A New Coherent Demodulation Technique for Land-Mobile Satellite Communications

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ABSTRACT
This paper describes an advanced coherent demodulation technique for land-mobile satellite (LMS) communications. The proposed technique features a combined narrow/wide band dual open loop carrier phase estimator, which is effectively able to compensate the fast carrier phase fluctuation by fading without sacrificing a phase slip rate. Also included is the realization of quick carrier and clock re-acquisition after shadowing by taking open loop structure. Its bit error rate (BER) performance is superior to that of existing detection schemes, showing a BER of $1 \times 10^{-2}$ at 6.3 dB $E_b/N_0$ over the Rician channel with 10 dB $C/M$ and 200 Hz (1/16 modulation rate) fading pitch $f_d$ for QPSK. The proposed scheme consists of a fast response carrier recovery and a quick bit timing recovery with an interpolation. An experimental terminal modem has been developed to evaluate its performance at fading conditions. The results are quite satisfactory, giving prospects for future LMS applications.

1. INTRODUCTION
Satellite based land-mobile communications have received increasing attention over recent few years because of its extended service to the rural area, where terrestrial mobile systems cannot be incorporated from an economical viewpoint. In LMS systems, the use of power and spectrally efficient transmission scheme is intensely requested to overcome the large space loss, and to conform the limited available frequency band. To meet such requirements, coherent detection combined with forward error correction (FEC) is in common practice. However, in the LMS environment, there exist two serious degrading factors for coherent detection. One is multipath fading, which ranges to 100-200 Hz at maximum. Since a 4800 bps data rate is sufficient for a current digital voice transmission technique, good phase coherence cannot be counted on over long bit period, thus it results in serious BER degradation. The other is frequent received signal interruption by obstacles (i.e. shadowing). A phase lock loop (PLL) used conventionally in carrier and clock synchronization is very vulnerable to such environments, and often loses its track, taking a lot of time for the recovery. Although the phase tracking speed and/or recovery time can be improved by making loop bandwidth wide, it induces frequent phase slips as a penalty. It is quite difficult to find a good compromise between these two conflicting factors. Authors propose a new coherent demodulation technique, which is almost able to remove PLL's deficiency.

2. NEWLY PROPOSED COHERENT DEMODULATION SCHEME
2.1 Carrier Recovery by Dual Open Loop Phase Estimator
In order to resolve aforementioned problems, authors propose a new carrier phase estimator, which consists of two different bandwidth estimators to compensate the fast phase fluctuation by fading without increasing phase slips. An LMS channel is modeled by the mixture of a strong direct-path signal component and a scattered weak multipath signal component, that is Rician. Moreover the received signal is contami-
nated with thermal noise, as depicted in Fig. 1.

The fast phase fluctuation due to the multipath is estimated by the wide band estimator. The wide band estimator takes the same configuration as the narrow band estimator except its bandwidth. A wide band estimator’s output $\theta_w(n)$ is also expressed by

$$\theta_w(n) = \arg\left[\sum_{k=-n+(N_2-1)/2}^{n+(N_2-1)/2} C_w(n-k)S_M(k)\right]$$

$$= \arg\left[\frac{1}{N_2} \sum_{k=-n+(N_2-1)/2}^{n+(N_2-1)/2} S_M(k)\right]$$

$$(C_w(i) = 1/N_2 \text{ for } \forall i), (2)$$

where $C_w(i)$ and $N_2$ are tap coefficients and tap number of the wide band estimator respectively. An impulse response of the respective estimators is designed rectangular to reduce a computational load.

A carrier phase is estimated by combining the narrow and wide band estimator’s outputs so that the wide band estimator’s output cannot induce carrier phase slips. First, the narrow band estimator’s output is subtracted from the wide band estimator’s output, and the result is divided by modulation phase $M$, thus a fast phase component scattered by the multipath is obtained within $\pm \pi/M$ radian, for example $\pm \pi/4$ radian for QPSK. The narrow band estimator’s output is also divided by $M$, and then its phase range is extended to $\pm \pi$ radian by quadrant correction. A recovered carrier phase is obtained by adding the estimated fast phase component to the quadrant corrected slow changing phase. Thus, a recovered carrier phase $\theta_r(n)$ is calculated by using the following equation,

$$\theta_r(n) = \text{mod}\left\{\frac{1}{M} \theta_n(n) + \frac{2\pi}{M} i(n)\right\}$$

$$+ \frac{1}{M} \text{mod}[\theta_w(n)-\theta_n(n), 2\pi], 2\pi\}, (3)$$

where $i(n)$ denotes $\text{mod}\{i(n-1) - \text{sign}[\theta_n(n) - \theta_n(n-1),1],M\}$ for $|\theta_n(n) - \theta_n(n-1)| > \pi/M$ and $i(n-1)$ otherwise. In this carrier recovery scheme, a carrier phase slip rate depends only on the narrow band estimator’s performance. Finally, the recovered phase is converted to a complex form, and a received signal is coherently detected by the complex carrier. Delay time $T_1$ and
Fig. 2 Proposed carrier recovery block diagram

