Timing Synchronization for Cooperative Wireless Communications

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Declaration

The contents of this thesis are to the best of the candidate's knowledge and belief, the results of original research, except as acknowledged in the text, and the materials have not been submitted for a higher degree at The Australian National University or to any other university or institution.

Much of the work in this thesis has been published or has been submitted for publication as journal papers or conference proceedings. These papers are:

Journal Articles

1. Md. Tofazzal Hossain, David B. Smith, Rodney A. Kennedy and Sithamparanathan Kandeepan, "Effect of Timing Error on the Performance of BPSK Modulation over a Fading Channel", *IEEE Communications Letters*, vol. 14, no. 10, Oct. 2010.

2. Md. Tofazzal Hossain, David Smith and Sithamparanathan Kandeepan, "Timing Synchronization for Cooperative Communications with Detect and Forward Relaying", *Springer Journal of Wireless Personal Communications*, DOI: 10.1007/s11277-010-0057-x, In Press, 2010.

3. Md. Tofazzal Hossain, David B. Smith, Rodney A. Kennedy and Sithamparanathan Kandeepan, "Error Probability Performance with Timing Synchronization Errors for Cooperative Communications", *Submitted to IEEE Transactions on Wireless Communications.*

4. Md. Tofazzal Hossain, David B. Smith, Rodney A. Kennedy and Sithamparanathan Kandeepan, "Decode-and-Forward Cooperative Communications with Various Architectures: Performance Analysis with Timing Synchronization", *Submitted to IET Communications.*

5. Md. Tofazzal Hossain, Sithamparanathan Kandeepan and David Smith, "Timing Synchronization for Fading Channels with Different Characterizations us-

ing Near ML Techniques", *Academy Publisher Journal of Communications*, vol. 4, no. 6, pp. 404–413, July 2009.

Conference Papers

1. Md. Tofazzal Hossain and David Smith, "Cooperative Communications: Synchronization in Fast-Fading Channels with Various Signal Constellations", in *Proceedings of IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, pp. 1-5, Marrakech, Morocco, June 2010.

2. Md. Tofazzal Hossain, Sithamparanathan Kandeepan and David Smith, "Decode-and-Forward Cooperative Communications: Performance Analysis with Power Constraints in Presence of Timing Error", in *Proceedings of International Workshop on Cognitive Radio and Cooperative Strategies for Power Saving collocated with MOBIMEDIA 2010*, Lisbon, Portugal, Sept. 2010.

3. Md. Tofazzal Hossain and David Smith, "Data and Channel Aided Symbol Timing Estimation for Cooperative Communications", in *Proceedings of IEEE Australian Communication Theory Workshop*, pp. 48–53, Canberra, Australia, Feb. 2010.

4. Md. Tofazzal Hossain and David Smith, "Symbol Timing Estimation Using Near ML Techniques and Statistical Performance Evaluation for Binary Communications", in *Proceedings of IEEE International Conference on Computer and Information Technology*, pp. 486–491, Khulna, Bangladesh, Dec. 2008.

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Abstract

In this work the effect of perfect and imperfect synchronization on the performance of single-link and cooperative communication is investigated. A feedforward non-data-aided near maximum likelihood (NDA-NML) timing estimator which is effective for an additive white Gaussian noise (AWGN) channel and also for a flat-fading channel, is developed. The Cramer Rao bound (CRB) and modified Cramer Rao bound (MCRB) for the estimator for a single-link transmission over an AWGN channel is derived. A closed form expression for the probability distribution of the timing estimator is also derived. The bit-error-rate (BER) degradation of the NDA-NML timing estimator with raised cosine pulse shaping for static timing errors over an AWGN channel is characterized. A closed form expression is derived for the conditional bit error probability (BEP) with static timing errors of binary phase shift keying modulation over a Rayleigh fading channel using rectangular pulse shaping.

The NDA-NML timing estimator is applied to a cooperative communication system with a source, a relay and a destination. A CRB for the estimator for asymptotically low signal-to-noise-ratio case is derived. The timing complexity of the NDA-NML estimator is derived and compared with a feedforward correlation based data-aided maximum likelihood (DA-ML) estimator. The BER performance of this system operating with a detect-and-forward relaying is studied, where the symbol timings are estimated independently for each channel. A feedforward data and channel aided maximum likelihood (DCA-ML) symbol timing estimator for cooperative communication operating over flat fading channels is then developed. For more severe fading the DCA-ML estimator performs better than the NDA-NML estimator and the DA-ML estimator. The performance gains of the DCA-ML estimator over that of the DA-ML estimator become more significant in cooperative transmission than in single-link node-to-node transmission.

