figure 4. Simulation results showing degree of success of network with 10 and 20 stations being widely separated


Figure 5. Simulation results showing achievable performance using 10 dB power step sizes but large transmitter powers

Case 2: Performance Limited by Power Matching Accuracy and Other-UserInterference

For the case of 50 stations the total power of all interference reaches the -140 dBW noise floor, using the minimal required power cost of 3.75 dB and perfect power matching. (The power matching is named perfect for 0.01 dB power steps).

The use of 50 stations and power step sizes of 1 dB and 3 dB requires approximately 4 dB and 6.5 dB of power cost in order to perform close to the $100 \%$ success line.

Using 10 dB power step sizes resulted in no success whatever power cost was used. The largest power step size which gave some degree of success was in this case 7 dB and a power cost of 20 dB . However in this case the perfornatuce results were very sensitive to the power cost value and did, for example, drop when the power cost was increased to 30 dB . This in fact shows that the degree of success achieved with 7 dB power step size very much depends on the optimisation of the power cost, placing stations in favourable power bins. Such an optimisation is hardly realistic for a deployed radio system.

The use of equation (11) shows that 50 stations do approach the estimated theoretical maximum under the assumption of a 8 dB threshold.

For the 10 dB power step size it becomes impossible to operate 50 stations with any success whatever power cost is chosen. The results are shown in Figure 6.

### 5.3 SUMMARY OF SIMULATION RESULTS

The simulation results are summarized in Table 1. The table shows the power cost as a function of $\alpha$ for upper performance limits given in the form of percentages of network success.


Figure 6. Simulation results showing degree of success of network with 50 stations

TABLE 1

## Summary of Results Obtained from Network of Groundwave Links

table showing results of coma for network of hf groundwave links CODES: 1023 BIT GOLD CODES, SNR $=$ BdB, MEAN DISTANCES $15 \mathrm{~km}-80 \mathrm{~km}$

| No of Stations | Geographic Spread | Attenuation | \% of Success | Power Cost ** |
| :---: | :---: | :---: | :---: | :---: |
| M | d (km) | (dB) | $\mathrm{P}_{\mathrm{C}} \quad 1$ | (dB) |
| 10 | 10 | 1 | 100 | 1 |
| 10 | 10 | 3 | 100 | 1 |
| 10 | 10 | 10 | 96-99* | 3 |
| 10 | 10 |  | 0-80 | - |
| 10 | 20 | 1 | 100 | 1 |
| 10 | 20 | 3 | 99-100 | 1 |
| 10 | 20 | 10 | 94-100 | 3 |
| 10 | 20 |  | 0-6 | - |
| 20 | 10 | 1 | 100 | 1.5 |
| 20 | 10 | 3 | 99-100 | 1 |
| 20 | 10 | 10 | 94-100 |  |
| 20 | 10 |  | 0-20 | - |
| 20 | 20 | 1 | 100 | 1.5 |
| 20 | 20 | 3 | 100 | 1.85 |
| 20 | 20 | 10 | 85-97 | 10 |
| 20 | 20 |  | 0 | - |
| 50 | 10 | 1 | 100 |  |
| 50 | 10 | 3 | 100 | ${ }_{20}{ }^{5}$ |
| 50 | 10 | 7 | ${ }_{0}^{3-27}$ | 20 |
| 50 | 10 | 10 | 0 | - |

* Where $P_{C}$ is given by a range of values rather than one unique value, the probability of success will vary within this range as a function of master-slaves mean distance.
** Power cost is the power required by the slaves to operate in a CIMMA system and is
in $d B$ above the single user requirements.

The results show that performance is generally improved and power cost is lowered using good power matching. With no power matching at all, the network deteriorates quickiy, even for a small number of users.

### 5.4 EXPERIMENTAL RESULTS

In order to get a practical knowledge on how well one may expect the slave stations to calculate their required transmitter powers, as well as check the assumption of master-slave/slave-master path loss reciprocity, a simple on-the-air experiment was arranged. The accuracy achieved in this
experiment will indicate the lower practical limit for the step size in which to vary the slave output power.

