Low Signal-to-Noise Ratio Underwater Acoustic Communications

Channel Effect and Signal Processing for Direct-Sequence Spread-Spectrum Signaling

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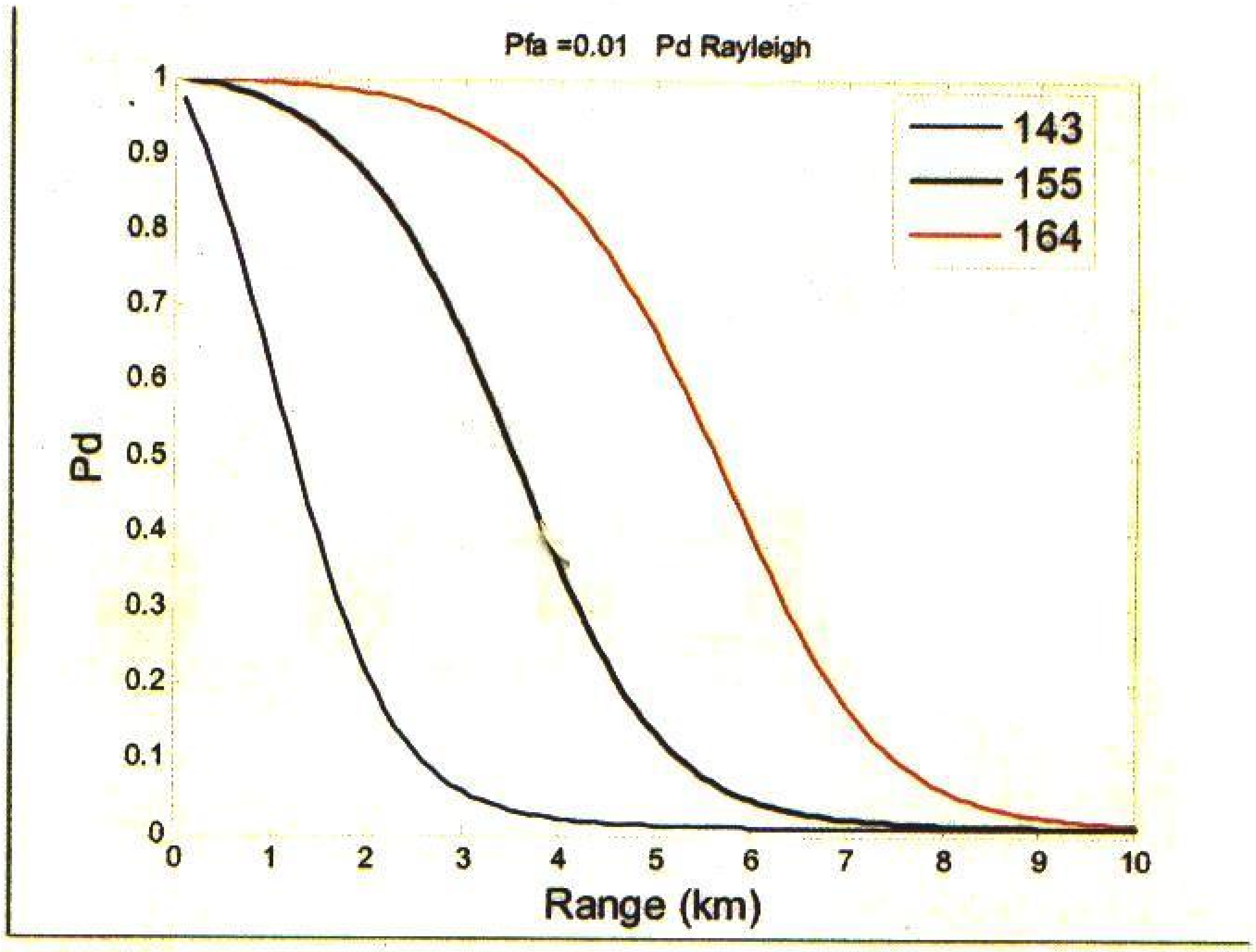
Communications with low input signal-to-noise ratios (SNRs) are often called covert communications, as the probability of detection and interception decreases with decreasing SNR. Direct-sequence spread-spectrum (DSSS) signaling works at low SNRs because of the processing gain derived from the signal time bandwidth product. The underwater acoustic channel faces high multipath spread and rapidly changing channel conditions. Symbol estimation based on the matched filter output (as in radio frequency communications) is often erroneous, based on at-sea data analysis. New algorithms have been proposed and shown to work well with both fixed and moving source data.

