

Time Tracking Error in Direct-Sequence Spread-Spectrum Networks Due to Coherence Among Signals

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Abstract—High data rate communications networks, navigation, and some types of time synchronization networks which use spread-spectrum modulation in a CDMA (code-division multiple-access) mode are subject to a time tracking (or time synchronization) error related to the degree of signal frequency agreement or coherence among involved communicators. As reference oscillator stabilities improve and various frequency offsets decrease in networks involving several interfering spread-spectrum signals, the degree of carrier and code coherence increases. In this paper, data are presented showing more than a twenty-fold increase in the time synchronization uncertainty (from 0.3 to 7 ns) due to interference of two spread-spectrum signals having a high degree of signal coherence.

I. INTRODUCTION

ORDINARILY, one tries to reduce phase noise and mutual frequency offset in the generation of direct-sequence spread-spectrum signals in a simulcast (shared frequency) spread-spectrum network [1], [2]. Coding (spreading) of the data bit stream increases the fineness of its temporal (phase) structure, so at some level phase "jitter" of the reference oscillator can degrade identification of signal zero-crossings more than communication link noise [3]. On the receiver side, oscillator noise degrades the tracking loop. We attain improved code and RF carrier coherence by using low noise, high stability reference oscillators at each network site. This shortens acquisition of lock time and also enables higher communication data rates or conversely fewer errors for a given data rate.

While doing a routine test for code orthogonality, a time tracking error which was over 20 times greater than the normally expected level appeared when a second modem signal (having a different PN sequence) was combined at equal power with the first. This unusually high degradation was apparent only when there was a high degree of relative phase stability and low-frequency offset between one and another spread-spectrum modem RF carrier signal.

II. PROCEDURE

The procedure in this paper involves combining two stable signals separated by a small frequency and transmitting two orthogonal PN sequences [4]. The spread-spectrum modem is a commercially available unit with a standard deviation of the time synchronization errors of order 0.3 ns (1 s samples) using a Cs atomic frequency standard as the reference oscillator and a communications link C/N_0 (carrier-to-noise density) ratio of 65 dB-Hz or better [5]. The modem is used for sending and receiving (through a geostationary communications satellite) a precisely timed 1 Hz signal between timekeeping labs. The modem generates a PN code of 10 000 bits every 4 ms (truncated MLS sequence). The PN sequence rate is therefore 250 frames/s and the chip rate is 2.5 Mb/s. The occurrence of an inverted sequence marks the 1 pulse/s epoch. There are eight dissimilar PN sequences having cross-correlation components

at least 20 dB below the peak in the autocorrelation function and are therefore considered "orthogonal" for implementing a CDMA network.

Fig. 1 shows a block diagram of the apparatus. The modem consists of a spread-spectrum modulator and a delay-lock loop demodulator driven by a common reference signal and contained in one box. For clarity, the modulator and demodulator are separated in Fig. 1. The data are a 1 Hz signal derived from the 10 MHz reference, and a coherent I.F. output of the modulator is generated at 70 MHz (designed for satellite up-conversion). The signal representing PN code #1 is combined with an interfering orthogonal signal from modem #2 with PN code #2. PN code #1 is demodulated and the 1 Hz data are recovered. The derived (transmitted) 1 Hz pulses and received 1 Hz pulses of modem #1 respectively start and stop a time interval counter. The phase difference of these two signals (transmit/receive) is indicated on the counter and is recorded for various offset frequencies from the interfering (modulator #2) signal with PN code #2. Values of offset frequency ($\Delta\nu$) are taken at the 70 MHz IF (ν_0). The normalized fractional frequency difference is $\gamma(t) = \Delta\nu/\nu_0$ which can be introduced at the 10 MHz reference input to modulator #2 through a synthesizer.

The average measurement by the counter in Fig. 1 represents the mean value of the time delay between the 1 Hz signal as encoded by modulator #1 and decoded by its demodulator. A deviation from this mean value represents a time synchronization error, that is, a time lead or lag received by the demodulator. The noise process in this series of phase measurements should be white, that is, random, uncorrelated and not deterministic about this constant mean value. We shall see that the noise in the synchronization data of a link is not white in the presence of another orthogonal spread-spectrum signal having a low RF carrier frequency offset.

III. DATA

Fig. 2 is a record of the time-interval counter-readings taken once each second of modem #1 in a loop test (modulated 70 MHz is connected to demodulator as in Fig. 1). A constant 1520 ns has been subtracted to show residual errors more clearly. The first one-third of the series of measurements is without the presence of a signal from modem #2. The middle part is with a signal from modem #2 combined at a frequency offset of about $\gamma(t) = 5 \times 10^{-7}$. This represents a frequency difference of 35 Hz with respect to the 70 MHz I.F. One sees an increase in the scatter of the counter-readings due to reduced C/N_0 ratio from the presence of the signal from modem #2 and a 0.5–1.5 ns change compared to the first one-third which is explainable by the discussion to follow.