The measurement set up formed a closed loop where the master transmits a call signal, and the slave receives the signal and from a given algorithm, calculates the required power to get back to the master station. The slave station then transmits back to the master station, with the given power. The master station in turn calculates its received signal to noise ratio and compares this to the threshold value used in the slave station's algorithm. An error signal proportional to the difference between the received signal to noise ratio and the threshold value is then produced. Figure 7 is a block diagram of the experimental set-up.

The equipment used in this experiment, consisted of two small HF radio transceivers connected to two microprocessors and a programmable attenuator. The signalling scheme chosen is FSK with a simple tone signal. Thus the mark filter may contain the data signal and noise all the time and the space filter will only contain noise. Two bandpass filters with bandwidths of 200 Hz and centered at 1.1 kHz and 1.9 kHz respectively separate the mark and space signals. The signals are then envelope detected and sampled for $A / D$ conversion at a rate of 1 kHz . Thirty-two samples are taken in each signalbranch and the samples are summed and averaged, and a signal to noise ratio is calculated. The microprocessor then compare its calculated result with a pre-entered signal to noise requirement and in the slave case, calculates the attenuation required to match the power to the path. The value of attenuation calculated is printed out in hard copy form. A programmable attenuator, variable in 1.5 dB steps, is used to change the output power of the slave station.

At the master station a similar signal processing takes place, but now the calculated difference between received signal to noise ratio and the preentered requirement is printed out as an error figure.

The experiment was repeated a number of times to collect statistics in the form of means and variances on the data-outputs. The outputs are an attenuation value $A$ and the error in power matching $E$.

Since the system does not involve signal bit-error rate measurements at the master station the signal to noise measurement here may have errors due to quantization and approximations in the algorithm similar to those incorporated in the calculations at the slave station. Thus:

$$
\begin{aligned}
& \text { Calculation performed at slave: }\left(S_{S} / N_{S}+e_{1}\right)-T=A-k \\
& \text { Calculation performed at master; }\left(S_{M} / N_{M}+e_{2}\right)-T H=E
\end{aligned}
$$

where $S_{S} / N_{S}$ and $S_{M} / N_{M}$ are the signal to noise ratios calculated at slave and master respectively, TH is the SNR threshold in the algorithm, A is a precise value of the required attenuation of the slave output power relative to the master output power and $k$ is a variable subtracted from $A$ in order to vary the output power in discrete steps, $e_{1}$ and $e_{2}$ are the errors in describing the actual signal to noise ratios due to quantization and approximations at the slave and master respectively and $E$ is the final error in power matching caused by $e_{1}, e_{2}$ and $k$.


MASTER STATION
Figure 7. Power matching experimental set-up

The final error in power matching then becomes

$$
E=\left(S_{M} / N_{M}+A\right)-S_{s} / N_{s}+e_{2}-e_{1}+k
$$

Assuming $N_{M}=N_{s}$ gives

$$
E=e_{2}-e_{1}+k
$$

The value of $k$ is restricted to the range $0<k \leq 1.5 \mathrm{~dB}$.
In a final system, with power matching, the master would obviously not calculate the received $\mathrm{S} / \mathrm{N}$ ratio but could deduce the real $\mathrm{S} / \mathrm{N}$ value from the error rate achieved. Thus the only parameter of interest is $e_{I}$. If $e_{I}$ and $e_{2}$ are considered to be normally distributed taking on positive and negative values equally likely and to be generated from two similar but time uncorrelated processes, the mean of ( $e_{2}-e_{1}$ ) would tend to zero. However the variance of $\left(e_{2}-e_{1}\right)$ is also calculated in the experiment and under the assumption that $e_{1}$ and $e_{2}$ are approximately of the same size, this parameter will be useful in indicating expected errors $e_{1}$ in a power matching algorithm. The effect of $k$ would be to merely shift the mean of $E$.