Underwater acoustic communications are needed for acoustic networking and data telemetry between nodes of distributed antisubmarine warfare systems in the littoral. However, acoustic communications cannot alert a hostile target collecting intelligence, surveillance data or traversing the area (within the detection range of the nodes).

To avoid detection/interception by the target, signaling schemes with a low probability of detection and interception are often considered. Since the probability of detection (P_D) and the probability of interception are strongly dependent on the SNR, the question from the system point of view is: At what ranges will the signal likely be detected by the interceptor?



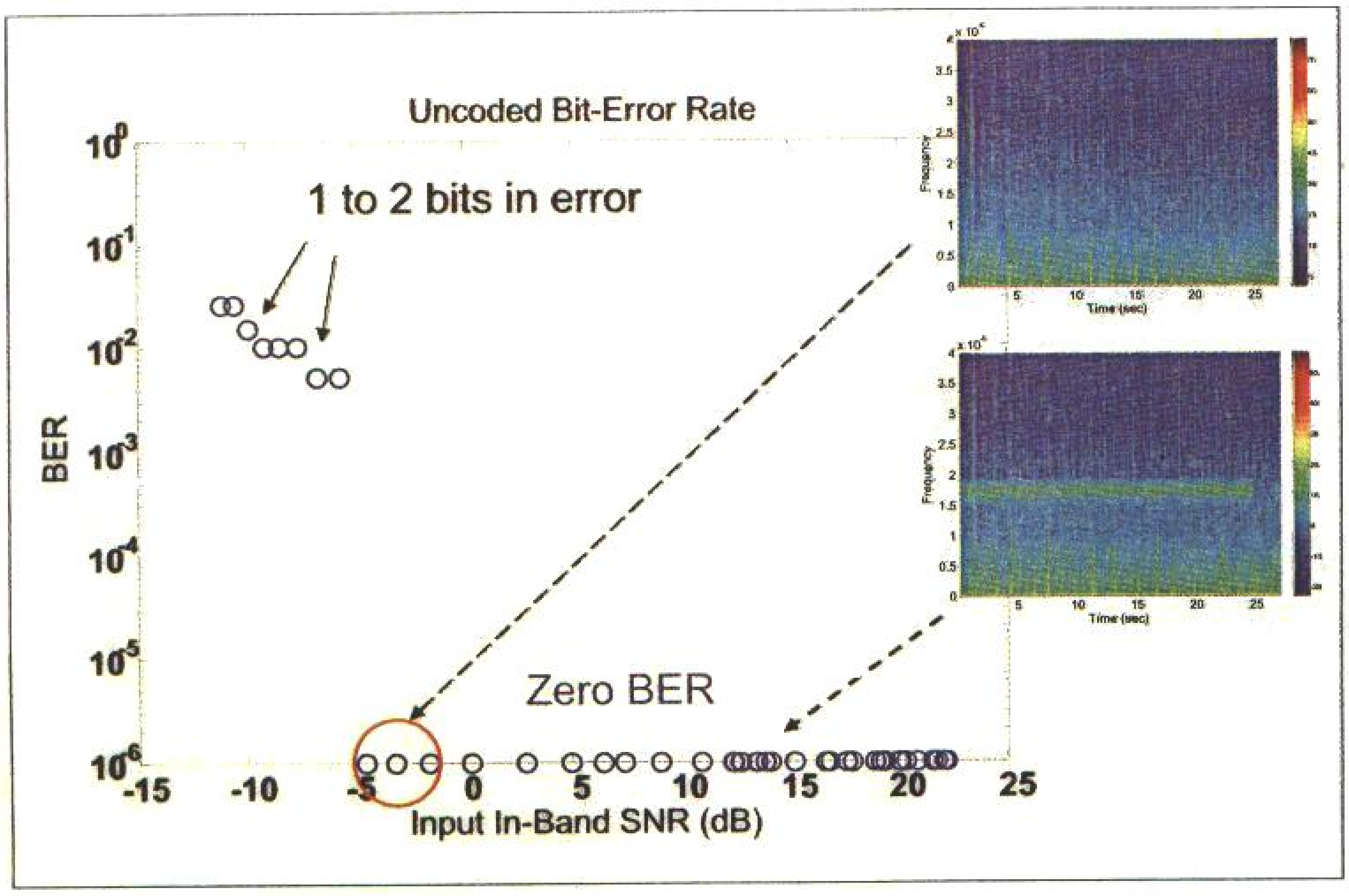
P_D as a function of range for different source levels, assuming Rayleigh fading statistics.

