NOTES FROM AIM WORKSHOP ON TIME REVERSAL COMMUNICATIONS IN RICHLY SCATTERING ENVIRONMENTS

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Contents

1 Monday October 18th, 2004

Morning Session

I. Discussion after Lecture of A. Paulraj

RC: For the ISI problem, rate-backoff is a huge price to pay. Is it possible to construct a multi-stage equalizer, which starts off with low complexity for low-rate transmission (large rate-backoff factor), and then gradually increases the complexity, hence brings up the transmission rate, until a specified complexity limit is reached?

FL: One simple solution is to use an adaptive LMS LE or DFE, where adding or removing taps can be done easily. The drawback is that the tap values need to be re-adjusted whenever the number of taps changes.

GP: Is there any equalizer which allows taps to be added without the need to re-adjust the existing taps?

AP: Lattice-type equalizers, which assume the channel remains unchanged as the number of taps increases or decreases. (They are not directly applicable as a multi-stage equalizer for the rate-backoff scenario, since the channel changes as the transmission rate changes, but could possibly be modified for this application.)

RC: Flexible precoding can eliminate the shaping loss, which is an advantage over THP. It was adopted into the ITU V.34 standard for telephone line modem.

II. Discussion after Lecture of M. Fink

Afternoon Session

I. Discussion after Lecture of R. Calderbank

RC: Although the maximum shaping gain is only 1.53 dB, it is still worth pursuing. This is because it is much harder to squeeze out the same gain from the already complex coding schemes.

II. Open Discussion

RH: Beside the ISI problem, what other new challenges HDB channels bring to communication theory?

TS: Will pre-equalization preserve SF?

MF: TR is good for one-to-one communications. The question is how to apply it and communicate with many users simultaneously. Should it be done in an ad-hoc sense to reduce interference?

HS: The basic principle of TR in a MISO system with M transmit antennas is captured in the expression

$$r(t) = s(t) \otimes \sum_{i=1}^{M} h_i(t) \otimes h_i(-t)^*,$$

where $r(t)$ is the received signal, $s(t)$ is the transmitted signal, $h_i(t)$ is the channel impulse response between transmit antenna i and the receive antenna, and $\otimes$ denotes convolution. Let $Q(t) = \sum_{i=1}^{M} h_i(t) \otimes h_i(-t)^*$. The ideal situation is to have $Q(t) = \delta(t)$, so there is no ISI. However, for TR, it is always true that $Q(t) \neq \delta(t)$. Using multiple transmit antennas can suppress significantly more ISI than using only one transmit antenna, thus make $Q(t)$ resemble $\delta(t)$ more.

- Other issues with equalization:

  1. Fractionally spaced equalizers

  JPF: Pulse shape selection

  2. Iterative techniques

- Channel effects:

  MF : In a cavity, there is some information loss because the Rx is inevitably at the null of some mode.

  GP: Channel taps are not always uncorrelated. Similarly, in the frequency domain, not all frequencies are uncorrelated.

- Ideas to try:

  - RC : TR-based algorithms. E.g., only doing phase conjugation. It appears to be a better power allocation scheme but we do not know how it performs in terms of SF.

- GP : Driving ideas:
  - AP : If processing in a cellphone is done in software, there is a lot of processing power left that can be used for iterative techniques.
  - ST : Watermarking applications
  - MF : Lithotripsy
  - GP : Non-destructive testing

2 Tuesday October 19th, 2004

Morning Session

I. Discussion after Lecture of L. Borcea

- Analogies between imaging and communications

MF : There is an analogy between the number of achievable focal spots and the number of eigen-channels in a MIMO system.

HS : When doing echo-mode TR, the signal from a signal Tx does not suffice because it is received with too much attenuation.

MF: Given a TR mirror and a number of objects, what is the optimal way to illuminate only one object? In other words, what is the optimal function to send?

Afternoon Session

I. Discussion after Lecture of H. Song

II. Open Discussion

MF: An application of iterative TR in medical imaging is locating kidney stones. A beacon is sent to the kidney, where the stones will reflect the signal, forming a radar map at the Tx.

GP : The imaging analysis using SVD has been applied to frequency independent scatterers. In reality, scatterers are frequency dependent and are illuminated differently.

GP : To evaluate the performance of an imaging algorithm, the criterion should be the quality of the image. What is the equivalence in communications?

GP: Why is beamforming not popular in current communication systems?

RC: First, channel estimates are difficult to obtain. Second, base stations will become expensive. (Hence, AT&T in the past prefers open loop systems to close loop systems.)

GP: What are the main problems in TR?