In the experiment, sites were chosen in order to satisfy the assumption of equal noise levels at slave and master stations. The experiment was repeated for a number of frequencies between 5 MHz and 20 MHz . Two threshold values of 8 dB and 15 dB respectively were used during the tests. With thirty-two samples taken in each signal branch, the standard deviation of the error signal at the master varied from 2.3 dB to 2.8 dB . This was for a threshold of 15 dB and measurements at the selected frequencies. With a threshold value of 8 dB the standard deviation of the error varied from 2.7 dB to 2.98 dB . The choice of a low number of samples (32) was made in order to reflect the possible low processing capability of a portable radio. However, tests were also performed when the samples taken to calculate the signal to noise ratio were increased to 256 . In this case the performance improved to give a standard deviation of the error signal varying from 0.95 dB to 1.5 dB for a threshold of 15 dB . For a threshold of 8 dB the standard deviation varied from 1 dB to 1.4 dB .

Assuming the signal level to be constant and the noise to be Gaussian distributed the error in the calculated signal to noise ratio will be less than one standard deviation from the mean for approximately $70 \%$ of the time.

It is reasonable to make the error due to the attenuation step size small enough to not greatly influence the overall error in the power matching algorithm. With uniformly distributed slaves a possible choice is to choose the step size to match one standard deviation in the error signal distribution. This implies an attenuation step size of 3 dB for an algorithm using 32 samples of signal and noise.

## 6. SKYWAVE NETWORKS

### 6.1 InTRODUCTION

In this section the effect of power matching in a HF skywave network is considered by means of simulation. Within a 100 km slave to slave distance all stations are expected to transmit on the same carrier frequency. For larger relative distances the stations are probably forced to transmit on different frequencies due to change in MUF. As for groundwave networks any particular configuration will be characterized by a random normal configuration but with restrictions as mentioned due to change in MUF.

The radio network seeks to avoid any near-far problem and to lower their detectability by trying to match the individual transmitter's output power to the path length in question. Thus an approach where the master initiates the operation by transmitting a broadcast signal to the slaves is chosen. Since the signal is contaminated by fading and the slaves to not know where on the fading cycle they are calculating the signal to noise ratio, they assume the signal value to represent the mean. However, to reduce the effect of the most extreme fading values the slaves may be assumed to take uncorrelated measurements of the signal to noise ratio and choose the average to represent the mean. Based on this mean value the slaves estimate their required transmit power according to some predetermined algorithm. Alternatively the slaves may use the smallest SNR measured to calculate the required transmitter power. The last approach would tend to result in transmitter powers matched to the maximum fading depths. The master may be assumed always to transmit with a power known to the slaves.

The fading between the master and the individual slaves are considered uncorrelated. In addition the fading on the slave-master and the masterslave signaliing is considered uncorrelated due to time separation.

One of the questions thus becomes how useful a power matching procedure is in a situation where signals traversing in opposite directions undergo uncorrelated fading. The only thing the slaves can do if the averaging procedure is used, is to assume the measured signal strength values are representative for the path and allow for fading by adding a fading allowance before they calculate the required transmitter power.

A radiowave reflected from the ionosphere is not reflected from a point but rather from a region, and thus the received wave may be composed of a number of individual wavelets. The received signal will be the vector sum of the individual signals and due to movements in the ionosphere the relative phases of the individual signals will vary, giving rise to fading. In addition, the wave may be reflected from different layers by a mixture of high and low angle rays each having extraordinary and ordinary components. The amplitude distribution of the resulting signal under these conditions is usually approximated by a Rayleigh distribution law. However, with spreadspectrum direct sequence modulation, it will be possible to resolve reflections from different layers as well as multihop paths and it may also be possible to resolve high and low angle rays having extraordinary and ordinary components, leaving only scattering due to electron density irregularities. In
this situation the individual wavelets are reflected from a close region and it may be expected that they will be correlated. The effect of correlation in the wavelets making up the scattered signal is very similar to the effect of a specular component, giving amplitude distribution with a shallower fading. It may therefore be predicted that the use of spread spectrum modulation may give rise to a "pseudo-specular" reflected wave where signals are better described by a Rice distribution.