The NDA-NML symbol timing estimator is applied to three-node cooperative communication in fast flat-fading conditions with various signal constellations. It is found that timing errors have significant effect on performance in fast flat-fading

channels. The lower complexity NDA-NML estimator performs well for larger signal constellations in fast fading, when compared to DA-ML estimator. The application of cooperative techniques for saving transmit power is discussed along with the related performance analysis with timing synchronization errors. It is found that power allocations at the source and relay nodes for transmissions, and the related timing errors at the relay and the destination nodes, have considerable effect on the BER performance for power constrained cooperative communication.

The performance of multi-node multi-relay decode-and-forward cooperative communication system, of various architectures, operating under different fading conditions, with timing synchronization and various combining methods, is presented. Switch-and-stay combining and switch-and-examine combining are proposed for multi-node cooperative communication. Apart from the proposed two combining methods equal gain combining, maximal ratio combining and selection combining are also used. It is demonstrated that synchronization error has significant effect on performance in cooperative communication with a range of system architectures, and it is also demonstrated that performance degradation due to synchronization error increases with increasing diversity. It is demonstrated that decode-and-forward relaying strategy with timing synchronization, using a very simple coding scheme, performs better than detect-and-forward relaying with timing synchronization.

Analytical expressions are derived for BEP with static and dynamic timing synchronization errors over Rayleigh fading channels using rectangular pulse shaping for amplify-and-forward and detect-and-forward cooperative communications. Moment generating function (MGF) based approach is utilized to find the analytical expressions. It is found that timing synchronization errors have an antagonistic effect on the BEP performance of cooperative communication. With the relay intelligence of knowing whether symbols are detected correctly or not, detect-and-forward cooperative communication performs better than the low complexity amplify-and-forward cooperative communication.

List of Acronyms

AAF	amplify-and-forward
ABER	average bit-error-rate
AWGN	additive white Gaussian noise
BEP	bit error probability
BER	bit-error-rate
BPSK	binary phase shift keying
CRB	Cramer Rao bound
DA	data-aided
DAF	detect-and-forward
DCA	data and channel aided
DF	decode-and-forward
CSI	channel state information
DPSK	differential phase shift keying
EGC	equal gain combining
ERC	equal ratio combining
FM	frequency modulation
IF	intermediate frequency
ISI	inter-symbol interference
MAC	medium access control
MCRB	modified Cramer Rao bound
MIMO	multiple input multiple output
MISO	multiple input single output
ML	maximum likelihood
MLE	maximum likelihood estimation
$\mathbb{M}$-PSK	$\mathbb{M}$-ary phase shift keying
$\mathbb{M}$-QAM	$\mathbb{M}$-ary quadrature amplitude modulation
MRC	maximal ratio combining
NDA	non-data-aided
NML	near maximum likelihood

NRZ	non-return-to-zero
OFDM	orthogonal frequency division multiplexing
PAM	pulse amplitude modulation
pdf	probability density function
pmf	probability mass function
PSK	phase shift keying
QAM	quadrature amplitude modulation
QoS	quality-of-service
QPSK	quadrature phase shift keying
RC	raised cosine
RF	radio frequency
SC	selection combining
SEC	switch-and-examine combining
SNR	signal-to-noise ratio
SNRC	signal-to-noise ratio combining
SoMRC	sub-optimal maximal ratio combining
SoSC	sub-optimal selection combining
SRC	square root raised cosine
SSC	switch-and-stay combining

Notations and Symbols

α	roll-off factor
E_b	average energy per bit
E_s	energy of a symbol
$E_z\{\cdot\}$	statistical expectation with respect to the subscripted variable
f_D	maximum Doppler shift
f_s	sample rate
$g(t)$	continuous time impulse response of a Nyquist filter with the raised cosine characteristic
$g_{src}(t)$	continuous time impulse response of a square root raised cosine filter
$G(f)$	frequency response of $g(t)$
$h(t)$	fading channel gains
$I_0(\cdot)$	modified Bessel function of the first kind and zero-th order
K	samples per symbol
L	number of symbols to estimate timing offset
M	number of parallel branches in cooperative network
N_0	noise power spectral density
N	number of relays in each parallel branch in cooperative network
$p(t)$	continuous time impulse response of a pulse shaping filter
$P(f)$	frequency response of $p(t)$
P_b	theoretical bit error probability over AWGN channel
$r(t)$	received signal before passing through matched filter
γ	instantaneous-signal-to-noise ratio
$\overline{\gamma}$	average signal-to-noise ratio
t	time

τ	timing offset
$\widehat{\tau}$	timing offset estimate
T_c	coherence time
T_s	sample period
T	symbol period
ν_ξ	standard deviation of the Tikhonov distribution
$z(t)$	received signal after passing through matched filter
ξ	normalized static timing error
$\ln(\cdot)$	natural logarithm
$Q(\cdot)$	Gaussian Q-function
$\mathfrak{R}[\cdot]$	real part

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