The last one-third of the counter readings of Fig. 2 is with modem #2 mixed in at a frequency offset of $\gamma(t) = 1 \times 10^{-9}$, or 0.07 Hz at 70 MHz used here. A large periodic term shows up in the loop test of modem #1 in the presence of a signal from modem #2 in this case. The period of this term is equal to the period of the beat frequency of the RF carriers between modem #1 and #2. (The carriers are not separately observable in the spectrum of the spread signal.)

Fig. 3 is counter readings over 1000 s (about 17 min) for a case similar to the last third of Fig. 2, that is with modem #2 mixed with a fractional frequency offset of 1×10^{-9} . Long-term features different from the short-term periodicity are prevalent. Cross-corre-

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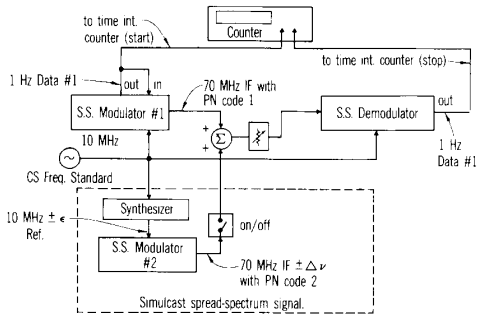


Fig. 1. A simulcast spread-spectrum signal from modulator #2 is combined with the normal link between modulator #1 and the demodulator. Data are a 1 Hz signal internally generated in the modulator (10 MHz ref. divided by 10^7) and recovered in the demodulator.

Loop Test of PN Code 1
mixed with PN Code 2

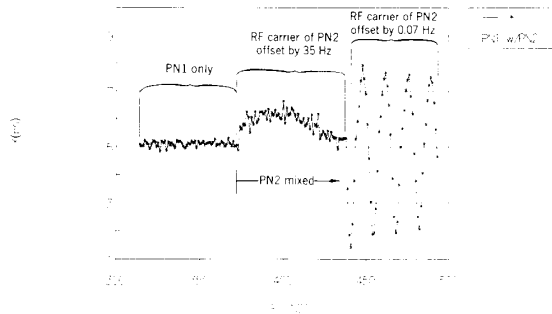


Fig. 2. Time interval counter readings for (1) loop test of PN code 1 only, (2) PN code 1 combined with PN code 2 and RF carrier offset by 35 Hz, and (3) combined with RF carrier offset by 0.07 Hz.

lation values at times separated by one chip period typically differ by K/\sqrt{L} or approximately 0.01 here (K is a numerical factor usually around 1 and $L = 10\,000$ is the code period). Assuming the delay-lock loop discriminator has a slope of one, a perturbation in the autocorrelation of order 0.01 due to cross-correlation of an interfering sequence will cause a 4 ns fluctuation in time tracking, approximately the observed effect.

The cross-correlation adds to the early or late autocorrelation at a phase determined by the beat of the carriers, hence, the vector resultant periodically increases and decreases differently on the late correlation than on the early correlation. Thus, the code tracking loop will be perturbed at the rate of the carrier beat frequency. Furthermore, the difference between the peaks and valleys of the envelope of the plot of Fig. 3 is 200 s which represents the time that the interfering code has slipped by one PN chip.

As the carrier beat frequency increases, the effect on the demodulator's tracking loop decreases due to the loop bandwidth. However, even outside the loop bandwidth, if the period of the carrier beat frequency coincides with a rational multiple or submultiple of the frame rate, then the effect is increased scatter and/or low-level periodicity in the time tracking loop counter readings. This is shown in Fig. 4 in which the carrier of modem #2 was offset by 250 Hz (the frame rate) for the first half of the countermeasurement series and 110 Hz (not rationally related) for the second half. Ordinarily, one would expect a direct relationship between this noise level and the link (loop) C/N_0 ratio [6]. Thus, in a network, one would reasonably conclude that the C/N_0 ratio was degraded in the first half, but no actual change was made in the link (loop) signal or

PN1 with PN2 and
1 ns/s rate offset

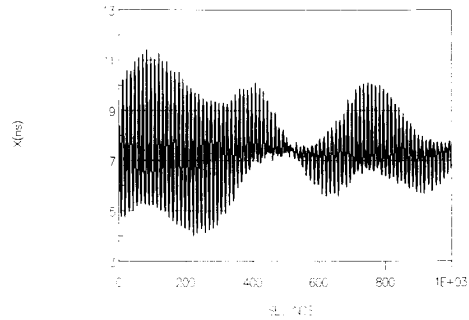


Fig. 3. PN code 1 combined with PN code 2 and with RF carrier offset by 1 ns/s (or $y(t) = 1 \times 10^{-9}$). Long- and short-term periodicity is evident.