The model allowed for fading specified by the division of power between any, specular component and a scattered component. Ratios of $10 \%$, $50 \%, 70 \%$ and $90 \%$ are available with the $10 \%$ case representing an approximation to the Rayleigh distributed fading.

The path loss is considered to consist of the free space loss $L_{d}$ and the absorption in the ionosphere $\mathrm{L}_{\mathrm{a}}$. Any focussing or defocussing of power is neglected. Thus the propagation loss in $d B$ to the ith slave is given by (7);

$$
\begin{aligned}
L_{i} & =L_{d_{i}}+L_{a_{i}} \\
& =(32.45+20 \log f+20 \log d)+430(1+0.0035 R) \cos ^{3 / 4} x \cdot \sec \phi_{D} \cdot(f+1.4)^{-2}+F(t)
\end{aligned}
$$

where f is the carrier frequency $\mathrm{in} \cdot \mathrm{MHz}, \mathrm{d}$ is the master-slave distance in $\mathrm{km}, \mathrm{R}$ is the sunspot number, X is the solar zenith angle, $\phi_{\mathrm{D}}$ is the angle between the radiowave and the normal to the ionosphere at the point of reflection and 1.4 is a constant taken to represent the gyro-frequency. $F(t)$ represents the instantaneous fading of the signals. The noise power used in performance calculations are assumed to be fixed, median values with the same noise bandwidth of 100 Hz as assumed in the groundwave study.

The HF master-slave system was modelled on a computer and the results were plotted on a coordinate system using "Percentage of time a given number of stations are successful" and "Number of stations" as X-Y variables. The Fading statistics, Power matching cases/No power matching case, were used as parameters for the curves. For the groundwave case, the "power cost" was the key parameter describing total performance of the network. In the skywave case the power cost and fading allowance is combined. A one to one link requires a certain fading allowance in order to operate successfully for a particular percent of time. For the cases considered here, the values are $8 \mathrm{~dB}, 7.5 \mathrm{~dB}, 2.5 \mathrm{~dB}$ and 1.0 dB for the $10 \%, 50 \%, 70 \%$ and $90 \%$ specular cases respectively if the systems are to operate for $90 \%$ of the time. If the systems are to operate for $99 \%$ of the time, the fading allowance must be approximately doubled.

A particular number of stations in a network configuration is said to have a certain percentage of time of successful operation defined as the time the number of slaves are received with required SNR at the master, thus:

$$
\begin{array}{rl}
\mathrm{T}_{\text {success }}^{1000} \mathrm{~W}_{\mathrm{L}}^{\mathrm{i}} & \mathrm{~W}
\end{array}=1 \text { for } \frac{S^{i}}{N+I} \geq R
$$

$S^{i} /(N+I)$ indicates the success of the ith master slave links. $W^{i}$ denotes the success parameter for $i$ slaves in a network of $m$ slaves.

### 6.2 BASIC SIMULATION RESULTS

The actual differential path loss for skywave propagation is small in a network configuration with a maximum of 100 km slave separation and slave master mean distances of more than 200 km . From equation (12) the differential value is about 4 dB for a slave-master distance of 150 km and 250 km and E layer reflection. For larger distances between master and slaves the pathloss differential drops further. The path focussing and defocussing have been neglected in the simulation model and the existance of this loss could introduce several $d B$ variations in path losses. Another factor which also may add to the path loss variation is the effect of different antenna patterns for the deployed radio sets.

The simulation results shown in Figures $8-11$ are all for a mean masterslave distance of 200 km and a geographic spread defined by a 25 km standard deviation. The sunspot number was chosen to be 40 and the solar zenith angle 1 rad . The short mean master-slaves distance introduces some path loss differential to the simulation. The power of the slave transmitters are assumed to be variable in 1 dB steps. The required SNR is 8 dB unless otherwise stated in the discussion of the results.