To study this question, a counter-detection range can be defined as the range below which the signal is easily detectable (e.g., P_D is greater than 0.5), assuming a given probability of false alarm, P_{FA} (e.g., P_{FA}=0.01).

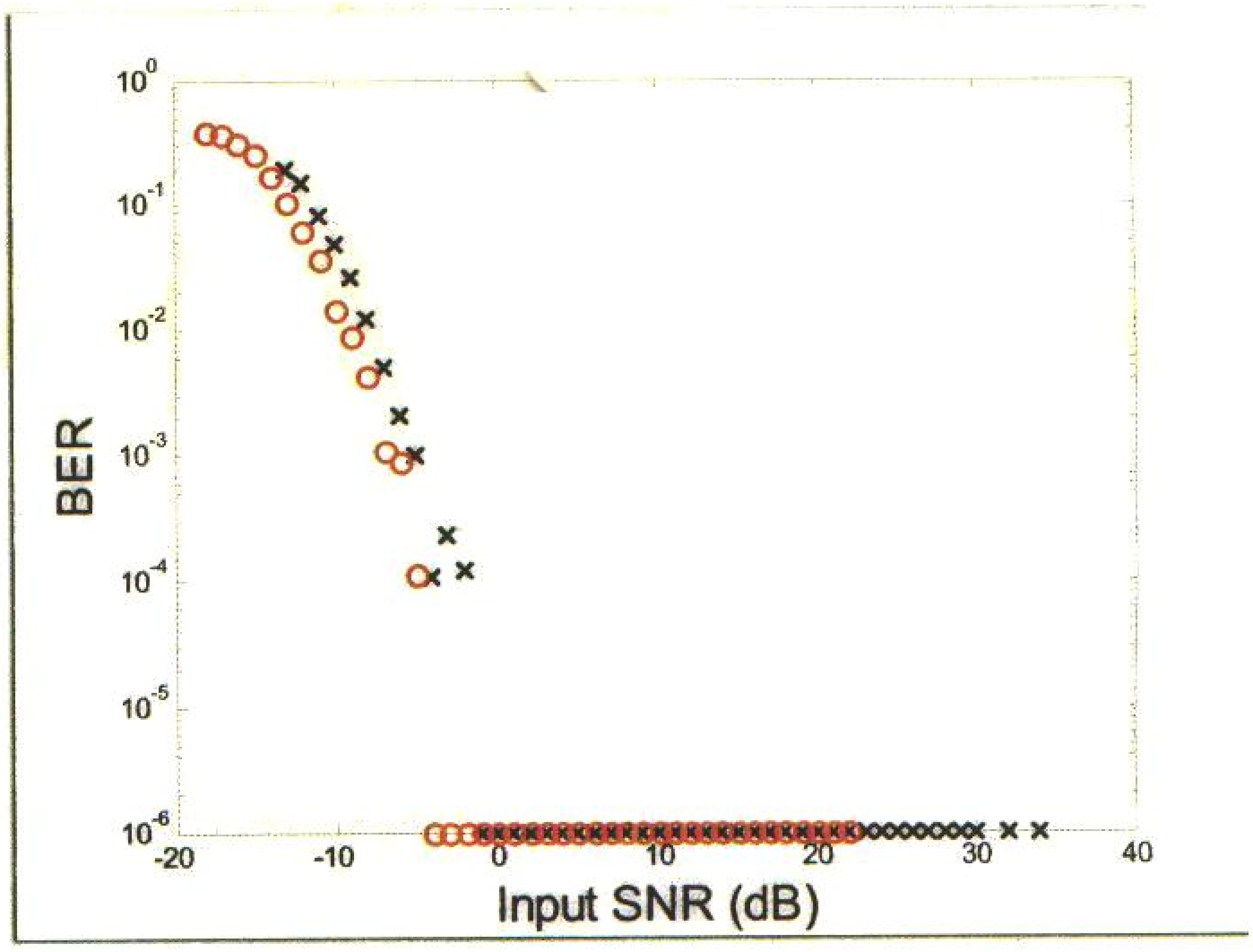
The counter-detection range can be estimated for a given ocean environment by first calculating the average SNR as a function of range for a given source level using a propagation model and an empirical noise model.

Next, for a given SNR and an allowed P_{FA}, one determines the P_D as a function of range, based on the signal and noise statistical distribution.[1] P_D and P_{FA} are calculated for a pulse energy detector, assuming that the detector/interceptor does not know the signal property except the signal bandwidth. Counter-detection range is reduced by lowering the source level.

