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A CDMA SYNCHRONISATION SCHEME

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INTRODUCTION

CDMA (Code Division Multiple Access) is known to decrease inter-service interference in Satellite Communication Systems. Its performance is increased by chip quasi-synchronous operation which virtually eliminates the self-noise; however, the theory (ref.1) shows that the time error on the synchronisation has to be kept at less than one tenth of a chip which, for 1 Mchip/sec. spreading rate, corresponds to 10^(-7) sec. This, on the return-link, may only be achieved by means of a closed loop control system which, for mobile communication systems, has to be capable of autonomous operation. Until now some results have been reported (ref.2) on the feasibility of chip quasi-synchronous operation for mobile communication systems only including satellites on GEO (Geostationary Earth Orbit). In what follows the basic principles are exposed and results are presented showing how low chip synchronism error may be achieved by means of an autonomous control loop operating through satellites on any Earth orbit; the complete theory may be found in ref.3.

SYSTEM DESCRIPTION

An overall scenario is shown in fig.1. Each mobile terminal generates Transmit Time Epochs, which correspond to the epochs of transmission of the PN codes, i.e. to the beginning of each transmitted symbol on the Return-Link. The reception of these signals at the hub earth station generates Receive Time Epochs which are compared with a locally generated stream of Reference Time Epochs. The processing of the resulting Time Error results in a correction signal which will be transmitted on the Forward-Link to each mobile terminal. The above quantities may be represented as:

1) Transmit Epoch $TX_i = T_i$

2) Receive Epoch $RX_i = TX_i + \frac{D_o}{c} - \frac{1}{c}\int_0^{T_i} V_r(t)\,dt$

3) Reference Epoch $REF_i = T_i$

4) Time Error $E_i = -\frac{D_o}{c} + \frac{1}{c}\int_0^{T_i} V_r(t)\,dt$

In the above c is the velocity of light, Do is the length of the transmission path between Transmitter and Receiver at the time instant t = 0, Vr(t) is the total radial velocity of the transmitter with respect to the receiver. The quantity Ei refers to the error occurring to the time epoch transmitted at the time t = i*T; its actual time of occurrence is therefore t = i*T + Tp in which Tp is the total propagation time at the time instant t = i*t. The temporal behaviour is shown in fig. 2 in which the sampling time interval Ts is defined; the error is supposed to be measured at each time instant

5) Ti = To + i*Ts

Assuming that the following conditions are met:

6) $T_s >> T_p \qquad \frac{1}{c}\int_{T_{i-1}}^{T_i} V_r\,dt << \frac{1}{F} \qquad \frac{D_o}{c} << T_s$

the quantity Ei' may be expressed as

7) Ei' = (1/F)*[INT(RXi*F)-RXi*F+0.5] {sec.}

in which INT(x) means "the first integer less than x". The conditions above imply that the sampling time interval is much greater than the propagation time and that the system behaves so smoothly that the magnitude of the difference between the Ei' belonging to two contiguous sampling times i*Ts and (i+1)*Ts is a small fraction of 1/F. The fulfillment of conditions (6) allows the system to behave as a linear delay-less sampled data control system which may be analyzed with the Z-transform formalism. The functional block diagram of the synchronisation system at the hub earth station is shown in fig.3. The initial acquisition of the received PN codes is assumed to be supported by fully parallel correlators. This because the initial time error may take any value up to the time duration of one symbol and the corresponding values of the correction signals will not be compatible with the holding range of a DLL (Delay Lock Loop). The main requirements for the system are:

- the r.m.s. value of the time error has to be less than 0.1 chip (ref.1); this for 1 Mchip/sec. corresponds to 10^{-7}sec.;
- the transmission of control signals must take a fraction as small as possible of the available transmission capacity; therefore, the control system will operate in a sampling mode of which the sampling period has to be as long as feasible;
- operation with "real life" inaccuracies induced by hardware such as clock frequency generator errors and achievable resolution of the correction signals;
- operation in presence of noise;
- operation in voice activation mode;
- resistance to the outages induced by the mobile satellite communication channel.