## Case A: Specular to Scattered Power $=10 \%$

In this case five different situations were pictured for a network of 10 and 20 stations and a required SNR of 8 dB . Please refer to Figure8. As shown by performance curve $1(6)$ and $2(7)$ the ability of the slave to take two uncorrelated samples of the signal strength received from the master, calculate the average and use this as a basis for its power, greatly improve performance compared to the one sample case. However performance curve 3(8) shows that much better performance is obtained without any use of power matching. (The power used in this case is such that it is well above the maximum required for any link as shown by the power matching case). Increasing the number of signal strength measurements used for averaging to 10 or 100 does result in a rather small performance improvement compared to the no power matching case. The increase from 10 to 100 samples alter the performance result very little. With 10 or 100 samples used to calculate the average fading depth, the result seems to represent the actual average quite well. The stations will thus transmit with nearly equal power levels, the only differentation being due to the actual geographic spread of the slaves. This matching to the geographic spread is the reason for the slight improvement over the no power matching case. The matching effect is however nearly completely swamped out by the effect of the large fading.


Figure 8. Performance for CDMA for 10 and 20 stations and specular component $=10 \%$, mean distance 200 km , standard deviation 25 km, required $S N R=8 d B$.
1 and $6=$ power matching and 1 sample
2 and $7=$ power matching and 2 samples averaged or 10 samples taking lowest value
3 and $8=$ no power matching
4 and $9=$ power matching and 10 samples averaged
5
$=$ power matching and 100 samples averaged


Figure 9. Performance for CDMA for 10,20 and 40 stations and specular component $=50 \%$, mean distance 200 km , standard deviation 25 km , required $S N R=8 d B$.

1 and 6 and $9=$ no power matching
2 and 5 and $10=$ power matching with 10 samples averaged
3 and 7 and $11=$ power matching with 2 samples averaged
4 and 8 and $12=$ power matching with 1 sample


Figure 10. Performance of CDMA for 20 and 40 stations and specular component $=70 \%$, mean distance 200 km , standard deviation 25 km , required SNR $=8 \mathrm{~dB}$.
$1=$ power matching with 2 samples averaged
$2=$ no power matching
$3=$ power matching with 10 samples averaged
4 = result for all cases for network of 20 stations


Figure 11. Performance of CDMA for 20 and 40 stations and specular component $=90 \%$, mean distance 200 km , standard deviation 25 km.

$$
\begin{aligned}
& 1=\text { result for all cases in network of } 40 \text { stations and required } S N R=8 \mathrm{~dB} \\
& 2=\text { power matching with } 10 \text { samples averaged and required } S N R=12 \mathrm{~dB} \\
& 3=\text { no power matching and required } S N R=12 \mathrm{~dB} \\
& 4=\text { power matching with } 1 \text { sample and required } S N R=12 \mathrm{~dB} \\
& 5=\text { result for all cases in networks of } 20 \text { stations and required } S N R=8 \mathrm{~dB}
\end{aligned}
$$

Performance curve 2 also represents the result when the slaves take 10 samples to estimate the maximum fading depth and uses this in their power calculation. The results show however that 10 samples at each slave give greatly varying estimates of the maximum fading depth and become inferior to the performance obtained by using the 10 samples to calculate the average.

## Case B: Specuzar to Scattered Power - 50\%

In this case networks of 10,20 and 40 stations are represented. Please refer to Figure 9. The curves show the same general results as in case A. The overall performance is however improved. For example, in case A, for best obtainable performance, only 16 slaves out of a network of 20 would be able to work successfully for $90 \%$ of the time. In case B, between 18 and 19 slaves in a network of 20 would work satisfactory for $90 \%$ of the time. In a network of 40 stations however, only 28 slaves are able to work satisfactory for $90 \%$ of the time.

Case C: Specular to Scattered Power $=70 \%$
This case pictures networks of 20 or 40 stations. Please refer to Figure 10. In a configuration of 20 stations, all stations will work satisfactory for approximately $100 \%$ of the time, assuming that a minimum of 2 samples are averaged in the power matching cases. Enlarging the configuration to 40 stations shows best performance using power matching based on 10 samples averaged. In this case 38 stations out of 40 will work for $90 \%$ of the time, the same figure for the no power matching case being 37 stations.