1. TR is SNR dependent. It is more suitable for low SNR environments.
2. The Tx needs to know the channel estimate, which is hard to obtain in practice.

- Some issues regarding channel knowledge:

1. The effect of inaccurate channel estimates is not well-studied in the literature.

RC : How long are channel estimates good for? In these cases other ideas that relate to scheduling (such as proportional fair) become pertinent.

2. Is a smooth transition from open loop systems to closed loop systems possible?

UM : We need to distinguish between reciprocity and statistical reciprocity in the two directions of the communications link.

UM : What is the value of having channel knowledge at both the Tx and Rx? And what happens in asymmetric scenarios where only one end of the communication link has CSI?

- Cellular scenarios

1. Interleaved transmission to multiple users can compensate for rate back-off.

RC : TR can exploit diversity in the case when there is a user-initiated hand-off.

RC : Control and data channels do not have the same amount of power or error correction capability, because, for example, the control channel has to be heard everywhere.

- Ideas to try:

GP : Beamforming to several users at a time.

1. In iterative TR, we see a trade-off between the signal power and the suppression of the spatial interference. How can we quantify this effect?

GP : Imaging ideas can be applied to wireless location-finding technologies. E.g., for locating survivors in 911-type disasters.

3 Wednesday October 20th, 2004

Morning Session

I. Discussion after Lecture of B. Hassibi

AP: Sphere decoders are becoming popular for MIMO systems, and occupy the largest part of a chip. Turbo codes get within 1 dB of capacity, and ML decoding is possible for up to 64 QAM.

ME: The decoding complexity is proportional to the length of a block.

GP: There are several problems in communications that can be addressed as integer problems. The question becomes what to do if we don't know the channel exactly. This is analogous to coherent vs. incoherent detection, like differential detection (assuming the channel doesn't change).

AP: If the Tx has CSI, we can apply DPC, THP combined with outer coding, or some other advanced technique. If not, we need to apply ML or sphere decoding at the Rx. The problem is that Rx processing is costly, especially since linear equalization is not as effective as nonlinear equalization. Moreover, FIR filters can only force zeros and not poles, which means we would ideally need IIR filters. Therefore, we should look at joint Tx and Rx processing.

AP: Assume we know the channel within a certain error. As the SNR increases, the performance levels off. The effect of imperfect channel knowledge at the Tx and Rx is different. This needs to be simulated or analyzed. Usually, CSI is obtained at the Tx with feedback, which introduces delays. The updating frequency is related to the coherence of the channel, e.g., in TDD vs. FDD systems.

BH: A system is more sensitive to imperfect CSI at the Tx.

AP: Another issue is power allocation. Ideally we shouldn't send power at those frequencies where the channel has notches.

II. Discussion after Lecture of R. Nabar

GP: Relays have the added advantage that the roles of source and destination are lost. The relays are assumed to learn the channel from the transmitters and to the receivers. If this is done via feedback, the overhead in HDB channels can be prohibitive.

AP: Multi-user diversity, such as SDMA, is emerging in HSDPA and 802.16 systems. When applied to TR, the idea is to select K users out of N users in a cell that have the most 'orthogonal' channels at any given time instant. The probability of low interference improves as the number of users increases. (The benefit of SF disappears for full rate transmission to several users.)

BH: If there is no synchronization and the relays don't know the channel, they multiply the received signal with a random unitary matrix that is known to the Tx. The capacity does not increase but reliability increases.

HS: Antenna selection ideas become relevant, as has been demonstrated in underwater experiments.

4 Thursday October 21st, 2004

Morning Session

I. Discussion after Lecture of T. Strohmer

II. Discussion after Lecture of A. Kim

MF: TR can bring down the energy in the temporal sidelobes. This does not necessarily reduce ISI, which is the sum of the powers of signal samples at specific times.

GP: TR is not perfect for communications if one wants to do decoding. It does bring down the sidelobes, just not at the right places.

HS: Was multiple scattering implemented in AK's code?

AK: The code was of the phase screen type, and includes only forward scattering. However, other propagation models, e.g., discrete scattering models, have also been studied.

HS: One should look at the peak to sidelobe ratio. If it's less than 0.1, communication should still be possible.

III. Discussion after Lecture of J.P. Fouque

??: TR is good at low SNR.

GL: What is the effect of more sensors?

MF: TR is optimal with respect to signal power because it is equivalent to matched filtering. TR combined with equalization is better than equalization alone.

HS: We should distinguish between active TR and passive TR. (Passive TR means using correlation receivers.) The effect of noise has already been investigated: if there is noise, it does not affect SF but affects signal power. Spatially correlated noise can change this conclusion.