The synchronisation control loop

The feedback control loop will act, at the mobile terminal, on the transmission time of each symbol in order to achieve, at the control station, chip synchronisation between the received spread spectrum signal and a time reference locally generated. As the feedback control loop has to minimise the time error generated by the motion of the mobile terminal and of the satellite with respect to the hub station, a second order control loop has to be considered as a minimum. This is a loop in which the control signal is derived from a double integration of the error signal versus time. Its controller may look as shown in fig.4; fig.5 shows the equivalent mathematical model of the system. The controller generates a correction signal given by:

8) CORRi = A * Ci + B * Ci'

9) Ci = C(i-1) + Ei

10) Ci'= C(i-1)' + Ci

Ei is the time error as defined in 4), A and B are coefficients independent from the time. The two expressions 9) and 10) are equivalent to:

11) Ci' = 2*C(i-1)' - C(i-2)' + Ei

The model of fig.5 assumes that only the controller, shown as C(z), affects the dynamic behaviour of the control loop. In the same model the quantity R(z) is the reference time and the quantity M(z) is the timing alteration corresponding to the motion of TX towards RX. For the case of constant velocity motion, by means of Z-transform the limit value of the time error may be found to be zero. However, this only holds at sampling time instants; during the time interval between sampling instants the system is left free to evolve and a substantial time error will develop. According to the complete analysis (ref.3), the time error shows a triangular behaviour versus time and its peak value may exceed the specified values; for the simple case of constant radial velocity the peak value of the time error is given by:

12) Eipeak = (Vro/c)*Ts

This may be corrected applying the correction all along the time interval Ts. This implements an interpolation between two consecutive values of the correction signal which is still given by

13) CORRi = A * Ci + B * Cj'

14) Ci = Ci + Ci-1

15) Cj'= Cj-1' + Ci

but the term Cj' is updated at each transmitted symbol, i.e. at each time epoch TXj; the coefficient B has to be scaled down by a factor equal to F. A result of a computer run for this simple case is shown in fig.6. After an initial transient the time error shows the foreseen triangular shape; at the time instant T1 the control signal is switched to (13) and the error collapses to virtually zero. In the case of a system at constant radial acceleration the principle of interpolation of correction signal may be shown to reduce the error; besides, it also may be applied to control loops of higher order.

Operation in presence of noise

From fig.5 it will be seen that any correction signal is equal to the sum of the error signal proper plus a sample of noise. This affects the error signal generated in the next sample and so on, resulting in the variance of the time error plus noise being greater than the sum of the two. This could be seen by deriving the following from (1), (2), (3) and (13):

16) $$E_i = \frac{1}{c}\left[\int_{T_{i-1}}^{T_i} V_r\,dt - \int_{T_{i-2}}^{T_{i-1}} V_r\,dt\right] + kE_{i-1} + k'E_{i-2}$$

Assuming for simplicity that Vr(t) = Vro it will be:

17) $$E_i = -N_i + k\cdot E_{i-1} + k'E_{i-2}$$

in which Ni is the sample of noise at the sampling time t=i*Ts. This shows that, at any time, the noise appearing at the "error output" of the system is actually made of two components: the input thermal noise generated, at that time, by the receiver, and the response of the loop to the thermal noise generated in the past. The performance of the system in presence of noise is improved by taking as error sample the average on a number of consecutively received time epochs; the variance of the noise in the loop is reduced by a factor equal to the squared root of that number. Additional improvement is given by adaptive control of the noise bandwidth of the loop. This is needed by mobile terminals moving with high acceleration.

Voice Activated Operation

At each mobile terminal the transmission of the RF carrier is inhibited during the time intervals in which the user is silent. System synchronisation then may only be achieved during short and random transmission time intervals. This may result in an exceedingly low sampling rate and it leads to a "burst forcing" mode of operation by which, irrespective of the activity of the user, the mobile terminal is forced to transmit bursts with a minimum frequency. This frequency may be minimised by some computational capability at the mobile terminal. For each transmitted symbol the following may be shown to hold:

18) $$E_j = E_{j-1} + \frac{1}{c}\int_{T_{j-1}}^{T_j} v_r(t)\,dt$$

in which the quantity vr(t)/c is measurable as Doppler effect. Therefore, the mobile terminal, once synchronised, may execute Doppler measurements on the RF carrier of the Forward-Link and from these it can derive the correction quantities to be applied to the transmission timing. This is an open loop mode of operation; errors affecting Doppler measurements, due to hardware limitations, will cumulate and a large error transient will develop when the system is switched back to its closed loop mode of operation. Should this transient exceed 0.5 chips the synchronisation would be lost and the PN code would have to be reacquired. In this mode of operation the double integrator has to be continuously updated as if the system was in regular closed loop operation; missing this updating, the same large transient as before will eventually develop. The needed updating of the double integrator may be derived from (11).

