Are Amplify-and-Forward Relaying and Decode-and-Forward Relaying the Same?

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Outline

- Introduction
- Background
- Envelope-Based Coherent AF Relaying
- Numerical Results and Discussion
- Conclusion

Introduction

- Spatial diversity can effectively mitigate the performance degradation caused by multipath propagation
- It is not always possible to deploy multiple antennas at mobile devices
  - Size restrictions (correlation reduces effectiveness)
  - Limited power or computational resources
- Cooperation diversity has been proposed as an efficient technique for providing spatial diversity benefits in wireless applications where the terminals cannot be equipped with multiple antennas [J. N. Laneman, *et al.*, 1999]
  - Achieved by the virtual antenna array that is formed by the relaying terminals, distributed in space

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Introduction

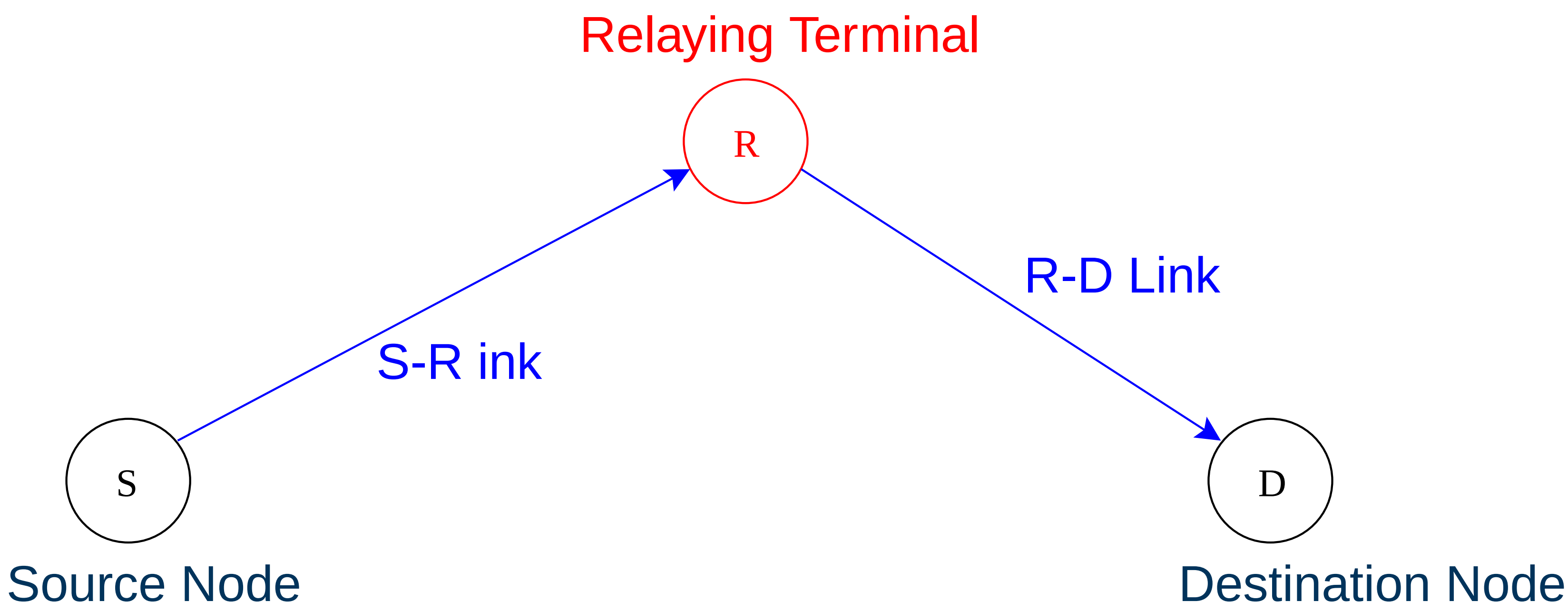
- Amplify-and-forward (AF) relaying
  - Non-regenerative relaying
  - Relay gain depends on channel state information (CSI) of source-relay link
  - Believed to be attractive for practical applications where the relay nodes implement only minimal data processing capabilities
- Decode-and-forward (DF) relaying
  - Regenerative relaying
  - Believed to have high complexity

Introduction

- Error performance of AF inferior to that of DF for the values of relay gains proposed so far

- Some works on improving AF relaying performance by modifying the relay gain have appeared
  - [N. C. Beaulieu, *et al.*, 2006] proposed a coherent AF relaying scheme for 1-D modulations which eliminates orthogonal noise
  - [M. A. Gatzianas, *et al.*, 2007] investigated the optimal gain when channel amplitude and noise power are known

Background



- Operating in time-division AF mode dividing each transmission period into two sub-periods
  - R listens to S in former sub-period
  - R amplifies received signal by a gain G and forwards it to D in latter sub-period

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Background

- [J. N. Laneman, *et al.*, 1999] chose a particular real-valued gain

$$G_1 = \sqrt{\frac{P_R}{P_S|h_{SR}^2| + N_0}}$$

where

P_S : Power transmitted by the source
P_R : Power transmitted by the relay
h_{SR} : Complex gain of the S-R link
N_0 : Noise power at the relay

- [N. C. Beaulieu, *et al.*, 2006] proposed a complex-valued relay gain for improving BPSK AF relaying performance

$$G_2 = \sqrt{\frac{P_R}{P_S|h_{SR}^2| + \frac{N_0}{2}}} e^{-\arg(h_{SR})}$$

  - Requires the phase of the S-R link as does DF relaying
  - Eliminates perpendicular noise as does DF relaying
  - Fairer comparison to DF relaying

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Background

- Both gains G_1 and G_2 require CSI, signal measurement and noise measurement
  - G_1 and G_2 require estimation of the amplitude of the source-relay link
  - G_1 and G_2 also require estimation of the signal power and the noise power
  - G_2 in addition requires estimation of the phase of the source-relay link
- Propose stochastic complex-valued relay gain

$$G = \frac{\sqrt{P_R} e^{-j \arg(h_{SR})}}{|\Re \{ s|h_{SR}| + n_{SR} e^{-j \arg(h_{SR})} \}|}$$

where

s : Signal transmitted by the source

$s \in \{\sqrt{P_S}, \sqrt{P_S} e^{j\pi}\}.$

Envelope-Based Coherent AF Relaying

A) BPSK

- The complex gain is

$$G = \frac{\sqrt{P_R} e^{-j \arg(h_{SR})}}{|\Re\{s|h_{SR}| + n_{SR} e^{-j \arg(h_{SR})}\}|}$$

- After counter-rotating the received signal by $\arg(h_{SR})$ and transmitting the real part of the rotated signal, the magnitude of the relay gain is

$$|G| = \frac{\sqrt{P_R}}{|\Re\{s|h_{SR}| + n_{SR} e^{-j \arg(h_{SR})}\}|}$$

- This gain satisfies the power constraint with unitary probability
- Relay power is constant

Envelope-Based Coherent AF Relaying

- The received signal at D

$$r_D = \Re\{r_R e^{-j\arg(h_{SR})}\}|G|h_{RD} + n_{RD}$$

where

r_R : Signal received at the relay
h_{RD} : Complex channel gain of the R-D link
n_{RD} : Noise component of the R-D link

- Two cases considered for the real part of r_D
  - r_R lies in the correct (right) 2-D half-plane

$$\Re\{r_D e^{-j\arg(h_{RD})}\} = \sqrt{P_R}|h_{RD}| + \Re\{n_{RD} e^{-j\arg(h_{RD})}\}$$

  - r_R lies in the incorrect (left) 2-D half-plane

$$\Re\{r_D e^{-j\arg(h_{RD})}\} = -\sqrt{P_R}|h_{RD}| + \Re\{n_{RD} e^{-j\arg(h_{RD})}\}$$

Envelope-Based Coherent AF Relaying

- The overall error probability

$$P_e = (1 - P_{e,S\text{-}R})P_{e,R\text{-}D} + P_{e,S\text{-}R}(1 - P_{e,R\text{-}D})$$

where

$P_{e,S\text{-}R}$: Error probability of the S-R link
$P_{e,R\text{-}D}$: Error probability of the R-D link

  - $P_{e,R\text{-}D}$ is the same as that in a DF relaying system
  - $P_{e,S\text{-}R}$ is the same as that in a DF relaying provided matched-filtering and optimal timing recovery at R

- For Rayleigh fading channels

$$P_{e,S\text{-}R} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}_{SR}}{1+\overline{\gamma}_{SR}}}\right)$$

$$P_{e,R\text{-}D} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}_{RD}}{1+\overline{\gamma}_{RD}}}\right)$$

Envelope-Based Coherent AF Relaying

B) QPSK

- Assume perfect carrier phase recovery and employ Grey coding
- The gain of each quadrature signal component chosen in a way corresponding to that done in the BPSK case
- Transmitted symbol $\in \{\sqrt{P_S}e^{j\pi/4}, \sqrt{P_S}e^{j3\pi/4}, \sqrt{P_S}e^{j5\pi/4}, \sqrt{P_S}e^{j7\pi/4}\}$
- Overall symbol error rate (SER) of envelope-based coherent AF relaying can be the same as that of DF relaying

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Envelope-Based Coherent AF Relaying

Gain Optimality

- $Theorem\ 1$: The optimal, in a minimal SER sense, value of relay gain in a coherent BPSK AF relaying system that satisfies an average power constraint is

$$G = \frac{\sqrt{P_R} e^{-j \arg(h_{SR})}}{|\text{Re}\{r_R e^{-j \arg(h_{SR})}\}|}$$