Fig. 3 BER characteristic by simulation

The proposed scheme shows the $E_b/N_0$ improvement of around 1-2 dB compared with conventional coherent detection using a single open loop phase estimator with narrow bandwidth, and the $E_b/N_0$ improvement of around 2 dB over non-coherent differential detection, at the operating 1x10^{-2}-5x10^{-3} BER point derived from the high coding rate FEC.

Although static BER performance of the proposed scheme is degraded by the wide band estimator, its amount is relatively small from the conventional scheme, and in an LMS environment its degradation becomes negligible compared with that by fading.

2.2 Quasi-Open Loop Bit Timing Recovery

In bit synchronization, quick recovery from frequent shadowing is another requested characteristic in an LMS environment. To meet such a requirement, authors propose a new bit timing recovery scheme, which is able to make free from acquisition problems by taking quasi-open loop structure. The block diagram is shown in Fig. 4. After root Nyquist filtering, a signal envelope is detected, and then phase correlation between the signal envelope and a complex sinusoidal local reference is calculated. A ROM table is referred to generate the sinusoidal reference at the input sample timing. $T_s$ as sample interval, phase correlation $S_c(nT_s)$ is expressed by

$$S_c(nT_s) = V_e(nT_s)\exp(-j2\pi n/N),$$

where $V_e(nT_s)$ is a signal envelope and $N$ is a sample number per baud interval. The correlated output is fed to a low-pass filter to smooth out the phase jitter, and tan$^{-1}$ operation of the filter's output is performed. The result represents a bit timing error against the local reference. In a case when a slight frequency difference exists between

$T_1$ in Fig. 2 are determined using baud interval $T_b$ as follows,

$$T_1 = \frac{N_1 - N_2}{2}T_b, \quad T_2 = \frac{N_1 - 1}{2}T_b.$$  \hspace{1cm} (4)

The BER performance for several detection schemes including the proposed scheme is evaluated by computer simulation over the Rician fading channel with carrier-to-multipath ratio (Rician factor) $C/M$ of 10 dB and fading pitch $f_d$ of 1/16 modulation rate for QPSK. These results are shown in Fig. 3.
a modulation clock and the local reference, the slow bit timing change is observed. To track the bit timing continuously, a wide band first-order PLL is introduced. A \(2\pi/N\) radian phase step size is sufficient for controlling a digital VCO, because its request is to specify the nearest sample to real bit timing from the input \(N\) samples. Hence, the PLL's loop gain \(K\) is represented as

\[
K = \frac{1}{N}. \tag{6}
\]

The loop gain \(K\) is designed large enough that the PLL's bandwidth is sufficiently wide compared with the open loop phase estimator's bandwidth (low-pass filter's bandwidth). Thus, the whole response is solely determined by the low-pass filter's characteristics, showing this loop virtually open.

Fig. 4 Bit timing recovery block diagram

A real sampled value at bit timing is obtained by an interpolation. The second-order's Lagrange's formula is selected as the interpolation scheme to facilitate the calculation. An interpolated signal \(S_i(r)\) is calculated by using the following equation,

\[
S_i(r) = \frac{r^2 - r}{2} S(-T_s) - \frac{(r^2 - 1)}{2} S(0) + \frac{r^2 + r}{2} S(T_s) = C_1(r) S(-T_s) + C_0(r) S(0) + C_{-1}(r) S(T_s) = \sum_{n=-1}^{1} C_n(r) S(nT_s) \quad (|r| \leq \frac{1}{2}), \tag{7}
\]

where \(S(0)\) is the nearest sample to real bit timing, \(S(-T_s)\) and \(S(T_s)\) are its adjacent samples, and \(r = T_i/T_s\) is normalized interpolation timing. This calculation can be implemented by an FIR filter with time variant three tap coefficients \(C_i(r)\). These coefficients are written in a ROM table in advance.