Resistance to transmission outages

Transmission outages given by mobile channels and occurring on the forward link may induce unrecoverable transmission errors on the control signal which will then be erased by the decoder. During a transmission outage occurring on the forward link and including consecutive correction signals the integrators may be left running on the last input value. This, in general, will result in an increased time error at the end of the outage itself; the eventual magnitude of the error is function of the radial acceleration to which the system has been subject during the outage. In the ideal case of a system at constant radial velocity the time error during a communication outage on the return link will only increase if the link is noisy; this because the last correction signal refers to an error measurement corrupted by noise. The random walk of the clock frequency generator during the outage may also give a contribution to the build-up of the error.

COMPUTER SIMULATION IMPLEMENTATION AND RESULTS

The system was modeled as shown in fig.7 in which M(t), S(t), N(t) represent the motion of the mobile terminal, the motion of the satellite, the thermal noise generated by the receive front end at the control earth station. The thermal noise is assumed to impress, on the time of occurrence of the receive time epochs, a Gaussian distributed time jitter. The dynamic behaviour of the PN code tracking device is accounted for as a linear second order low-pass filter (ref.4). The model is only valid if:

- all the de-spreaders are of the same type and have the same parameters,
- all the PN-code tracking devices operates in a linear region.

Output "1" represents the noise versus time in open loop conditions, output "2" represents the total time error versus time of the received time epochs. Clearly this model does not take into account transmission specific aspects but only deals with the control system. Several cases were actually implemented including a quasi geostationary earth orbit, i.e. a 24 hours period circular orbit having 10 degrees inclination, 12 hours and 8 hours Molnya orbits as considered by the Agency for its ARCHIMEDES satellite system; also orbits proposed for future commercial systems were simulated, such as a 10000 Km altitude 6 hours period circular earth orbit and a 900 Km altitude circular earth orbit. The latter case needs a third order control loop. For brevity, only the results for the 10000 Km and for the 900 Km circular Earth orbits are presented, these cases being the most critical. The acquisition phase is shortened by means of variable sampling rate; for the six hours earth orbit it goes from 4 samples per second, during the initial acquisition phase, to 1 sample per second in steady state. This value was selected in view of the assumed dynamic of the mobile terminal; for reduced dynamic it could be increased. The effect of the resolution of the time control signal was taken into account by quantisation of the correction signal in steps of magnitude ranging from 1/64 to 1/8 of a chip. The acquisition phase is declared to be completed when the error Ei is found to be <= 10^(-7); the system is declared to have gone out of track if at any Ti is

19) ABS{E(i)-E(i-1)} >= 0.5*10^-6

This to reflect the holding properties of a DLL, the presence of which is also taken into account by imposing that, at steady state, the magnitude of the difference between two time contiguous and quantised correction signals has not to exceed 0.25*10^(-6) sec. which corresponds to +/- 25% of a chip. With this the DLL always operates in its holding region. The used parameters give a 14 sec. acquisition time. To shorten the time taken by each run, the frequency F has been assumed to be 1 Ksymbol/sec.; the system however has been sized in view of the achievement of a time error not greater than 10^(-7) sec. as requested by the transmission of 8 Ksymbols/sec. with a spreading factor equal to 127. This is also equivalent to the 8 Ksymbols/sec. transmission with a spreading factor equal to 127 in which the interpolator output is taken every 8 symbols. Noise is averaged across 120 msec.

The 6 Hours Circular Earth Orbit

Fig.8 shows the time error resulting from the application to the mobile of an acceleration equal to 0.01 Km/(sec*) for 10 seconds, after which the mobile moves at constant speed equal to 360 Km/h. For simplicity the motion of the mobile is supposed to take place towards the satellite. The time error only develops during the accelerated phase of the motion of the mobile terminal; due to the second order control loop, the error at constant velocity of the mobile terminal is very small, being very small the acceleration of the satellite. The effect of finite quantisation, from 1/64 to 1/8 of a chip, is shown in fig.9. Fig.10 shows the error resulting from the application of the same acceleration to a mobile constrained to move along a circular track having 1 Km radius. The control signal is quantised at 1/64 of a chip. The noise performance of the system is shown in figs.11 and 12 which refer to the two above cases with noise corresponding to operation at 5 dB Eb/No.

The 900 Km altitude Circular Earth Orbit

Results for this orbit are shown in fig.13.