- $Corollary\ 1$: The optimal value of relay gain in a coherent QPSK AF relaying system that satisfies an average power constraint is

$$\Re\{G\} = \frac{\sqrt{P_R/2}}{|\text{Re}\{r_R e^{-j \arg(h_{SR})}\}|}$$

$$\Im\{G\} = \frac{\sqrt{P_R/2}}{|\text{Im}\{r_R e^{-j \arg(h_{SR})}\}|}$$

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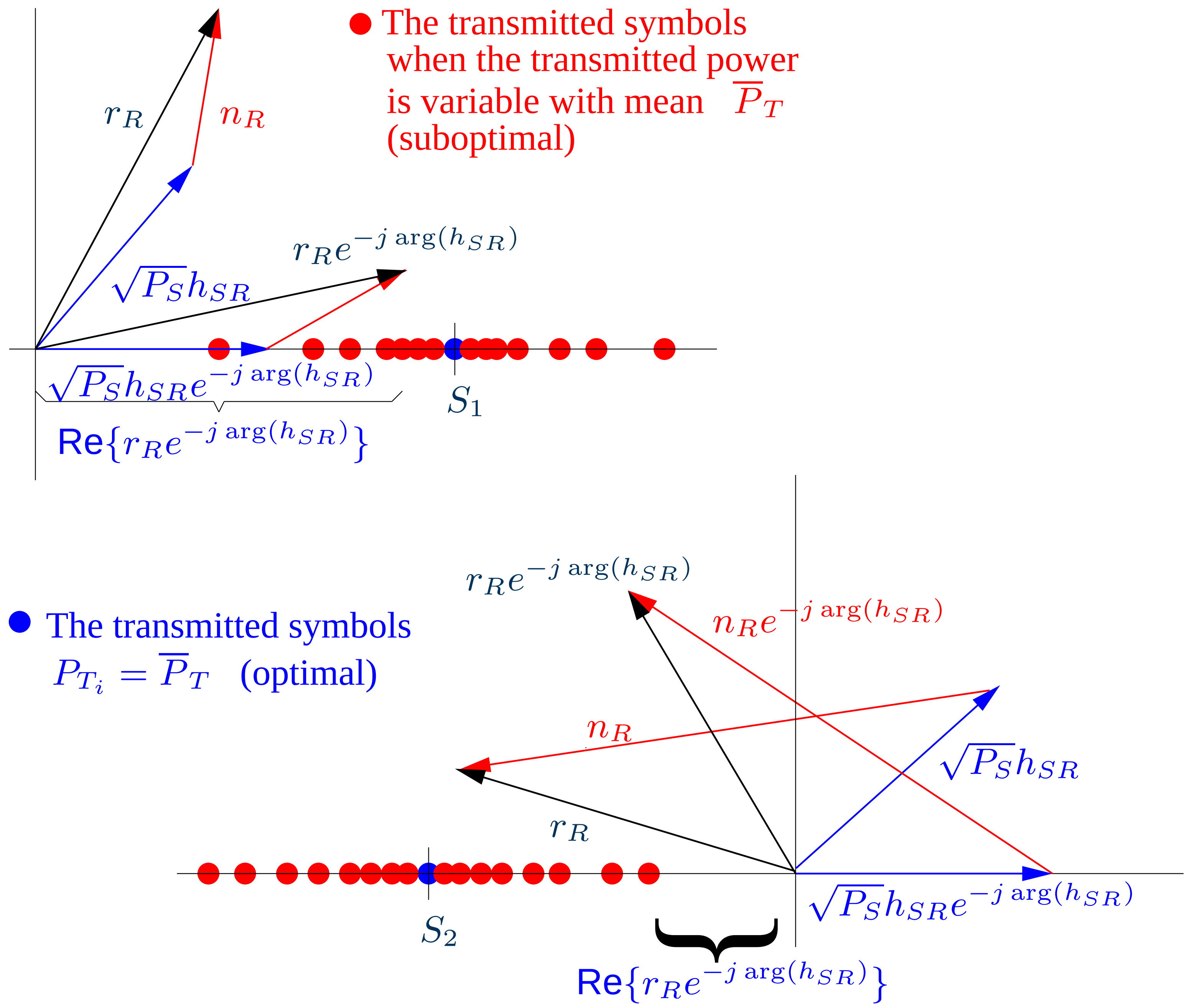
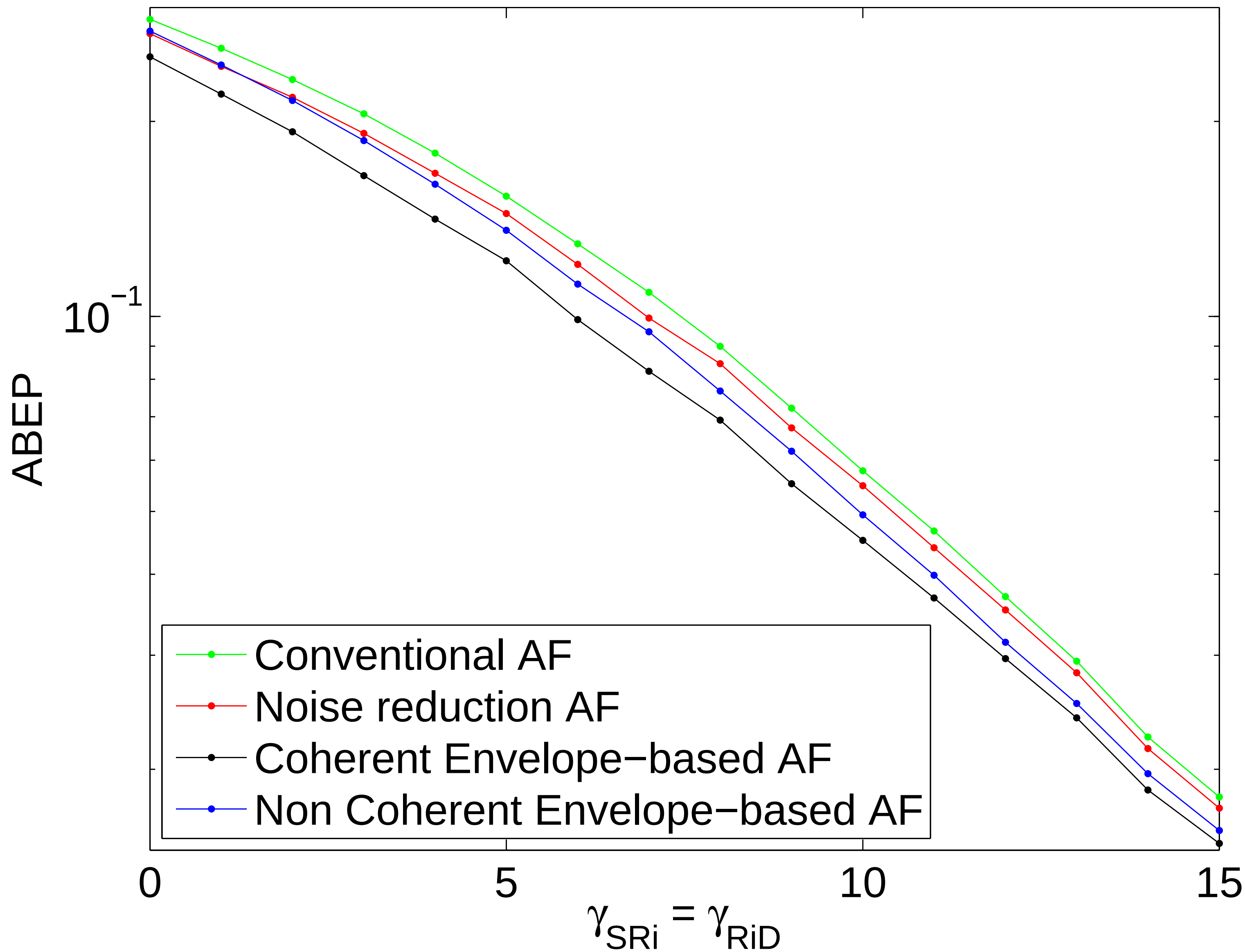
Envelope-Based Coherent AF Relaying