### 3. MODEM IMPLEMENTATION

An experimental terminal modem is developed to evaluate our proposed scheme. From a viewpoint of the spectral efficiency, 5 kHz channel spacing is strongly requested in LMS systems. Therefore, the modulation rate is determined to be 3.2 kbaud for QPSK modulation using band-limit filters with 0.5 roll-off factor. Thus, it enables redundancy for FEC with 3/4 coding rate. Table 1 shows the modem specifications summary.

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation scheme</td>
<td>3.2 kbaud QPSK</td>
</tr>
<tr>
<td>Band-limit filter</td>
<td>Raised cosine roll-off</td>
</tr>
<tr>
<td>Operation mode</td>
<td>SCPC continuous mode</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Carrier deviation</td>
<td>Less than (\pm) 3 kHz</td>
</tr>
<tr>
<td>A/D sampling rate</td>
<td>606 667 kHz (455 kHz x 4/3)</td>
</tr>
<tr>
<td>A/D quantization</td>
<td>8 bits</td>
</tr>
<tr>
<td>Sample number (N)</td>
<td>6 samples per baud interval</td>
</tr>
<tr>
<td>FEC</td>
<td>K=7, R=3/4, 4/7</td>
</tr>
<tr>
<td>Voice codec</td>
<td>4.8 kbps multi-pulse coding</td>
</tr>
</tbody>
</table>

Table 1 Modem specifications summary

Figure 5 shows the demodulator block diagram. A 455 kHz intermediate frequency (IF) signal is fed to a single A/D converter, and directly sampled by 4/3xIF clock. Quadrature detection is performed all by digital circuit using these samples, and the digitized orthogonal signal is appropriately decimated. After that, demodulation is performed by three NEC's \(\mu\)PDT77230 digital signal processors (DSP) except Viterbi decoding using a dedicated LSI chip, and the following tasks are assigned for each processor.

1) Root Nyquist filtering (FIR filter)
2) Bit timing recovery, AFC and carrier recovery
3) Frame synchronization, de-interleaving, Viterbi decoder interface and Voice decoder interface

Since an open loop phase estimator is very sensitive to a carrier frequency offset, an AFC circuit [3] is necessitated to eliminate this offset before the carrier phase estimation. The AFC circuit is composed of slow and fast tracking parts. The slow tracking AFC part is requested so as to calibrate a local oscillator at all times stably, and the fast tracking AFC part is for the purpose.
of compensating the fast frequency fluctuation by Doppler.

A demodulated signal after Viterbi decoding is sent to a 4.8 kbps voice decoder and converted to a voice signal in it.

4. PERFORMANCE OBTAINED

The modem has been tested using a radio channel simulator. The bit error rate and carrier phase slip rate are measured in the presence of AWGN and Rician fading. The BER performance is shown in Fig. 6 with Rician factor $C/M$ of 10 dB and fading pitch $f_d$ of 200 Hz (1/16 modulation rate). The deviation from computer simulation is well within 1 dB at the operating BER point. To prove the effectiveness of our proposed scheme over the conventional scheme using a single open loop estimator with narrow bandwidth, the performance is measured removing a wide band estimator. As was expected from simulation, the proposed scheme showed the $E_b/N_0$ improvement of around 1-2 dB over the conventional scheme at the operating $1 \times 10^{-2}$-$5 \times 10^{-3}$ BER point. And, a low carrier phase slip rate of less than $5 \times 10^{-2}$ times/sec is realized at the operating $E_b/N_0$ of 6 dB with severe Rician fading, as seen in Fig. 7. The demodulated scattering diagrams for the proposed and conventional schemes are depicted in Fig. 8, which shows an appearance that the fast phase fluctuation by fading is effectively compensated by a dual open loop phase estimator.

5. CONCLUSION

A new carrier and bit timing recovery scheme is presented, which remarkably augments the demodulator's performance in an LMS environment. Furthermore, an actual experimental terminal modem has been manufactured to verify the effectiveness of the proposed idea. The results are quite satisfactory, achieving good bit error rate performance and stable synchronization. This scheme is applicable for different modulation schemes.

ACKNOWLEDGMENTS

Authors wish to thank Mr. Furuya, Dr. Hirotsuki and other members of C&C Systems Research Labs., NEC Corporation, for their helpful discussions.

REFERENCES

Fig. 6 BER characteristic

Fig. 7 Carrier slip rate characteristic

Fig. 8 Demodulated scattering diagrams

International Mobile Satellite Conference, Ottawa, 1990