CONCLUSIONS

A control loop has been analyzed and simulated for chip synchronisation in chip quasi-synchronous CDMA schemes including satellites on any earth orbit. The proposed system is based on a high order sampled control loop, a linear interpolator and an adaptive gain control; during steady state conditions, the mobile terminal may generate control signals and this decreases constraints on the periodicity of generation of control signal. The same control loop also may be used for burst synchronisation in a TDMA system, which is a much less critical case.

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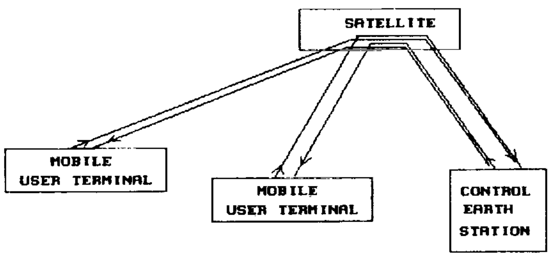

FIG 1 OVERALL SYSTEM ARCHITECTURE

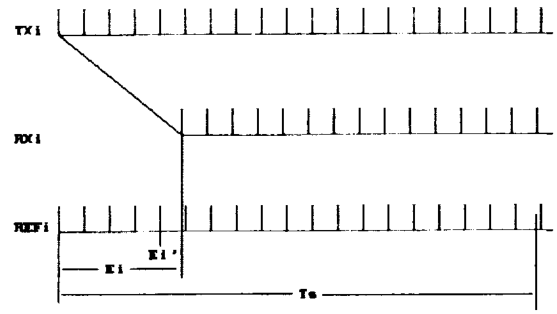