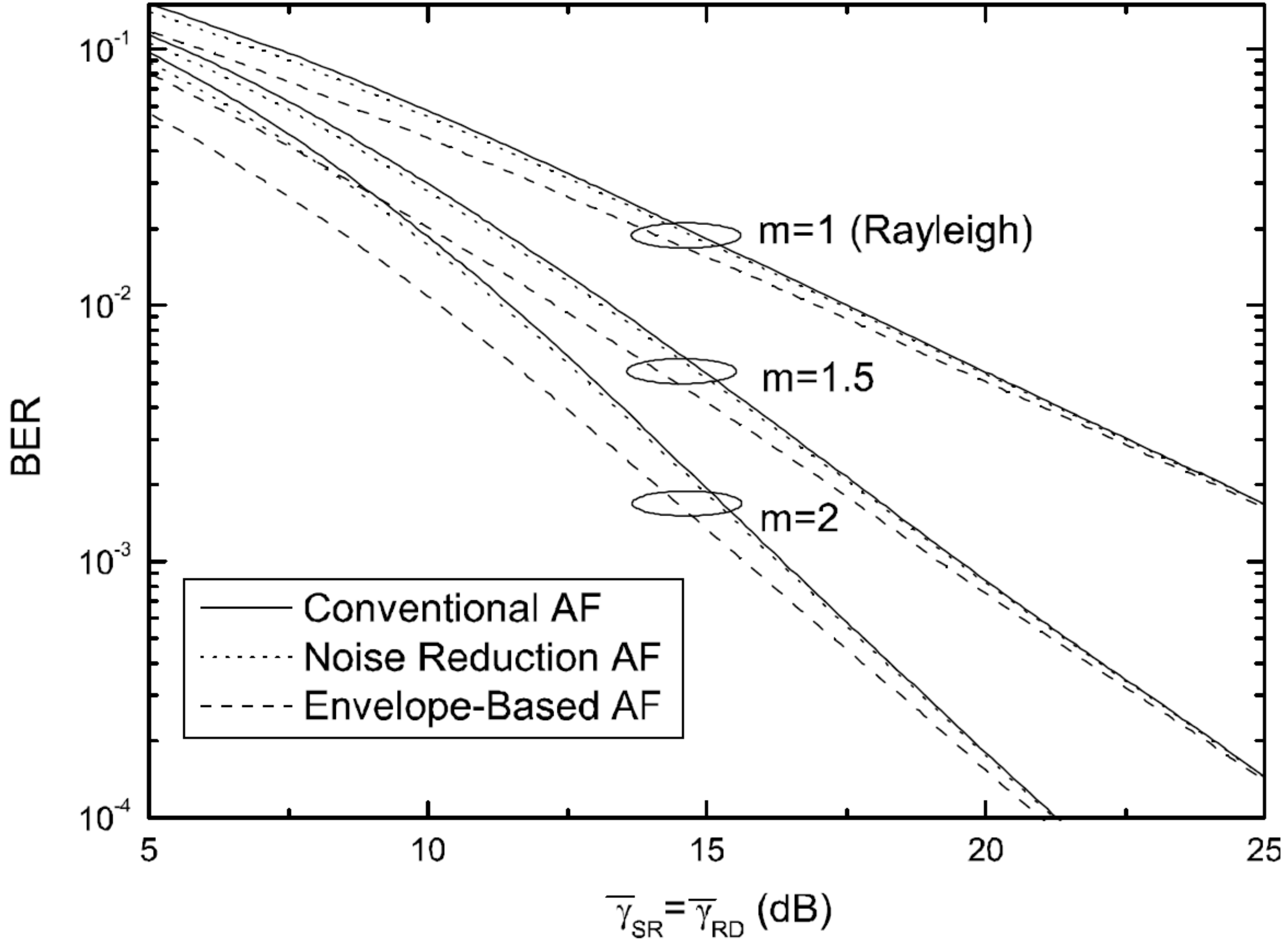


Numerical Results and Discussion



The average BER of envelope-based AF relaying compared with that of CSI-assisted relay gain and noise reduction relay gain, for BPSK modulation.

Numerical Results and Discussion



The average error rate of the envelope-based AF relaying versus average fading conditions, compared with that of the CSI-assisted relay gain and noise reduction relay gain, for BPSK modulation.

Conclusion

- An envelope-plus-noise-based relay gain for coherent AF relaying systems with BPSK and QPSK modulations optimizes the SER performance
- The proposed relay gain achieves exactly the same error performance as that of DF relaying for BPSK- and QPSK-modulated applications
- The relay gain does not require any channel amplitude estimation
- This model leads to a direct proof that DF relaying is always superior to AF relaying in a minimum SER sense
- Introducing the notions of coherent relaying and noncoherent relaying clarifies the comparison of AF relaying with DF relaying

Questions?

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2008 International Workshop on Advances in Communications

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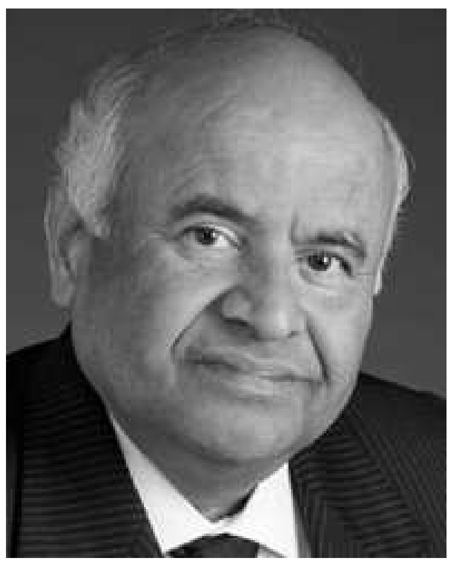

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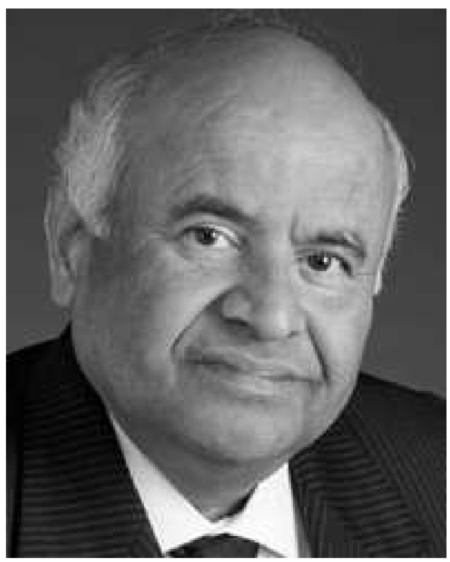

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Preface

Welcome to the 2008 International Workshop on Advances In Communication. This workshop was organized to honour Professor Vijay Bhargava on the occasion of his 60th birthday. For those of us that know Vijay, it is hard to believe he is turning 60, as his energy and travelling schedule have not diminished over the years. Here is the story thus far.

Vijay Bhargava was born in Beawar, India on 22 September 1948. He came to Canada in 1966 and received his B.Sc., M.Sc. and Ph.D degrees from Queen's University, Kingston, Ontario in 1970, 1972 and 1974, respectively. During the summer breaks of his undergraduate years he worked with Falconbridge Nickel Mines in Sudbury, Ontario for a total of 60 weeks at 4000 feet below ground. While at Queen's he met Jack Stein, Gerald Seguin, Ian Blake, Jennifer Seberry, Robert Matyas and Alan Winter. They played an important role in the development of his career. His first Stanley Cup playoff in Canada was in 1967 and the winner was the Toronto Maple Leafs.

Vijay started his academic career at the Indian Institute of Science, Bangalore in 1974 but returned to Canada in October 1975. After a brief stint as a Security Guard in Toronto, he joined the University of Waterloo as a Post-Doctoral Fellow under the supervision of Professors Ian Blake and Jon Mark. In September 1976, he joined Concordia University in Montreal as an Assistant Professor. He was promoted to Associate Professor in 1979 and to Full Professor in 1984. He met his wife Yolande Henri of Warwick, Quebec in September 1976 and their first date was a hockey game between the Philadelphia Flyers and the Montreal Canadiens. Their children Alexandre and Maude were born in Montreal. In 1981 the book *Digital Communications by Satellite* (co-authored with David Haccoun, Robert Matyas and Peter Nuspl) was published by Wiley. It has since been translated into Japanese and Chinese. During 1982-1983 he spent a sabbatical year at École Polytechnique de Montréal funded by the Augustin Frigon fund. The visit was hosted by David Haccoun. In September 1983 he organized (with Ian Blake and L. Lorne Campbell, who had taught him calculus) the IEEE International Symposium on Information Theory in St. Jovite. In 1979 he met Han Vinck with whom he has had a long association. His first M.Eng student was Micha Avni (now Vice President of Mobixell in Israel) and his first Ph.D. student was Mujibul Hayat Khan (now Vice President of Samsung America). He met Tho Le-Ngoc in 1977. Together (along with Yusuf Shayan), they developed a programmable Reed-Solomon CODEC in 1990 using 1.3 micron gate array technology.

In 1984, at the invitation of Andreas Antoniou, the founding Head of the ECE Department, Vijay joined the University of Victoria, and served as the founding Graduate Advisor and had a productive career for the next 19 years supervising a large number of graduate students. The same year he met Zeljko Blazek and T. Aaron Gulliver with whom he has had a long association. His first M.Eng. student at UVic was David Gregson (now senior Manager at Questar Tangent in Victoria), who was one of the first to demonstrate the implementation of a Reed-Solomon CODEC using commodity based components at a cost of less then twenty dollars. His first Ph.D. students were Qiang Wang and T. Aaron Gulliver. In 1985 Norm Beaulieu introduced him to Pete McConnell of MDI Inc., from whom he learned much about mobile data communications. Since 1984, continuing for well over a decade, Alan Winter, through MPR Teletech, has supported his NSERC Strategic Projects and his British Columbia Advanced Systems Institute Fellowship. In 1987 he founded the IEEE Pacific Rim Conference on Communications, Computers and Signal Processing. One of the presenters at that conference was Steve Wicker with whom he co-edited the book *Reed-Solomon Codes and their Applications*, a 1994 IEEE Publication. Steve and Vijay organized special sessions in memory of Gus Solomon at the 1997 Pacific Rim Conference. In 1988 he founded the Canadian Conference on Electrical and Computer Engineering and used the surplus funds to nurture back to health the ailing Canadian Journal of Electrical and Computer Engineering, which is now available on IEEE Xplore.