DSSS signaling allows communications at a lower SNR, at the expense of a decreased data rate. DSSS uses a code sequence to spread the symbols at the



(Above) BER as a function of input SNR from the AUVFest07 experiment.



(Right) BER as a function of input SNR from the TREX04 data (x and o denote moving and fixed source data).

transmitter and a de-spreader at the receiver to recover the transmitted symbols. The de-spreader (a correlator or a matched filter) provides a processing gain (matched filter gain) that enhances the symbol energy over noise, thus allowing communications at a low input SNR. DSSS uses a pseudo-random signal that is noise-like and, hence, less likely to be recognized and intercepted.

A problem for communications at low SNRs is symbol synchronization. Normally, a high SNR (e.g., greater than eight decibels) probe signal is used for synchronization in underwater acoustic communications. To avoid detection, such a loud probe signal should be avoided.

Another problem is signal fading, which can be severe (around 10 decibels) in a dynamic ocean environment. Multiple receivers (spatial diversity) are often needed to minimize the probability that all signals fade at the same time. DSSS does not need a probe signal and can tolerate signal fading using a single receiver due to the large time bandwidth of the signal. However, the large multipath spread and the rapid channel variation commonly found in many underwater acoustic channels require new signal processing approaches for communications at low input SNRs.[1]

Experimental Results

DSSS underwater acoustic communications were evaluated using the 2004 Time Reversal Experiment (TREX04) data and tested during the 2007 Autonomous Underwater Vehicle Festival (AUVFest07). TREX04 was conducted by the Naval Research Laboratory (NRL) in April 2004, taking place off the coast of New Jersey in about 70 meters of water. DSSS acoustic communication data were transmitted from both a fixed source and a towed source to a fixed receiver.

AUVFest07 was conducted in June 2007 in the coastal water near Panama City, Florida. The water depth was about 20 meters. DSSS communications were tested using a fixed source and a fixed receiver deployed one to two meters above the bottom at a range of five kilometers. Data were processed in real time with a decreasing source level, using acoustic modem software originally developed by the Woods Hole Oceanographic Institution. This is PC-based software that uses the CPU as the processor.

Bit error rate (BER) was measured as a function of input (in-band) SNR. One can clearly see the signal in the spectral gram of a single receiver when SNR is high (greater than zero decibels). At less than negative five decibels input SNR, the signal is hardly visible in the spectrum, yet the receiver algorithm can decode the signal with a BER of less than one percent.

DSSS signals were transmitted using binary phase-shift keying modulation. Using the m-sequence with a code length of 511, one expects a theoretical matched filter gain of $10_{\log}(511)=27$ decibels. The measured matched filter gain, after multipath combination, is approximately 26.5 decibels. With a bandwidth of four kilohertz, centered at 17 kilohertz, the code duration is

> ***"Several methods have been proposed for low-SNR underwater acoustic communications using DSSS signaling."***

longer than the multipath spread, so there is no inter-symbol interference after de-spreading.

The matched filter (correlator) output is, in principle, the channel impulse response modulated by the data symbol.

In a relatively stable propagation channel without multipath spread, the symbol can be directly estimated from the correlator output, as is often the case in radio frequency communications.

In an underwater acoustic channel, one finds that the symbol phase is often path dependent and rapidly varying with time. As a result, symbol estimation based on the matched filter output yields high symbol errors.

To remove the multipath-induced inter-symbol interference and the symbol phase error, the conventional approach uses a decision feedback equalizer jointly with a phase-locked loop; the channel is updated at the symbol or the chip rate. This approach is computationally intensive and requires high SNR (greater than 10 decibels).

Another method uses a Rake receiver to combine the multipath arrivals, when multipath arrivals are separated in time. At low input SNRs, identifying the multipath arrivals is a problem. Also, as mentioned above, symbol synchronization and tracking are imprecise at low SNRs.[1]

New Signal Processing Approaches

Several methods have been proposed for low-SNR underwater acoustic communications using DSSS signaling. One simple method that works well for fixed-fixed node communications correlates the matched filter output of two adjacent symbols to determine the differential phase between the two symbols.[1]

The matched filter yields the channel impulse response multiplied by the symbol. Assuming that the channel impulse response has not changed much within the two-symbol time period, the correlation of the impulse responses is approximately a delta function.