Thus for a channel where most of the power is enclosed in the specular component, the effect of the power matching becomes more apparent than on a Rayleigh distributed channel.

Case D: SpecuZar to Scattered Power $=90 \%$
In this case the fading becomes very shallow and network configurations of 20 and 40 stations are able to operate successfully for approximately $100 \%$ of the time. Please refer to Figure 1l. In order to see the effect of the power matching, curves 2,3 and 4 shows performance for a configuration of 40 stations and a required $\operatorname{SNR}$ of 12 dB . The effect of raising the required SNR is to amplify the effect of the other-user-interference. The same effect is achieved by raising the number of stations in the network. In this case the power matching cases all significantly outperform the no power matching case. Thus when the fading is shallow and the number of stations in the network are close to the theoretical maximum number of stations for a given SNR, any reduction in power differential greatly improves performance.

### 6.3 SUMMARY OF SIMULATION RESULTS

Even though power matching, referred to the average fading on the master-slave links, takes place at the slaves, the fading of the opposite directed slave-master links gives an apparent network with large power
differentials. Thus the power cost is generally large in an HF skywave network. However, the final transmitter powers derived in the network simulation are still less than 25 W .

Table 2 lists the power cost in dB for the various conditions discussed. The general result is that the power cost does not change much whether 2 or 10 samples are used to calculate average path losses. However the figures in brackets, which are the maximum possible percentage of time all stations can operate simultaneously, shows the performance improves significantly for the 10 sample case compared to the 2 sample case for the same power cost. Since the time percentages listed represent performance limits, any increase in the power cost does not increase the percentage of success. The last column shows that the performance without power matching compares with the power matching when the specular signal component is small.

## 7. CONCLUSION

The path losses encountered in groundwave propagation are very sensitive to path distances, especially for shorter paths, and will for most practical cases introduce near far problems. The maximum possible number of users will for a given set of multiplexing codes, depend on the accuracy of the power control system. The experiment carried out shows that power step sizes of 3 dB reflects the achievable accuracy in the path loss calculation. However it may generally be concluded that for situations where the other-user-interference is less than the radio system's noise level, poor power control can be compensated for by increased transmitter output powers. With no power control at all the CDMA system deteriorates quickly.

The general small differences in mean path losses in the networks of HF skywave links discussed, introduces only a limited near far problem due to geographic spread. Since no experiment with skywave links has been carried out numerical results on effects of focussing and defocussing or change in antenna patterns can not be given. However the fading of the signals give an apparent network with possible large irreducible power differentials. For situations with small specular to scattered power ratios, the fading will greatly reduce the effect of any power control. The use of a limited number of signal strength samples to estimate a mean path loss value result in performance comparable to no power matching but with the advantage that the output power is controlled. As more power goes into a specular component, power matching will improve performance if any path loss differentials exist in the network configuration.

Network configurations using a mixture of groundwave links and skywave links have not been discussed. The reason is that only master slave configurations with limited station to station distances as in an area network have been modelled. If, in this situation, some links rely on skywave propagation and some on groundwave propagation it is most likely that the groundwave links would use frequencies in the upper part of the HF band not suitable for short distance skywave links. This would result in the use of different carrier frequencies and separate CDMA networks.

TABLE 2

## Power Cost and Fading Margin for CDMA Networks of Skywave Links

TABLE SHOWING RESULTS OF COMA FOR NETWORK OF HF SKYHAVE LINKS COOES: 1023 BIT GOLO COOES, SNR $=8 \mathrm{~dB}$, MEAN OISTANCE 200km