In the mid nineties he met Ibrahim Gedeon (now CTO, TELUS), Vahid Tarokh (who was in the process of inventing Space-Time Codes), H. Vincent Poor and Khaled Ben Letaief (who along with Ross Murch have graciously hosted Vijay for sabbaticals at the Hong Kong University of Science and Technology). With Vahid Tarokh and H. Vincent Poor, Vijay organized BlakeFest in 2001 and edited a book in Ian's honour entitled, *Communications, Information and Security*, a 2003 Springer publication. In 1994, concerned with the state of wireless communications research in India, he launched the IEEE International Conference on Personal Wireless Communications (ICPWC). At the 1996 conference in Mumbai, Vijay met Ekram Hossain of the Bangala Desh University of Engineering and Technology. They co-edited the book, *Cognitive Wireless Communications and Networks*, a 2007 Springer publication. His collaborations with Ekram and Dong In Kim of South Korea, and with Annamalai Annamalai, Jr. and Chintha Tellambura, have resulted in a large number of interesting papers in wireless communications. He has published extensively with T. Aaron Gulliver, Qiang Wang, Anwarul Hasan, Hlaing Minn, Ivan Fair, Charlie Yang, Gang Li, Jialin Zou and with almost 70 of his graduate students. A popular teacher, Vijay was voted Professor of the Year by the graduating class of 2000, and in 2002 received the IEEE Graduate Teaching Award.

During 1994, Vijay was a Visiting Researcher at the NTT Wireless Research Lab, hosted by Shuzo Kato. Since then, he has been a frequent visitor to Japan travelling from Shakotan Hanto in Hokkaido to Nagasaki in Kyushu. He has visited places collectively known as Nihon Sankey and Dewa Sanjam and several places mentioned in the 17th century classic *Oku No Hosomichi* by Matsuo Basho.

Over the years, Vijay and his students have had the pleasure of hosting many visitors to their research lab including Angel Bravo, Hiroyuki Yashima, Fortunato Santucci, Dong In Kim, M.-Slim Alouini, Yukitoshi Sanada, Shuzo Kato, Kazuhiko Seki, Hisashi Kobayashi, Han Vinck, Hideki Imai, David Haccoun, Norm Beaulieu, Ramjee Prasad, Chengshan Xiao, Hamid Jafarkhani, Poramate Tarasak, Takahika Saba, V. Prasada Kodali, François Gagnon and Charles Despins.

In 2003, Vijay joined the University of British Columbia as Head of the Department of Electrical and Computer Engineering for a five year term, to lead its expansion under a provincial initiative known as Double The Opportunity (DTO). During his tenure, a new building was constructed (and the existing one renovated), 20 new faculty were hired, student numbers doubled and options were developed in Biomedical Engineering, Nanotechnology and Microsystems, and Electrical Energy Systems. In 2007, he succeeded Khaled Ben Letaief as Editor-in-Chief of the *IEEE Transactions on Wireless Communications*.

An active IEEE volunteer, Vijay served as President of the IEEE Information Theory Society in 2000 and was twice an IEEE Board nominated candidate for the office of IEEE President-Elect. As an IEEE Speaker, Vijay has lectured in seventy countries and has marveled at the ingenuity and culture of people in every country he has visited. He fancies himself a traveller along the lines of Xuan Zhang, Matsuo Basho and Paul Theroux.

Program

Session 1 Coding and Information Theory

Session 2 Communications I

Session 3 Communications II

Session 4 Cognitive and Cooperative Communications

Session 5 Coding

Session 6 Cognitive Radio

Tight Finite-blocklength Bounds in Channel Coding
H. Vincent Poor, Princeton University
(joint work with Yury Polyanskiy and Sergio Verdú)

With the advent of modern coding techniques that come very close to Shannon limits, the characterization of fundamental limits of communication has become increasingly meaningful in applications. Traditionally, information theoretic analyses of limits on communication rates have focused primarily on the asymptotic regime, in which the channel capacity characterizes maximal signaling rates. However, in many modern applications, delay is a critical factor, and hence finite blocklength analysis is necessary in such situations in order to understand the fundamental limits on practical systems. In particular, it is desirable to be able to analyze the effects of finite transmission time and small, but fixed, probability of error on the maximum achievable rate. This talk will discuss the best known upper and lower bounds, both classical and new, on channel coding rate in the finite blocklength regime. These bounds will enable the approximation of the finite blocklength behavior of the coding rate using a two-parameter expression: one parameter is the classical Shannon capacity, and the other is the channel dispersion. Closed form expressions for these parameters are given for the discrete memoryless channel and the additive white Gaussian noise channel, and numerical results are provided to illustrate the efficacy of this characterization in the finite blocklength regime.

Capacity Bounds and Signaling Schemes for Bi-Directional Coded Cooperation Protocols
Vahid Tarokh, Harvard University

In coded bi-directional cooperation, two nodes wish to exchange messages over a shared two way half-duplex channel with the help of a relay. We consider 3 main protocols of interest:

1. The first protocol is a two phase protocol where both users simultaneously transmit during the first phase and the relay alone transmits during the second.

2. The second protocol (3 phase protocol) considers sequential transmissions from the two users followed by a transmission from the relay. This protocol was independently proposed by Larsson, Johansson and Sunnel at Ericsson and Wu, Chou and Kung at Microsoft Research. This is a special case of Network Coding.

3. The third protocol (our proposal) is based on a hybrid of the first two protocols and has four phases.

We also consider the possibilities that the relay may forward information in one of four manners:

I) Amplify and Forward (AF),

II) Decode and Forward (DF) relaying schemes

III) Compress and Forward (CF), and

IV) Mixed Forward schemes.

An Information Theoretic Study of Stock Market Behavior
Charlie Yang, Charles Schwab Co.

Information theory involves the quantification of information. The central paradigm of classical information theory is the engineering problem of the transmission of information over a noisy channel. In my ongoing effort to understand stock market behavior, I view the fundamental problem of investing as the engineering problem of the buying and selling of investments over a volatile market. Here the information is the long term intrinsic value trend (primary trend) of the underlying investment, and short term market events have an effect similar to channel noise.

Correct determination of the primary trend is the most important factor in successful investing, similar to that of coding to achieve error free communications. The fundamental of a company does not change suddenly when its daily stock price is fluctuating as driven by market volatility. However, over a longer time period, a company's fundamental does change and thus its price moves accordingly. This presentation summarizes my technical analysis research in understanding primary trend extent and duration from an information theory view based on statistical analysis of market behavior.

Simple Iterative Decoding Using Convolutional Doubly Orthogonal Codes
David Haccoun, École Polytechnique de Montréal

This paper presents a novel coding /iterative decoding technique using so-called Convolutional Doubly Orthogonal Codes. These codes may be decoded iteratively using the well known low complexity threshold decoding algorithm. Neither the encoding nor the decoding requires interleaving but the iterative decoding process requires second order orthogonal properties on the code generators in order to achieve independence between the observables during successive iterations.

Convolutional doubly-orthogonal codes (CDOCs) are a new class of convolutional self-orthogonal codes featuring the order-2 self-orthogonal properties which allow these codes to be decoded by a low complexity iterative threshold decoding algorithm. They could also be viewed as a class of low-density parity-check (LDPC) nonrecursive convolutional codes, and thus they are also well suited for an efficient iterative belief propagation (BP) decoding algorithm in a pipeline structure.

Capacity and Coding for Impulse Noise Channels
Han Vinck, University of Duisburg-Essen

On powerline channels, impulse noise is disturbing the communications. We discuss a specific model, introduced by Middleton and give some evaluations of channel capacity. We also discuss a simple detection scheme.

Near-optimal Receiver for Multiuser UWB Systems

Dong In Kim, Sungkyunkwan University

1 Introduction

Recently, ultra-wideband impulse radio (UWB-IR) technology has gained much attention due to the availability of low-cost and low-power wireless devices for indoor wireless communications, as well as location and ranging purpose, being standardized to the IEEE 802.15.4a. The UWB-IR systems considered time-hopping (TH) multiple access for supporting multiuser access, along with very narrow-width pulse transmission with low duty cycle. In this scenario, the authors have analyzed the multiuser performance by simply invoking the Gaussian approximation for the multiuser interference (MUI). But, recent contributions to the MUI analysis confirmed that the Gaussian approximation is not accurate enough to predict the multiuser performance. More recent contribution has further clarified this by showing that the impulsive nature of UWB-IR signals is not well mitigated for relatively large number of users.

The above observation has motivated an optimal receiver design for multiuser UWB-IR systems, one hand modeling the MUI as a Laplace distribution and a *generalized* Gaussian distribution, the other hand modeling it to be a Gaussian *mixture*, as a weighted sum of several Gaussian densities with unequal individual variances.

In this work, the MUI statistics seen at each finger are evaluated analytically, in terms of the second and fourth order moments, considering the channel *sparseness* and *cluster overlapping*. The sparseness of the UWB channel indicates that there could be no multipath arrival in a time bin, which largely affects the energy capture as well as the MUI across fingers at *partial*-Rake receiver. To design a practical near-optimal receiver for multiuser UWB-IR systems, generalized Gaussian (GG) distribution is adopted, thereby the second and fourth order moments drived under realistic UWB channels can be used to effectively model the MUI statistics.

2 Near-Optimal Receiver

First, it is noted that the MUI is caused by any possible collisions with other user pulses, thereby exhibiting the nature of impulsive noise, which necessitates nonlinear processing to properly deal with occasional undue increases in the MUI across both frames (j) and (l) fingers. This is in contrast to conventional linear processing to mitigate the MUI by virtue of averaging over frames and fingers with linear weights. In determining a proper form of nonlinear processing, it is prerequisite to characterize the MUI statistics that are modeled as *non-Gaussian* distribution.

To characterize the MUI statistics as impulsive noise (i.e., non-Gaussian), this work attempts to invoke the *generalized* Gaussian (GG) distribution and theoretically estimate a GG parameter (ν) by directly evaluating the second and fourth order moments of the MUI below. The following propositions are useful in evaluating the MUI statistics for realistic UWB channels with *sparseness* and *cluster overlapping*.