PN1 with PN2 and RF offset
by 250Hz then 110Hz

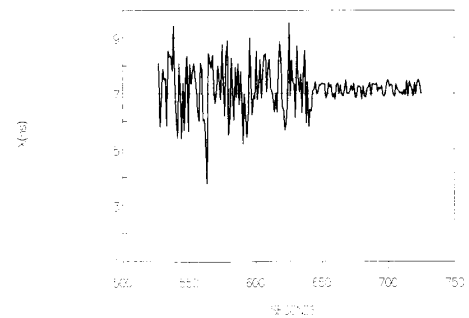


Fig. 4. PN code 1 combined with PN code 2 and with RF carrier offset by 250 Hz (frame rate) then by 110 Hz (no rational relationship to frame rate or chip rate).

noise between the first half and the second half; only a frequency change was made by another simulcast spread-spectrum signal.

IV. CONSEQUENCES OF THE OBSERVED EFFECT

In order to discuss simulcast spread-spectrum interference, we distinguish two separate but interacting types of interference: RF carrier and code. The code represents the baseband signal and biphasic modulates an RF carrier signal having a high degree of phase stability owing to its derivation from stable frequency standards. A high degree of carrier and code phase stability may cause periodicity in time tracking in a CDMA network. If the carrier and code phase stability were poor, one might see only an inordinate increase in the noise of the time tracking data. With improved phase stability, an arbitrary phase relationship between interfering carriers and codes may yield large time tracking errors. For example, Fig. 5 shows synchronization data as a function of time where a simulcast spread-spectrum signal (code #2) is offset by $y(t) = 2.15 \times 10^{-10}$. A periodic term with period of 1 min and a peak-to-peak amplitude of 8 ns is a component of the data which otherwise is in the presence of white noise. The short-term (1 s) signal-to-noise ratio yields a precision below 0.3 ns as indicated by the low amplitude of the noise, yet a 15 s average of segment "A" (measurement time interval) will yield a value different than that over segment "B" by 7 ns. An improvement in signal-to-noise ratio will shorten the required averaging time but will not reduce the size of the error.

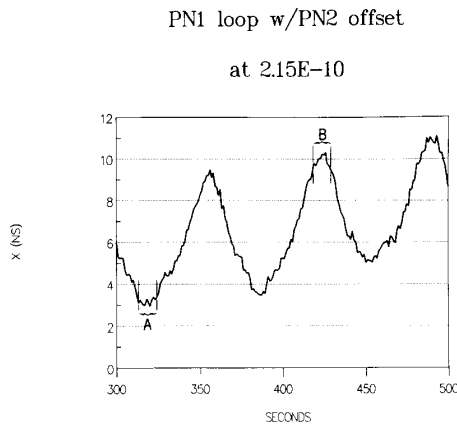


Fig. 5. PN code 1 combined with PN code 2 and with RF carrier offset by $y(t) = 2.15 \times 10^{-10}$. White noise level (precision) is at 0.3 ns yet average of segment "A" differs from segment "B" by 7 ns.

In present-day navigation and timing networks, a 7 ns tracking error is significant. However, in data communications networks, a receiver cares not so much "when" but "whether" a PN sequence occurs. Agreeably, a 7 ns error in code tracking relative to a 400 ns chip period is of little consequence. But if the chip period were 40 ns or less (representing a high data rate network), a 7 ns error would increase the BER (bit error rate). A topic of future study would be to determine the dependence of the code tracking error on chip rate.

V. CONCLUSION

Data are presented which reveal a time synchronization error in CDMA spread-spectrum networks where mutual signal phase coherence is high among communicators. The error is not white noise but is, in fact, periodic with an amplitude, phase, and mean offset which

appears to be related to a mixture of the carrier frequency, chip rate, and code frame rate. This periodicity is more evident as carrier and code phase coherence increases among participants in a network and high tracking accuracy is the goal. This has implications particularly on future high-rate data communications and navigation networks in which errors may be attributed to local oscillator instabilities more than a transmission link [1]–[3]. The data using a commercial modem suggests that improvements in local oscillator stabilities will, of course, improve coherence among network participants but will not necessarily reduce time synchronization errors.

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- [4] Holmes [Op. Cit., pp. 505–511] and others to whom he refers have done two analyses that represent different cases of interference than in this paper but are nevertheless related: 1) single-tone interference effects on time tracking and 2) multipath effects on time tracking. In the first case, there is an increase in the variance of the white noise as a result of a single tone. A delay-locked loop demodulator multiplies incoming signals by an internally generated (identical) PN sequence which effectively "spreads" a single tone that is filtered by a narrow-band, post-correlation filter. The resulting timing error variance depends on the level of interference, pre-correlation and post-correlation bandwidths, and chip rate. The second case involving a multipath reflection predicts up to an 18% static timing error bias relative to a chip period. In this case, the interfering (reflected) spread-spectrum signal is coherent and has the identical PN sequence. This paper addresses the issue of different sequences.
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