| number of stations | 10 |  |  | 20 |  |  | 40 |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| SPECULAR/SCATTER COMPONENT | 2 | 10 | No Power Matching | 2 | 10 | No Power Matching | 2 | 10 | No Power Matching |
| 10\% | $28(31.18,8)$ | $33(51.88$, 8) | $(55.68$, 9) | 27(0.78,13) | $25(4.8 \%$, 16) | $(3.98,15)$ |  |  |  |
| $50 \%$ | $31(43.18,8)$ | $30(59.68$, 9) | $(65.38,9)$ | $25(1.98,14)$ | 23(4.88,16) | $(7.68,16)$ | 25(0.0\%,22) | $25(0.08,27)$ | (0.08, 28) |
| $70 \%$ |  |  |  | 18(98.5\%, 20) | 14(100\%, 20) | $(99.78 .20)$ | 25(40.8\%,36) | $25(64.08,38)$ | $(43.88,37)$ |
| 90\% |  |  |  | 4.5(100\%,20) | 4.0(100\% , 20) | $(100 \%, 20)$ | 7.5(100\%,40) | 6.5(100\%,40) | $(100 \%$, 40) |

Table showing power cost in dB for networks of 10,20 and 40 stations and fading statistics as indicated. The figures shown in brackets, indicate the percentage of time all stations in the network can operate simultaneously and successfully as well as the number of stations in the network which will operate successfully for $90 \%$ of the time.

## 8. ACKNOWLEDGEMENT

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## APPENDIXA

## CALCULATION OF MULTIPLE USER INTERFERENCE FOR NON SYNCHRONIZED SLAVES

The sequence codes chosen for the CDMA system are Gold codes. Gold (2) in his original paper describes an analytical technique that tells how to select maximal-length sequences with a known bound on the cross-correlation function. His theorem takes a starting point in the vector space of linear sequences generated by recursive relations. Let $\alpha$ be any primitive element of $G F\left(2^{N}\right)$, and $f_{1}$ be the minimal polynomial of $\alpha$. Then let $f_{t}$ be the minimal polynomial of $\alpha \mathbf{t}$ where

$$
t=2^{(N+2) / 2}+1
$$

for $N$ even, $N$ being the number of shift-register stages.
Then a sequence $a \varepsilon V\left(f_{1}\right)$ and a sequence $b \varepsilon V\left(f_{t}\right)$ implies;

$$
|\rho(a, b)| \leq t
$$

where $\rho$ denotes the cross-correlation between sequences $a$ and $b$.
$x^{10}+x^{7}$ this case the m-sequence a is generated by the polynomial $f_{1}(x)=$ $x^{10}+x^{7}+1$ and the m-sequence $b$ is generated by the polynomial $f_{t}(x)=$ satisfying

$$
|\rho(a, b)| \leq 65
$$

In fact the cross-correlation function is three valued with values; $-65,-1$, 63.

Using this preferred pair of m-sequences a family of 1025 sequences all satisfying the bound on the cross correlation is easily generated. These sequences are assigned to the slave stations.

The interference produced in the CDMA system will basically consist of the average ( dc ) value of the code-cross correlation plus any spectral components occuring at frequencies within the final filter matched to the data rate.

To somewhat simplify the interference calculations, the data is considered to be all ones or all zeros. This avoids the calculation of the non-periodic cross correlation values.

For m+l channels in code division multiple access the signal to interference can then be expressed as;

$$
(S / I)_{m+1}=20 \log \frac{S}{\left(m\left(\rho^{2}+T_{c} / T_{s}\right)\right)^{\frac{1}{2}}}
$$

Where $T_{c}$ is the code chip rate and $T_{s}$ is the data bit rate. However, the individual slaves may not have exact clock synchronization and this must be taken into account by modifying the interference expression.

Assume the wanted code and the interfering code to be a fraction $t_{c}$ of a code chip out of phase. To obtain the power spectral density of the interference after correlation the auto-correlation must be calculated.

With a "phase difference" equal to a fraction $t_{c}$ of a code chip, the resulting interfering code will after correlation basically be made up of two sequences with "chip" time of $t_{c}$ and $\left(1-t_{c}\right)$ respectively. Please refer to Figure A1.