Afternoon Session

I. Discussion after Lecture of F. Lee

MF: TR is not designed for quantized signal levels.

GP: What is the SF performance of THP? What is the performance of THP with 1 bit TR? (1 bit TR potentially destroys some of the channel zeros.)

GP: The effect of erroneous CSI is different at Tx and Rx. Erroneous CSI at the Rx is not too harmful (based on TS's results), but can be detrimental at the Tx. There is a spectrum of transmission schemes that are appropriate for full knowledge of CSI (beamforming) to no knowledge of CSI (coding).

FL: Flexible precoding depends on the selected lattice. Also, the Rx needs an inverse filter, which can cause error propagation.

GL: Are there DFE for MIMO systems?

FL: Yes, there are DFE structures for both single-user and multi-user MIMO systems.

- Open questions:
    1. Comparison of DFE and THP
    2. Digital vs. analog filtering

II. Discussion after Lecture of M. Emami

MF: What would have been the performance of the equalizers for these specific channels if TR hadn't been used? How does rate back-off compare to other techniques?

??: TR is analogous to precoding (it is the simplest form of precoding) and maximizes the peak received power.

III. Open Discussion

GP: Topics for discussion

1. Equalization at Rx (CSI is necessary)
2. Channel estimation (at both Tx and Rx)
3. Pre-equalization
4. Bandlimited coding of pulses
5. Open loop vs. closed loop techniques
6. Power management at Tx
7. SINR for multiple users
8. When is TR useful in communications and why?

MF: Experiment vs. theory in TR
TR in any application needs to be demonstrated experimentally, as is done in ultrasound. For wireless, TR becomes interesting in UWB, but poses challenges in hardware. We need measurements and experiments that go way beyond the SONAR bandwidths. Polarization is an additional parameter that needs to be accounted for.

GP: Good simulations of the propagation phenomenon also need to be developed to allow for verification.

HS: Numerical simulations are needed even more to design the experiments and process the measurements (underwater experiments are expensive). Usually, receivers have limited dynamic range. However, in scattering media, we are not limited by the dynamic range of the receivers because we just need to capture a small portion of the scattered energy.

GP: What if there is error in the CSI? Usually, CSI is assumed to be perfect, although it is inevitably erroneous. One can improve a noisy estimate by repeating the training process. However, the throughput (ratio of useful data to training data) will decrease. These questions are open for HDB channels.

5 Friday October 22nd, 2004

Morning Session

I. Discussion after Lecture of G. Lerosey

GP, MF: Compact antenna arrays
Since the performance of TR is proportional to the number of transmit antennas used, the objective is to design compact antenna arrays, such as the design proposed by Lucent, that picks up all the components of the electric / magnetic field. The question is whether there is coupling among the array elements.

AP: Hardware considerations
Synchronization and local oscillator stability are essential. The electronics are not perfect and introduce phase shifts, which are dependent on temperature. These, as well as other differences, need to be calibrated for between the transmit (downlink) and receive (uplink) chains. Such calibrations are also required for beamforming, where accurate phase information is needed. Since different cables are used for the uplink and the downlink, this is not something that is automatically corrected for with TR. Also, the dynamic range of the receivers was not considered.

KS: Spatial focusing
SF improves as bandwidth increases, in the sense that the sidelobe levels diminish whereas the focal spot stays the same.

II. Discussion after Lecture of P. Kyritsi

PK: The types of measurements needed are

1. Doppler spread
2. Parametrization of the PDP (clustering)
3. How SF and ISI depend on Doppler / PDP
4. How to reflect SF in measurements
5. SF vs. number of transducers

III. Discussion after Lecture of H. Song

HS: SF improves as the number of antennas increases, while keeping the total aperture the same.

HS: It is possible to have received power higher at an off-target location than on the target if a single Tx is used.

IV. Discussion after Lecture of D. Berebichez

JH: Keyhole is similar to Huygen's principle.

AP: Experiment through keyhole is similar to concatenated TR, as observed in MIMO systems.

MF: One can measure the channel H_1 from the source to the keyhole, the channel H_2 from the keyhole to the Rx, and concatenate the two. By finding the eigenvalues of H_1 and H_2, one can calculate the available degrees of freedom.

V. Open Discussion

1. Spectral efficiency

   AP: One can consider spectral efficiency (bps/Hz) for

   (a) a single user
   (b) multiple users within the same cell
   (c) multiple cells

   AP: HDB cannot improve capacity. (This fact has not been proven for the multi-user case, although it is believed to be true.)