Proposition 1: The second order moment or variance of the MUI $I_{l,j}$ can be evaluated as

$$\sigma_l^2 = \mathbf{E}\{I_{l,j}^2\} = \sum_{k=2}^{K} \left(\frac{E_k}{E_1}\right)\left(\frac{2\kappa}{N_f}\right) \tag{1}$$

where E_k is the symbol energy of user k, $\kappa = \mathbf{E}_\epsilon\{R_w^2(\epsilon)\}$ for the chip pulse correlation function $R_w(\epsilon)$ and time-offset ϵ, uniformly distributed over $[0, T_c)$ and $N_f = T_f/T_c =$ frame time/chip time.

Proposition 2: The fourth order moment of the MUI $I_{l,j}$ can be evaluated as

$$\begin{aligned}\mathbf{E}\{I_{l,j}^4\} = &\sum_{k=2}^{K}\left(\frac{E_k}{E_1}\right)^2\Bigg[\left(\frac{2\varphi}{N_f}\right)\sum_{n=0}^{L-1}\mathbf{E}\Big\{a_n^{(k)4}\Big\} \\ &+\left(\frac{6\rho}{N_f}\right)\sum_{n=1}^{L-1}\mathbf{E}\Big\{a_n^{(k)2}\Big\}\mathbf{E}\Big\{a_{n-1}^{(k)\;2}\Big\}\Bigg] \\ &+6\sum_{k=2}^{K-1}\sum_{k'=k+1}^{K}\left(\frac{E_k}{E_1}\right)\left(\frac{E_{k'}}{E_1}\right)\left(\frac{2\kappa}{N_f}\right)^2 \end{aligned} \tag{2}$$

where $\varphi = \mathbf{E}_\epsilon\{R_w^4(\epsilon)\}$ and $\rho = \mathbf{E}_\epsilon\{R_w^2(\epsilon)R_w^2(T_c-\epsilon)\} \cong 0$.

To find $\mathbf{E}\{I_{l,j}^4\}$ in *closed-form*, the second and fourth order moments of the channel gains $\{a_n^{(k)}\}$ should be evaluated, considering a realistic, standard UWB channel with lognormal channel gain distribution and double independent Poisson arrival distribution of cluster and ray.

Proposition 3: The second order moment of the composite channel gain $a_n^{(k)}$ can be evaluated as

$$\mathbf{E}\Big\{a_n^{(k)2}\Big\} = \begin{cases} \Omega_0, & \text{for } n=0 \\ \Omega_0 P_c \exp\left[-\dfrac{nT_c}{\Gamma}\right] + \Omega_0 P_r \exp\left[-\dfrac{nT_c}{\gamma}\right] & \\ +\,\Omega_0 P_c P_r \dfrac{\eta^2(1-\eta^{n-1})}{1-\eta} & \\ \times \exp\left[-\dfrac{(n+1)T_c}{\gamma} + \dfrac{T_c}{\Gamma}\right], & \text{for } n \geq 1 \end{cases} \tag{3}$$

where $P_c = \Lambda T_c$ and $P_r = \lambda T_c$ (Λ and λ denote the cluster and ray arrival rates, respectively), Γ and γ denote their power decay factors, and $\eta = \exp\left(\frac{T_c}{\gamma} - \frac{T_c}{\Gamma}\right)$. Also, by defining $\bar{E}_c \triangleq \sum_{n=0}^{L-1}\mathbf{E}\Big\{a_n^{(k)2}\Big\}$, the mean power of the first ray of the first cluster Ω_0 can be theoretically determined as

$$\Omega_0 = \frac{1}{\bar{E}_0} \triangleq \frac{1}{\bar{E}_c|_{\Omega_0=1}} \tag{4}$$

so as to make $\bar{E}_c = 1$ (normalized).

Proposition 4: The fourth order moment of the composite channel gain $a_n^{(k)}$ can be evaluated as

$$\begin{aligned}\mathbf{E}\Big\{a_n^{(k)4}\Big\} = &\sum_{q=0}^{n}\Omega_0^2 P_q^{(n)}\exp\left[-\frac{2qT_c}{\Gamma}\right] \\ &\times\exp\left[-\frac{2(n-q)T_c}{\gamma}\right]\exp\left[\frac{\sigma^2}{\xi^2}\right] \\ &+6\sum_{q=0}^{n-1}\sum_{j=q+1}^{n}\Omega_0^2 P_q^{(n)}P_j^{(n)}\exp\left[-\frac{(q+j)T_c}{\Gamma}\right] \\ &\times\exp\left[-\frac{(2n-q-j)T_c}{\gamma}\right] \end{aligned} \tag{5}$$

where σ^2 is the variance of the lognormal channel gain, $\xi = 10/\ln 10$, and the probability that qth ($q = 0, 1, \ldots, n$) time bin has a MPC (either ray or cluster) contribution to nth ($n \geq 1$) time bin $[nT_c, (n+1)T_c)$, denoted by $P_q^{(n)}$, can be calculated in three cases:

$$P_q^{(n)} = \begin{cases} P_r, & q = 0 \\ P_c \cdot P_r, & 1 \leq q \leq n-1 \\ P_c, & q = n \end{cases}$$

with $P_q^{(n)} = 1$ for $q = n = 0$.

3 Results

For near-optimal receiver, the non-Gaussian nature of the MUI can be identified in Fig. 1 which shows the GG parameter ν as a function of the number of taps L_p at *partial*-Rake. Here, $\nu = 2$ corresponds to the standard Gaussian distribution of the MUI, initially invoked for analysis of UWB systems. It is to be noted that the MUI statistics associated with near-optimal receiver do not depend on the number of taps L_p. As expected, ν increases with the number of users K, but it should be noted that *the non-Gaussian nature of the MUI persists even for relatively large* $K = 30$.

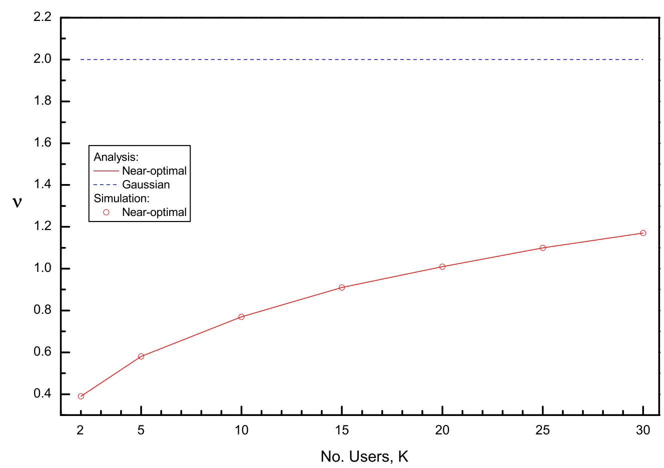

Figure 1: *Generalized* Gaussian (GG) parameter ν versus K when $N_s = 8$, assuming the *partial*-Rake with $L_p = 10, 30, 200$ taps.

Meanwhile, the performance improvement offered by near-optimal receiver is illustrated in Fig. 2 when the number of frames per symbol is $N_s = 8$. The performance improvement by the near-optimal receiver over classical MRC is shown to be significant for the range of $K = 2$ to 10, which is typical in indoor UWB communications.

4 Conclusions

A near-optimal receiver has been realized for UWB-IR systems by inserting nonlinear processing befor MRC in each frame, where the *generalized* Gaussian modeling of the MUI was shown to be effective in deriving an order of such nonlinear processing, depending only on the second and fourth order moments. The order of nonlinear processing, namely the GG parameter ν was determined analytically for the assumed UWB channels, which reveals that the non-Gaussian nature of the MUI still exists for relatively large $K = 30$. From the BER analysis, it was observed that the diversity gain against MUI increases as the number of frames per symbol increases, as anticipated, but it decreases as K increases.

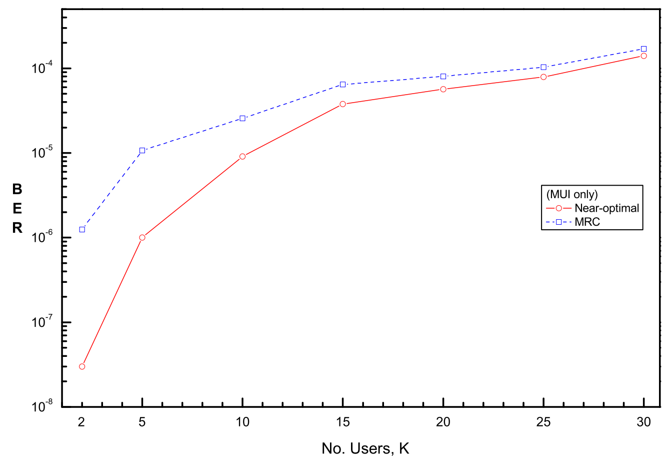

Figure 2: *Channel-averaged* BER versus K when $N_s = 8$ and the MUI only exists, assuming the *partial*-Rake with $L_p = 10$ taps.