Figure A1. The Effect of "Non-synchronized" User Codes In CDMA

Denoting the sequences 1 and 2 respectively gives;

$$
\begin{aligned}
& R_{1}(\tau)=\lim _{T \rightarrow \infty} \frac{1}{2 T} \int_{-T}^{T} f(t) \cdot f(t-\tau) d t=1-\frac{\tau}{t_{c} T_{c}},\left(\frac{\tau}{T_{c}}\right)<t_{c} \\
&=0 \quad\left(\frac{\tau}{T_{c}}\right)>t_{c} \\
& R_{2}(\tau)=1-\frac{\tau}{\left(1-t_{c}\right) T_{c}}, \frac{\tau}{T_{c}}<\left(1-t_{c}\right) \\
&=0, \frac{\tau}{T_{c}}>\left(1-t_{c}\right)
\end{aligned}
$$

Then the power spectral density can be calculated using;

$$
S(\omega)=2 \int_{0}^{\infty} R(\tau) \cdot e^{-i \omega \tau} d \tau
$$

This gives;

$$
\begin{gathered}
S_{1}(\omega)=T_{c} t_{c}\left(\frac{\sin ^{2} \omega t_{c} T_{c} / 2}{\left(\omega t_{c} T_{c} / 2\right)^{2}}\right) \\
S_{2}(\omega)=T_{c}\left(1-t_{c}\right)\left(\frac{\sin ^{2} \omega\left(1-t_{c}\right) \cdot T_{c} / 2}{\left(\omega\left(1-t_{c}\right) T_{c} / 2\right)^{2}}\right)
\end{gathered}
$$

Then if the two spectra are linearly superimposed;

$$
S_{0}\left(\omega, t_{c}\right)=t_{c} \cdot T_{c} \cdot t_{c}\left(\frac{\sin ^{2} \omega t_{c} T_{c} / 2}{\left(\omega t_{c} T_{c} / 2\right)^{2}}\right)+\left(1-t_{c}\right) \cdot T_{c} \cdot\left(1-t_{c}\right)\left(\frac{\sin ^{2} \omega\left(1-t_{c}\right) T_{c} / 2}{\left(\omega\left(1-t_{c}\right) T_{c} / 2\right)^{2}}\right.
$$

If the same nominal carrier frequency is assumed for all the slaves, then the interference can be calculated at $\omega=0$.

Expanding $\sin ^{2} x$ in series form and neglecting higher terms than those to the power two gives: $\sin ^{2} \mathrm{x}=\mathrm{x}^{2}$, and thus the spectral density at $\omega=0$ becomes;

$$
S_{0}\left(0, t_{c}\right)=2 t_{c}^{2} T_{c}-2 t_{c} T_{c}+T_{c}
$$

The "phase displacement" will also modify the dc cross-correlation according to;

$$
\rho=\rho^{\prime}+\left(\rho^{\prime \prime}-\rho^{\prime}\right) \cdot t_{c}
$$

where $\rho^{\prime}$ and $\rho^{\prime \prime}$ are the cross-correlation between two codes for two consecutive chip shifts. The interference due to CDMA can then be written in the form;

$$
I_{m+1}=20 \log \left(m\left(\rho^{\prime}+\left(\rho^{\prime \prime}-\rho^{\prime}\right) t_{c}\right)^{2}+\left(2 t_{c}^{2}-2 t_{c}+1\right) \frac{T_{c}}{T_{s}}\right)^{\frac{1}{2}}
$$

One way to introduce possible values of the "phase displacement" $t_{c}$ in a radio network is to use the different propagation delays. Assuming the propagation speed of radio waves to be $3.10^{8} \mathrm{~m} / \mathrm{sec}$, the delays between stations are given by; ( $\mathrm{d}_{\mathrm{i}} / 3.10^{8}$ ) sec. For example a code chip frequency of 100 KHz , would result in an expression for the "phase displacements" $\mathrm{t}_{\mathrm{c}}$ equa1:

$$
\left.t_{c_{i}}=\frac{\frac{d_{i}}{3.10^{8}}}{10^{-5}} \text { modulo } 10^{-5}\right) \cdot 10^{5}
$$

This gives values of $0 \leq t_{c}<1$.

SKAUG, R.
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