   BH: In the multi-user case, HDB provides frequency diversity.

2. Coverage (SNR + fade margins)

   AP: SF does not buy coverage. HDB only buys coverage through diversity.

   GP: There is a trade-off between coverage and transmission rate.

3. Reliability

AP: Reliability is a measure on the statistics of the link and HDB helps, but there is no benefit from SF.

AP: Tx processing does not gain over Rx processing.

CT: The capacity of a SIMO channel is the same as the capacity of a MISO channel (if CSI is available at Tx), but the SIMO channel does not have SF.

4. Channel estimation

AP: For the same amount of power, you have to estimate a lot more parameters in a HDB channel than in a non-HDB channel. This is problematic, especially for the weaker taps.

AP: What is the interaction with SF? This relates to iterative TR.

5. Signaling overhead

AP: Current systems have about 25-30 % signaling overhead, which eats up spectral efficiency. In these scenarios, iterative TR would not be worth its cost in delay. However, channel estimation is especially important if there is fading.

6. Low probability of intercept

AP: In this case, SF is very important. In the context of TR, it can be achieved even with 1 transmit antenna. CDMA technology is not a competitive contender in this regard, because pseudo-random sequences are well-known. LPI applications are probably prepared to throw away bandwidth. In UWB applications, e.g., cable replacement applications, one is not interested in spectral efficiency. Also, the transmit power is limited.

GP: In each LPI transmission, the power delivered can be very low, but the power from several transmissions will add up.

GP: Are there commercial applications for LPI? Probably not, because they wouldn't tolerate the high rate back-off. In these cases, security is achieved with higher layer mechanisms.

BH: You don't have to do a complete rate back-off, but only to the point which the equalizer can handle the channel.

VI. Further Discussion on Topics from Open Discussion Session on Thursday

1. Equalization complexity

   AP: MC modulation, e.g., OFDM, can handle the equalization task easily. However, for HDB channels, one would need long symbols, and problems with channel variability and channel estimation arise. Equalization complexity in MC modulation is $O(N \log N)$, whereas in SC modulation, the complexity is exponential in N (N is the channel length).

   AP: Linear vs. nonlinear equalization
   Linear equalization algorithms are not efficient. It appears that nonlinear techniques, e.g., THP, DPC, perform better, but their interactions with SF have not been investigated.

   AP: Special equalization techniques
   The problem frequently reduces to that of equalizing a long but sparse channel. These channels are encountered in TV systems, and are handled in DVB-T with OFDM-like techniques.

2. OFDM

   AP: OFDM is the system of choice for 3.5G, 4G and Wi-Fi systems. The delay spread and the Doppler define the cyclic prefix, symbol length and FFT size for an OFDM system.

   BH: Coding in OFDM with fine frequency spacing, such as in HDB channels that are very frequency selective, becomes more complex.

   AP: Spatial focusing
   OFDM and SF have not been studied. We expect some performance and complexity trade-offs.

3. Waveform Selection

   TS: The waveform selection problem is not only relevant to HDB channels.

   AP: In UWB systems, OFDM and PPM are contenders.

4. Open vs. closed loop techniques

AP: What happens when you don't know the channel exactly? What happens when you estimate the channel on the uplink and use this knowledge on the downlink?

A Acronyms

Acronyms

CDMA	Code Division Multiple Access
CSI	Channel State Information
DFE	Decision Feedback Equalizer
DPC	Dirty Paper Coding
DVB-T	Digital Video Broadcasting - Terrestrial
FDD	Frequency Division Duplexing
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
HDB	High Delay spread Bandwidth
HSDPA	High Speed Data Packet Access
IIR	Infinite Impulse Response
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LE	Linear Equalizer
LMS	Least Mean Square
LPI	Low Probability of Intercept
MC	Multi Carrier
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood

OFDM	Orthogonal Frequency Division Multiplexing
PDP	Power Delay Profile
PPM	Pulse Position Modulation
QAM	Quadrature Amplitude Modulation
Rx	Receiver
SC	Single Carrier
SDMA	Space Division Multiple Access
SF	Spatial Focusing
SIMO	Single Input Multiple Output
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SONAR	Sonic Radar
TDD	Time Division Duplexing
THP	Tomlinson Harashima Precoding
TR	Time Reversal
TV	Television
Tx	Transmitter
UWB	Ultra Wideband

B Participants

Abbreviations of Names of Participants

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DB	Deborah Berebichez
FL	Frederick Lee
ES	Erik Stauffer
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GL	Gabriel Lerosey
GP	George Papanicolaou
HB	Harry Bims
HS	Heechun Song
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