Channel Equalization and Symbol Detection for Single Carrier Broadband MIMO Systems with Multiple Carrier Frequency Offsets

Chengshan Xiao, Missouri University of Science and Technology
(joint work with Yahong Rosa Zheng)

We consider the frequency-domain channel equalization and symbol detection of multiple input multiple output (MIMO) single-carrier broadband wireless system in the presence of severe frequency-selective channel fading and multiple unknown carrier frequency offsets (CFOs). We show that the constellation of the equalized data is rotating due to multiple CFOs, therefore, the equalized data can not be reliably detected without removing the rotating phases caused by the multiple unknown CFOs. Instead of estimating the CFOs, we propose a method to estimate the rotating phases caused by multiple CFOs, remove the rotating phases from the equalized data, and perform symbol detection. Numerical example indicates that the proposed method provide very good results for a 4 x 2 wireless system with 8PSK modulation and 75-tap Rayleigh fading channels. This algorithm has been applied to underwater acoustic communications with successful undersea experiments.

Cyclic/Phase Shifting for Active Interference Cancellation on Multiband OFDM UWB Transmission

Poramate Tarasak, Institute for Infocomm Research, Singapore

Ultrawideband (UWB) communication is a spectrum underlay communication system in which a UWB device is expected to endure interference from other primary-user devices while it is not allowed to cause interference to them. In this talk, an interference avoidance technique so-called active interference cancellation (AIC) will be explored for multiband OFDM UWB transmission. Few enhancement techniques using cyclic/phase shifting and their corresponding reduced complexity schemes will be discussed.

Multireception Systems in Mobile Environments

Angel Bravo, Universidad Carlos III de Madrid

This presentation is about Dr. Carlos Rodriguez Casals's Ph. D. Thesis, directed by Vijay in Spain. One of the problems studied in this thesis is the influence of a new user entering a CDMA system. A receiver structure was proposed for the estimation of the transmission delay of a new user entering the system. A de-noising technique based on Wavelet transforms was studied for this application. The author of this presentation was a visiting researcher with Vijay in Victoria and had the opportunity of knowing what a great person Vijay is. Some anecdotes about Vijay's trip to Spain will also be remembered.

On the Roots of Wireless Communications

Andreas Antoniou, University of Victoria

1 The Discoverers

Faraday started his professional life as a bookbinder's apprentice in central London. He acquired his early education by reading the books he had to bind as part of his employment and kept reading for the rest of his life. His formal education was minimal, less than five or six years. His break in life came about when a very famous chemist of the 1800s by the name of Humphry Davy appointed him as his assistant. Faraday had very little knowledge of mathematics but as Davy's assistant he became the consummate experimentalist in due course. In 1821, he demonstrated that a relationship exists between electric current and magnetism, namely, *Faraday's law*. Later on, in 1831, he discovered that a changing current in a coil of wire would induce a current in a nearby coil [1].

A few years later a young mathematics graduate from Cambridge University by the name of Thomson who was to become Lord Kelvin in later years read one of Faraday's papers entitled *Experimental Researches in Electricity* published in 1832 by the Royal Society of London and was surprised to find no equations in it. Around 1845, he was able to apply certain equations that had been used for heat conduction earlier to quantify the properties of Faraday's hypothetical lines of force around an electrically charged object. In due course, he was to discover the *electron*.

The work of Thomson was continued by Maxwell who was another young mathematics graduate from Cambridge University and who was also acquainted with Faraday both personally and professionally. Before too long, he extended the mathematical formulation of Thomson on Faraday's hypothetical magnetic lines of force and in 1855 and 1856 he delivered a two-part paper to the Cambridge Philosophical Society on his results. He showed that a few relatively simple equations, *Maxwell's equations*, can fully quantify the behaviour of electric and magnetic fields and their interactions. In 1862, he showed that the speed of propagation of an electromagnetic field is approximately the same as that of the speed of light and predicted that a relation must exist between light on the one hand and electric and magnetic phenomena on the other.

The work of Maxwell on the relationship between light and electromagnetic fields was continued by Hertz who received a PhD degree in physics from the University of Berlin in 1880 having studied under the supervision of Gustav Kirchhoff. In 1885, at the age of 28, Hertz was appointed professor of physics at the Karlsruhe University. In 1887, Hertz demonstrated by experiment that electricity can be transmitted by electromagnetic waves *which travel at the speed of light* and which possess many of the properties of light, e.g., reflection and refraction, thus verifying Maxwell's equations. His experimental set-up comprised a *transmitter* made from an induction coil, two large metal spheres which served as a capacitor, and a spark-gap mechanism as illustrated in Fig. 1. He also constructed a *receiver* using a loop of copper wire and a spark-gap mechanism similar to that of the transmitter. By selecting the sizes of the spheres and adjusting the distance between them and the widths of the two spark gaps, Hertz was able to *tune* the transmitter and receiver so as to obtain an observable spark at the receiver. It helped, of course, to perform the experiment in a dark room and also use a magnifying glass to observe the fleeting spark!

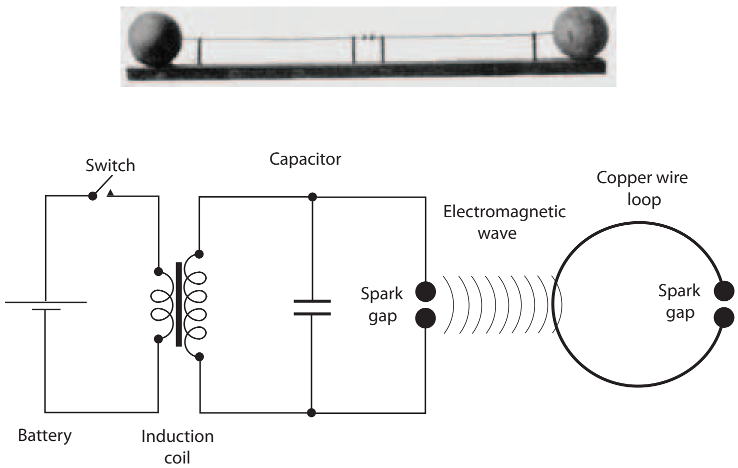

Fig. 1 Early wireless transmitter.

Hertz's students were impressed and asked what this marvelous phenomenon might be used for. "This is just an experiment that proves that Maxwell was right, we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there." "So, what next?" asked one of his students. Hertz shrugged. A modest man of no pretensions and, apparently, little ambition, he replied: "Nothing, I guess." [2].

2 The Innovators

With the verification of Maxwell's equations by Hertz, another group of illustrious innovators appeared on the scene determined to exploit the newfound knowledge. There were many such individuals but three of them, namely, Tesla (1856-1943), Marconi (1874-1937), and Fessenden (1866-1932) left a substantial legacy.

Tesla was a Serbian who emigrated to the US early in 1884 at the age of 28. He dedicated his life to the generation, transmission, and utilization of electrical energy. He invented single-phase and multi-phase alternators and induction motors. We use AC current today only because his AC current system won out over Edison's DC current system [3]. In 1881, he invented the *Tesla coil* which he used to generate spectacular sparks for the amazement of everybody and which was to be used soon after as a crucial component in many of the early wireless transmitters. The quest of his life was to transmit electrical energy, huge amounts, over wireless systems. In this respect, he filed a patent for a wireless system for the transmission of electrical energy on September 2, 1897, which was eventually granted by the US Patent Office in 1900 (see [4]). The system consisted of a transmitter and a receiver. The transmitter consisted of a bandpass filter (in today's language) tuned to a certain frequency followed by a step-up transformer whose secondary winding was connected between an antenna and the ground. Similarly, the receiver consisted of a step-down transformer whose primary winding was connected between an antenna and the ground followed by a bandpass filter tuned to the same frequency as the filter in the transmitter.

Inspired by the work of Hertz, Marconi began experimenting with spark transmitters in the attic of the family home in Pontecchio near Venice while still a teenager. He explored ingenious ways that would increase the distance over which effective transmission could be achieved. Soon he was able to transmit signals over an impressive distance of about 1.5 km. At the age of 21, Marconi traveled to London with his wireless system determined to make his fortune. While in London, he gained the attention of a certain William Preece, Chief Electrical Engineer of the British Post Office (now British Telecom). In a landmark presentation on December 2, 1896, Preece demonstrated Marconi's invention. When a lever was operated at the transmitting box, a bell was caused to ring in the receiving box across the room. Through a series of demonstrations, Marconi transmitted signals of Morse code over a distance of 6 km and after that over a distance of 16 km. In due course, he was able to send Morse signals over the Atlantic. Marconi was a smart system designer and a clever entrepreneur who would readily adopt and modify ideas reported by his peers. As time went by, he developed better and better wireless communication systems which established wireless telegraphy as a viable commercial enterprize during the early 1900s [5].

Fessenden was born in 1866 in East Bolton, Quebec. Not too long after completing his formal education in Canada, he moved to New York to solicit and eventually obtain employment in Edison's facilities. In 1886 he attracted the attention of Edison himself who appointed him as his assistant. In this capacity, Fessenden honed his skills as an inventor. He began to work with spark-gap transmitters and receivers. A key component in those transmitters was the coherer which on most accounts was a rather temperamental device. In Fessenden's words, *the coherer was a misfortune that retarded the development of practical receivers*. The coherer was essentially a two-state device that offered reduced resistance in the presence of an electromagnetic wave. To circumvent the problems associated with coherers, he experimented with novel two-state devices he called *barreters*. One of these devices used an extremely thin and short piece of platinum wire and its operation was based on changes in its resistance caused by the heating effect. While experimenting with various barreter designs of this type, Fessenden discovered by accident the *electrolytic barreter* which was essentially a rectifying device. In later years, he abandoned the spark-gap transmitter in favour of a continuous wave transmission system much like the one proposed by Tesla in 1897. In due course, he patented the heterodyne principle some ten years before it could be implemented [6].

Then came vacuum tubes, transistors, and integrated circuits and each technology, in its turn, revolutionized the state-of-the art of wireless communications.