FIG.2 DEFINITION OF TIME ERROR

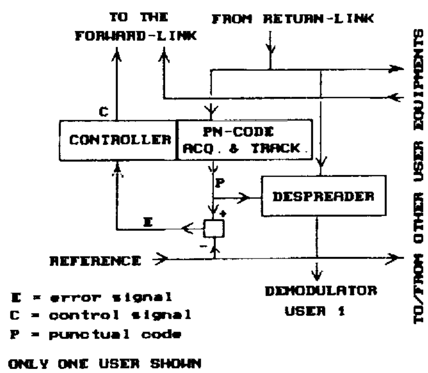

FIG.3 CONTROL EARTH STATION FUNCTIONAL BLOCK DIAGRAMME

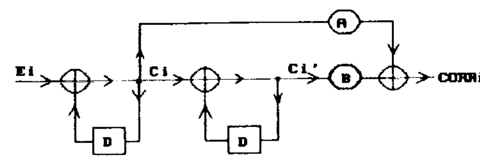

FIG.4 EXAMPLE SECOND ORDER CONTROLLER

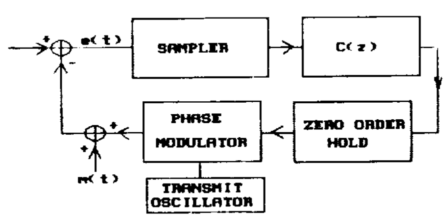

FIG.5 SECOND ORDER SAMPLED CONTROL SYSTEM

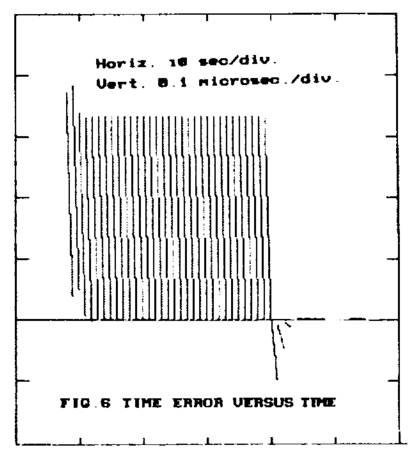

FIG.6 TIME ERROR VERSUS TIME

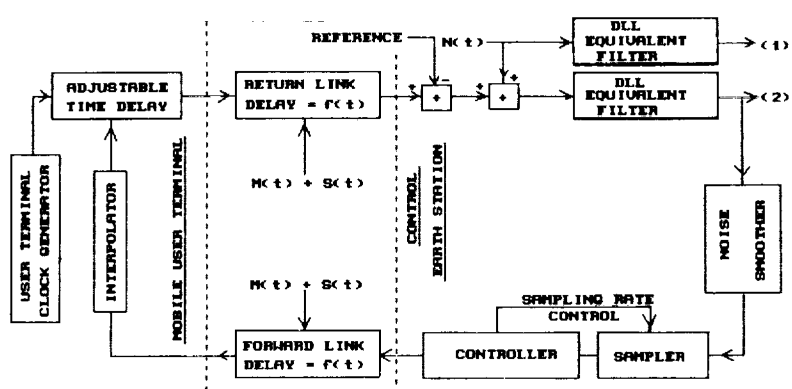

FIG.7 SYSTEM SIMULATION MODEL

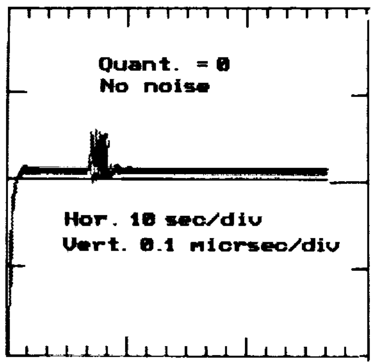

FIG.8

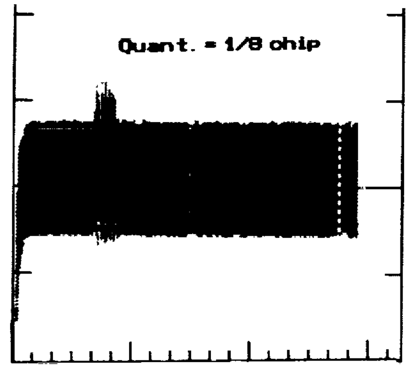

FIG.9

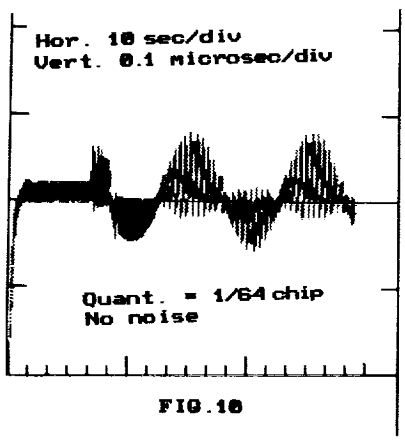

FIG.10

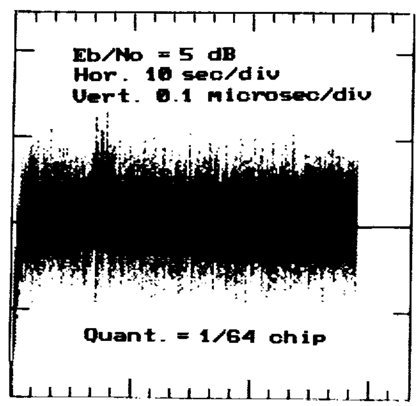

FIG.11

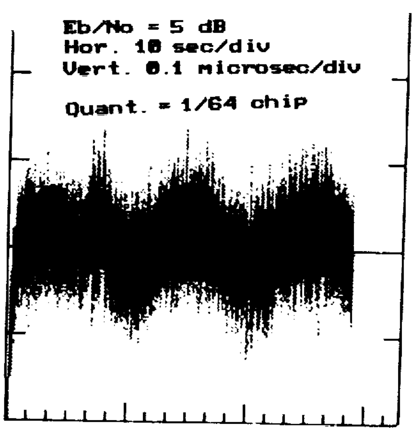

FIG. 12

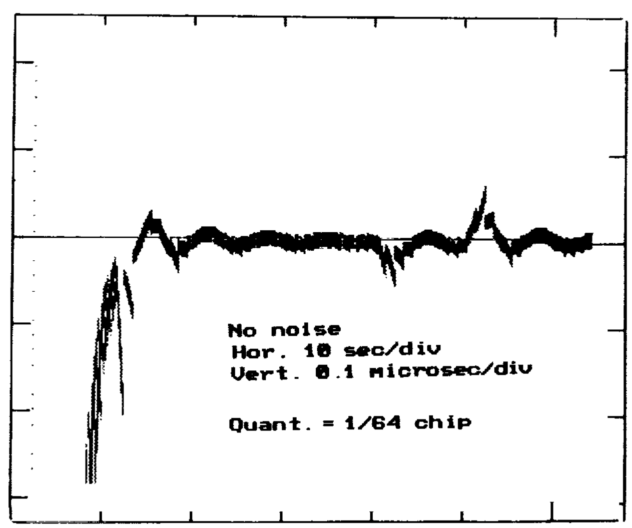

FIG. 13