The correlation peak of the matched filter outputs therefore reveals the product of the conjugate of the previous symbol with the current symbol, from which one can determine the differential phase between the two symbols. In this case, differential phase-shift keying modulation is preferred. Note that at high frequencies, the channel coherence time is short (of the order of 0.2 seconds at approximately 17 kilohertz). When the symbol duration is long (i.e., a long code sequence), the above assumption that the channel has not changed much may break down.

As a result, the peak correlation of the impulse responses between two adjacent symbols may be a complex number resulting in a phase error in

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symbol estimation. For the 511 code sequence, the data showed that the phase error is smaller than the symbol phase difference. Consequently, the method works fairly well for the two experimental data.

The reason is that the symbol duration (approximately 0.13 seconds) is of the order or shorter than the channel coherence time.

Using this method, the channel coherence time is the limiting factor for the code length, and hence the available processing gain.

At low input SNRs, this method is said to provide a coarse synchronization, as the positions of the peak of the matched filter and the peak of the correlation of two impulse responses fluctuate due to increasing noise and/or temporal variation of the impulse response. Coarse synchronization is responsible for some performance loss at low SNRs.

Another factor for performance loss is the temporal variation of the channel, which the above method does not track. If the code length is short and the channel has a limited multipath spread, the channel can be assumed to be quasi-stationary between two symbols, and the performance loss is negligible.

For low SNR communications, one needs a long code length to provide a high processing gain. Not being able to track the channel change (i.e., imprecise estimation of the channel impulse response) also contributes to performance loss.

A third factor contributing to the performance loss is signal fading, resulting in less-than-average SNR for symbol detection.

Based on numerical simulations, one finds that performance loss due to coarse synchronization, imprecise channel impulse estimation and signal fading is about four, eight and two decibels respectively.[1] Of the 27-decibel processing gain, one is left with five decibels for symbol estimation at an input SNR of negative eight decibels.

The above method does not work for communications from or to a moving source. The reason is that the differential phase between two symbols incurs an unacceptable phase error due to source/receiver motion. A different method is required.

For data processing from a moving source, the first thing is to estimate the Doppler shift for each symbol. For this purpose, a wideband ambiguity function is used, which correlates the Doppler-shifted transmitted symbol with the received data. A new symbol transition detector is used to determine the relationship between two adjacent symbols. The transition detector is an energy detector, thus avoiding the problem of large (differential) phase fluctuations.

The detector uses the same principle as the matched filter, except new code sequences are used instead of the original code sequence. The new sequence consists of the second half of the code sequence followed by the first half of the code sequence. They are Doppler-shifted based on the estimated Doppler shift and are correlated with the second half of the previous symbol data plus the first half of the current symbol data. If the previous and current symbols are the same, the matched filter output of the first sequence with the data produces the channel impulse response. Its energy will be higher than the energy of the matched filter output of the second sequence with data. The reverse will be true if the previous symbol and current symbol are not the same (i.e., change sign).

Around 230 packets of fixed-source and moving-source data from the TREX04 were analyzed and added with at-sea noise at different times to create more than 2,000 packets with input SNR varying from -15 to +23 decibels. Many packets achieve zero bit errors for input SNR as low as -15 decibels when the symbols have near uniform level. Bit errors generally occur when some symbols selectively fade.

On average, one can achieve less than one percent uncoded BER for input SNR as low as negative eight decibels. The result is shown by plotting the average BER as a function of the input SNR.

Conclusions

DSSS signaling takes advantage of the processing gain of the code sequence and allows communications at low input SNR.

New algorithms have been devised to counter the multipath spread and rapidly fluctuating symbol phase. The new algorithms tolerate coarse synchronization at a loss of performance of about four decibels. No probe signal is used to avoid detection. No training data is required. Only a single receiver is used, a limitation often found in many applications.

Acknowledgments

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References

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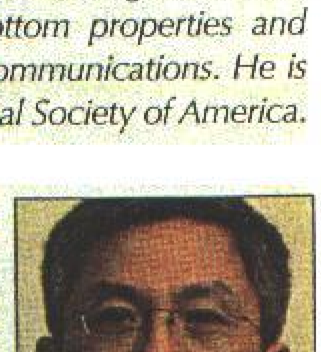

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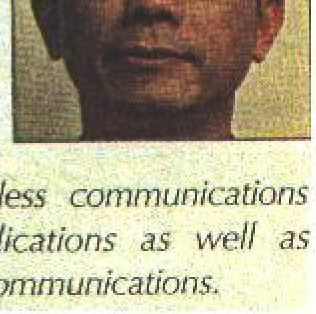

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