Coding of messages has been used from the beginning of civilization by kings and emperors to send secret messages to their administrators, and it did not take too long before it found widespread applications in wireless communications systems. An important contributor to coding theory and practice is Vijay Bhargava who is well-known for his Reed-Solomon codec, many other inventions, and numerous publications. Vijay received his doctorate from Queen's University, Kingston, Ontario, in 1974. He taught at Concordia University and the University of Victoria, and more recently served as Head, Department of Electrical and Computer Engineering, University of British Columbia. At the University of Victoria, he served as the first Graduate Advisor of the Department of Electrical and Computer Engineering and in this capacity he established a graduate program that is second to none. He won many awards including the 2007 IEEE Canada R. A. Fessenden Silver Medal for outstanding contributions to research and education in wireless communications.

Further details about the wireless systems developed by Tesla, Marconi, and Fessenden will be presented at VijayFest. A copy of the slide presentation can be downloaded from [7].

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An Improved Ranging Method in OFDMA Systems

Hlaing Minn, University of Texas at Dallas
(joint work with Jianqiang Zeng)

To avoid or suppress multiuser interferences and to maintain reliable uplink multiuser communications, orthogonal frequency division multiple access (OFDMA) systems require proper timing and power control among uplink users. The existing/emerging OFDMA systems such as the IEEE wireless metropolitan area networks standards 802.16a/e [1] [2] necessitate a ranging process to address these uplink synchronization and power control issues. A ranging process consists of two procedures - initial ranging and periodic ranging. Initial ranging allows a subscriber station (SS) to perform time and power synchronization with respect to the base station (BS) during the initial network entry. Periodic ranging allows the SS to adjust transmission parameters periodically to maintain reliable UL communications with BS. In this work, we consider the initial ranging process.

There are several existing works on initial ranging process of OFDMA systems in the literature [3].[7]. The ranging methods proposed in [3] and [4] use the ranging signal given in IEEE 802.16-2004 where the randomly chosen ranging codes are transmitted on the same ranging channel. Their common disadvantage is the high computational complexity and sensitivity to channel frequency-selectivity. The ranging method in [5] achieves low-complexity ranging signal detection by means of a ranging signal design. However, its iterative timing estimator requires high complexity. Recently [6] develops an efficient low complexity ranging detector, and timing and power estimators by means of a ranging signal design. Most recently, [7] proposes an improved ranging scheme using the principles of the minimum description length and the multiple signal classification together with the ranging signals similar to [5]. It requires the received signal to have at least one unoccupied ranging opportunity. Its performance advantage is achieved at the cost of higher complexity, larger overhead, and smaller number of ranging users it can support.

In this work, we present an improved ranging method which provides better performance with low complexity and low overhead for a large number of ranging users. The proposed method aims at slow-varying channels, and utilizes the downlink signaling, which exists in all OFDMA systems, to gain multiuser diversity in the ranging process. Simulation results corroborate that the proposed method provides better performance with lower complexity than the existing methods.

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MIMO Systems and Practical Antenna Considerations
Ross Murch, Hong Kong University of Science and Technology

An enormous amount of research and development has been performed on MIMO wireless communications systems over the last decade. However the full impact of MIMO antenna effects on the performance of these systems has not been so widely researched. This talk provides an introduction to the practical antenna effects from a MIMO systems perspective. In particular we discuss the effects of mutual coupling on the MIMO system and analyse the effect of the mutual coupling on capacity and also the power constraints. In addition we review the overall MIMO channel model that includes practical antenna effects. We also look at the number of degrees of freedom that MIMO antennas can have in a certain area and volume to give us a fundamental limit on the number of antennas we can have in a given area or volume. To highlight the practical antenna effects several examples of MIMO antenna are also introduced and simulation and experimental results are also provided.

Network Beamforming
Hamid Jafarkhani, University of California, Irvine

This talk in on beamforming in wireless relay networks. First, we consider a case in which the receiver has perfect information of all channels and each relay knows its own channels. Instead of the commonly used total power constraint on relays and the transmitter, we use a more practical assumption that every node in the network has its own power constraint. A two-step amplify-and-forward protocol with beamforming is used, in which the transmitter and relays are allowed to adaptively adjust their transmit power and directions according to available channel information. The optimal beamforming problem is solved analytically. Then, we consider a more practical case in which the relays have partial channel information. In this case, the receiver broadcasts a limited number of feedback bits quantizing the channel information. We optimize the bit error rate (BER) performance of the system. Achievable bounds for different performance measures are derived.

Multi-user Detection for Ad-hoc Networks in Emergency and Tactical Scenarios

François Gagnon, École de technologie supérieure, Montréal
(joint work with Olfa Ben Sik Ali, Christian Cardinal, Jinfang Zhang, and Zbigniew Dziong)

High performance wireless emergency and tactical communications systems are somewhat different from wireless communications systems used on a daily basis. They are the keystone of interventions in emergency situations, in disaster recovery and in tactical settings. The design of such systems is thus different from commercial applications. In particular, the power consumption and size objectives which are usually primary concerns for personal mobile systems are not as important as range, bandwidth efficiency and reliability in this case. These differences are even more important when considering the thriving interest in the development of ad-hoc and sensor networks, where power consumption is paramount.

An issue that makes ad-hoc networking particularly interesting is that it is very resilient for changing and unstructured rapid deployment systems. Furthermore, multi-user detection is an appealing approach to significantly increase performance at the cost of added digital signal processing. Two results are presented that support this idea: 1) An analysis of the outage probability for ideal and approximate multiuser detection schemes, and 2) a novel receiver initiated multiple access control protocol to fully exploit the increased bandwidth usage.

The first result is based on the fact that, under the power decay law model for large scale fading with an exponent greater than 2, the sum of the interference at a receiver is of the same order as the strongest signal. This fact is used to develop an approximation, which is also a tight lower bound, for the outage probability. The analysis also shows the efficiency of partial and approximate cancellation schemes, which can be used to reduce complexity.

The second result uses multiuser detection (MUD) and multiple packet reception as a more appropriate model for the physical layer. To take advantage of the new features at the MAC level, a shift of responsibility from transmitters to receivers is suggested. We propose a novel receiver initiated multimedia access control (MAC) protocol and a distributed generic additive increase multiplicative decrease (GAIMD) fair scheduling scheme to configure efficient transmissions in ad hoc networks. These schemes are very simple to implement. Simulation results demonstrate that the throughput can be significantly improved when compared to a transmitter initiated scheme at the price of increased queuing delay of priority packets.

Advanced Sensing Systems and the Right to Privacy

Stephen Wicker, Cornell University

In this talk I will explore the privacy concerns arising from the use of sensing systems to collect data in public and residential contexts. I will focus on the collection of power consumption data for demand response systems, though the results of our work are readily generalized. I begin with a discussion of the .right to privacy. from both a philosophical and a legal perspective. This portion of the talk will depend heavily on recent Supreme Court decisions that appear to prohibit the use of advanced sensing technology, without a warrant, to collect data that would otherwise have been unavailable without intruding into the home. As we will see, this is a thin, blurry line at best. I will then discuss the advanced metering systems that have been deployed in California for use in Demand-Response systems. I will show that the data being collected in these systems can be used to derive detailed information about activities within the home. Privacy metrics will be introduced that detect and quantify personally identifiable information within sensed data. I conclude by showing that power consumption data falls within the Court's Kyllo precedent, and discuss the implications for the handling and re-use of power consumption data by utilities.

Global Games Approach for Decentralized Spectrum Access

Vikram Krishnamurthy, University of British Columbia

Given a large number of secondary users that can access a spectrum hole, we illustrate how the theory of multivariate global games can lead to a simple characterization of the Nash equilibrium. We formulate Bayes-Nash equilibrium conditions for which a simple threshold strategy is competitively optimal for each secondary user, and propose a scheme for decentralized threshold computation. We show that there is a remarkable phase transition in the behavior as the variance of the estimate reduces. In obtaining the characterization of the Bayesian Nash equilibrium, we extend recent results in univariate global games to the multivariate case.

Are Amplify-and-Forward Relaying and Decode-and-Forward Relaying the Same?

Norman Beaulieu, University of Alberta

A stochastic relay gain is proposed for amplify-and-forward relaying cooperative wireless networks. It is proved that the proposed gain always outperforms the conventional choices of relay gain. It is further proved that the proposed gain is optimal in the sense of minimizing the symbol error rate at the destination. Interestingly, the new scheme requires neither noise power information nor channel gain amplitude information. New insights into amplify-and-forward relaying and decode-and-forward relaying are obtained by classifying the relay's signal processing as coherent and noncoherent.

Cognitive Radio MAC: Practical Issues, Potential Approaches and Open Problems

Ekram Hossain, University of Manitoba
(joint work with Dusit Niyato)

In a cognitive radio network where transmissions from secondary users are controlled by a cognitive radio controller, spectrum sensing at the MAC layer of the cognitive controller can be optimized based on the queueing performances of the secondary users. Assuming that round-robin scheduling is used to allocate transmission time slots to secondary users and packets for different secondary users are buffered in separate queues, a queueing model is developed to analyze the queueing performances under dynamic spectrum access. This model can be used to optimize the spectrum sensing policy (i.e., sequence of sensing channels) at the cognitive radio controller from the perspective of queueing performance at the secondary users. Also, it can be used to analyze the impacts of imperfect channel sensing, primary user activity, and number of channels on the queueing performance of secondary users.

Reliability and Efficiency Analysis of Distributed Source Coding in Wireless Sensor Networks

Fortunato Santucci, University of L'Aquila
(joint work with C. Fischione, S. Tennina, L. Di Paolo, and F. Graziosi)

We offer a complete theoretical framework to evaluate reliability and energy consumption of distributed source coding (DSC) in wireless sensor networks (WSN) applications. Specifically, the amount of measurements that can be successfully decoded in tree-based WSNs employing DSC in the presence of different coding topologies and packet aggregation schemes (PA) is accurately characterized. The system model includes a realistic network architecture with multi-hop communication, automatic repeat request protocol (ARQ), packet losses due to channel impairments and collisions. Four DSC topologies and three alternatives of PA are considered. The analysis is carried out by first computing the packet loss probability; then the reliability is evaluated in terms of loss factor, and the efficiency in terms of average energy consumption of the network. The theoretical framework proposed in this paper is exploited to perform a numerical evaluation of loss factor and energy consumption for scenarios of practical interest.

A Generalized Decoding Problem

Qiang Wang, Maxit Technology Inc.

In the world of media, advertisement is the primary source of revenue. Such revenue increases as the match improves between the interests or profiles of consumers and intended purposes of advertised products. Nevertheless, neither consumer interest nor product purpose is precisely characterized. Namely, consumers do not necessarily know exactly what they want and product designers can not precisely predict what purposes their products will eventually serve. The match problem appears to resemble a decoding problem except it is generalized decoding as we are matching two "noisy" copies of codewords. In the multi-products to multi-consumers matching, the output is not unique (i.e. each consumer may be interested in multiple products and each product may serve multiple consumers), which generalizes the decoding problem further. This talk will discuss the detailed formulation of the problem and related issues. This research has recently started and no results have been obtained. The talk will hopefully invite comments and suggestions on this apparently new area of decoding.

Detecting Errors in Elliptic Curve Scalar Multiplication Units

Anwar Hasan, University of Waterloo
(joint work with A. Dominguez-Oviedo)

In cryptographic systems, faults can occur naturally and/or due to some malicious acts of an attacker. In the past, researchers showed how an attacker could exploit computational errors to break some popular cryptosystems. This has made the task of verification of the correctness of cryptographic computations quite important. In some applications, further robustness in term of the ability to continue performing correct computations in presence of certain faults is also sought.

In elliptic curve cryptography, a well known technique to detect errors in its group operation is to verify whether or not the operation output is a point on the curve. This point verification (PV) scheme has however been shown to be insufficient against certain types of fault based attacks. In this talk, error-detecting schemes for elliptic curve scalar multiplication (ECSM), which is fundamental to elliptic curve cryptosystems, are considered. We present structures based on re-computation and parallel computation along with PV. These structures use encoding techniques that rely on proprieties of elliptic curves and provide a high probability of error detection.

Synchronization-Correcting Codes: Challenges and Applications

Hugues Mercier, Harvard University

Synchronization problems are an integral part of technological systems operating in environments affected by uncertainties in timing, or time noise. These include data storage systems like magnetic and optical recording, semiconductor devices and integrated circuits, and synchronous digital communication networks. Time noise introduces insertions and deletions of symbols for the recipient, and as a result, systems corrupted by timing errors do not know their exact position when processing data. Synchronization and additive noise are more often than not treated as different problems and overcome using different techniques. This being said, both have the same effect on communication channels, i.e., reducing their capacity. Unfortunately, although it has early and often been conjectured that error-correcting codes capable of correcting timing errors could improve the overall performance of communication systems, they are quite challenging to design, which partly explains why a large collection of synchronization techniques not based on coding were developed and implemented over the years. Channels corrupted by synchronization errors have memory, hence the techniques developed for memoryless channels and additive noise can seldom be used. Another challenge is that the boundaries of the blocks might be unknown to the receiver, thus symbol and word synchronization must be considered in order to design coding schemes for practical systems. Furthermore, a single uncorrected synchronization error can have catastrophic consequences by causing a huge burst of substitution errors lasting until the systems are resynchronized. In this talk, we present a comprehensive survey of synchronization error-correcting codes, their potential applications, as well as the obstacles that need to be overcome before such codes can be used in practical systems. Our motivation for such an overview is threefold. Firstly, most comprehensive books on error-correcting codes do not even mention synchronization-correcting codes, and the very few who do only do so in passing. Our opinion that there was a need for a list of pointers to relevant references was somehow reinforced when we realized that several results recently published seemed unaware of overlapping work done as far as forty years ago. Secondly, although major theoretical advances were made, many fundamental questions remain unanswered. Finally, most of the early work on synchronization-correcting codes was of little interest to communication systems designers. However, modern communication systems require more and more stringent synchronization constraints. Using increasingly faster and cheaper hardware as well as smaller high-capacity data storage devices, improved coding schemes might be able to complement existing synchronization techniques.

A Queueing Analytic Model for Opportunistic Spectrum Access in Cognitive Radio Networks

Mamunur Rashid, University of British Columbia

Cognitive radio technology is built on an innovative radio design philosophy aimed to increase spectrum utilization by exploiting the unused spectrum in dynamically changing environments. Specifically, the cognitive radio technology will allow a group of potential users (referred to as secondary users) to opportunistically access available spectrum resources unused by primary users for whom the band has been licensed. In this work, we develop a queuing analytic framework to study important performance measures experienced by secondary users in a cognitive radio network given the primary users' usage pattern of the available spectrum. In order to allocate available channels among the secondary users, an opportunistic channel allocation scheme is considered. The proposed framework facilitates cross layer design for improved quality of service (QoS) experienced by cognitive radio users. We also demonstrate the usefulness of the analytical model in designing a model based admission controller to meet important QoS requirements.

Cooperative Spectrum Sensing for Cognitive Radio Networks
Praveen Kaligineedi, University of British Columbia

In this work, we investigate cooperative sensing schemes to identify primary signals in fading environment for cognitive radio (CR) networks. We consider a parallel fusion architecture in which all the sensing devices send their sensing information to an access point, which then applies a fusion rule to determine the presence of the primary signal. We consider two major challenges in parallel fusion cooperative sensing schemes. First challenge is to tackle malicious users which send false sensing data to the access point. Another important challenge is to design fast and efficient methods to combine the sensing information available at various sensing devices. We present techniques to identify malicious users and mitigate their harmful effect on the performance of the cooperative sensing system, assuming independent and identical fading at the sensing devices. Then, considering identical binary quantization at the sensing devices, we study the optimal quantization and data fusion scheme. We further investigate the performance gain that could be obtained by using identical multi-bit quantization at the sensing devices.

Link-Adaptation in OFDM-based Cognitive Radio Systems
Gaurav Bansal, University of British Columbia

In this talk, our objectives are threefold. First, we explore some of the research challenges involved in the design of link adaptation algorithms, i.e., power and bit loading algorithms, for OFDM-based cognitive radio (CR) system. In such a system, the secondary users (also referred to as CR users) are considered to co-exist with the primary users by filling the unused portions of the frequency band and using OFDM modulation at the air interface. Second, we provide some solutions to these challenging problems. More specifically, we present interference versus capacity performance of the existing power and bit loading algorithms when they are employed in an OFDM-based CR system. An optimal power and bit loading algorithm for such a scenario is devised by formulating the loading problem as a constrained optimization problem. As the complexity of the optimal scheme is high, we also present low-complexity sub-optimal schemes. Third, the effect of subcarriers' nulling on system performance is presented.

Power Allocation for Cognitive Radios Based on Primary User Activity in an OFDM System

Ziaul Hashmi, University of British Columbia

Efficient and reliable power allocation algorithm in Cognitive radio (CR) networks is a challenging problem. Traditional water-filling algorithm is inefficient for CR networks due to the interaction with primary users. In this paper, we consider reliability/availability of subcarriers or primary user activity for power allocation. We model this aspect mathematically with a risk-return model by defining a general rate loss function. We then propose optimal and suboptimal algorithms to allocate power under a fixed power budget for such a system with linear rate loss. These algorithms as we will see allocate more power to more reliable subcarriers in a water-filling fashion with different water levels. We compare the performance of these algorithms for our model with respect to water-filling solutions. Simulations show that suboptimal schemes perform closer to optimal scheme although they could be implemented with same complexity as water-filling algorithm. Finally, we discuss the linearity of loss function and guidelines to choose its coefficients by obtaining upper bounds on them.

Blind Multi-source Detection and Localization for Cognitive Radio

Anjana Punchihewage, University of British Columbia

In this work, we present a novel method to detect, identify and localize primary and secondary users. We use eigenspace analysis to determine the number of users, and their angle of arrival. We use modulation classification to classify detected users as primary or secondary users.

Efficient Broadcasting in Wireless Ad hoc Networks

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The common belief is that localized broadcast algorithms are not able to guarantee both full delivery and a good bound on the number of transmissions. In this work, we propose the first localized broadcast algorithm that guarantees full delivery and a constant approximation ratio to the minimum number of required transmissions in the worst case. The proposed broadcast algorithm is a self-pruning algorithm based on one round of information exchange. Using the proposed algorithm, each node determines its forwarding status in $O(D \log D)$, where D is the maximum node degree of the network. By extending the proposed algorithm, we show that localized broadcast algorithms can achieve both full delivery and a constant approximation ratio to the optimum solution with message complexity O(N), where N is the total number of nodes in the network and each message contains a constant number of bits. We also show how to save bandwidth by reducing the size of piggybacked information. Finally, we relax several system-model assumptions, or replace them with practical ones, in order to improve the practicality of the proposed broadcast algorithm.

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