A Signal Space Diversity-Based TDBC Protocol in Two-Way Relay Systems

Hamza Umit Sokun
Mehmet Cagri Ilter
Halim Yanikomeroglu

Carleton University
Canada
{husokun, ilterm, halim}@sce.carleton.ca

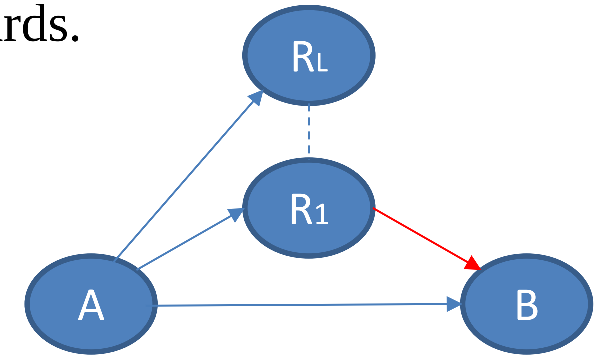
Salama Ikki

Lakehead University
Canada
sikki@lakeheadu.ca

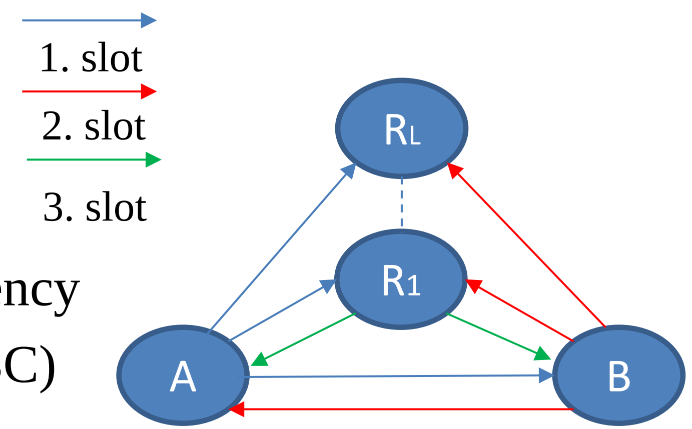
Two-Way Relaying

- Interest in terminal relaying (D2D) in 5G standards.

- Traditional one-way relay systems enable spatial diversity at the expense of spectral efficiency due to half-duplex transmission.



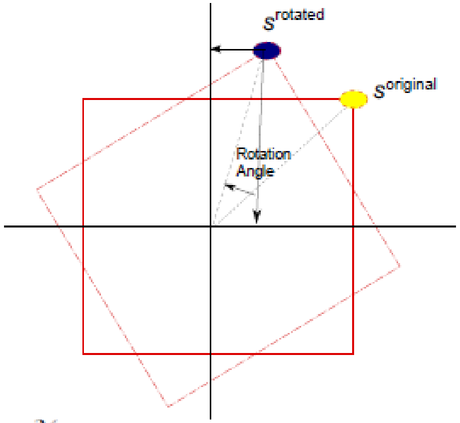
One-way Relaying



Two-way Relaying

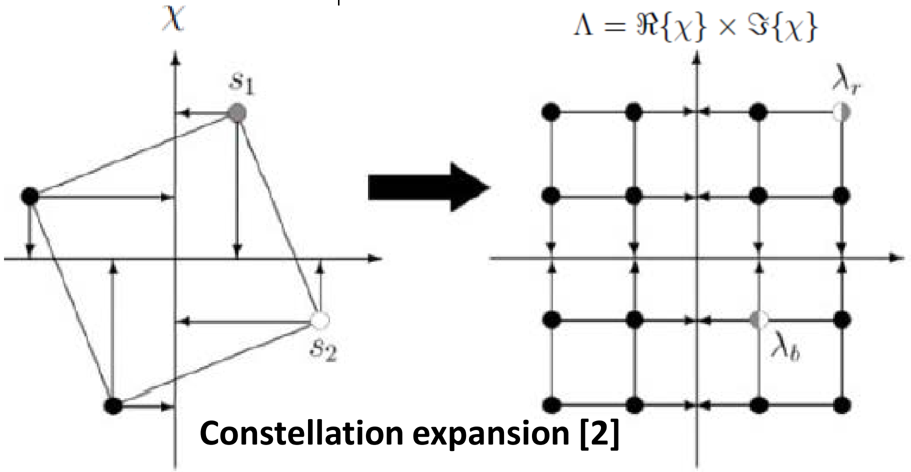
- Two-way Relaying → higher spectral efficiency
  - Time Division Broadcast Protocol (TDBC) (Using direct link → higher reliability)
  - Best-relay selection

Signal Space Diversity



- SSD [1] is a type of diversity that is extracted in the modulation signal space.

- In [2], the idea of SSD is applied to cooperative schemes (with single relay) and the constellation expansion method is proposed.



Constellation expansion [2]

- Using the constellation expansion method proposed in [2], the performance of multi-relay cooperative schemes is investigated in [3].

[1] J. Boutros and E. Viterbo, "Signal space diversity: a power-and-bandwidth-efficient diversity technique for the Rayleigh fading channels," *IEEE Trans. Info. Theory*., Jul. 1998.

[2] S. A. Ahmadzadeh, S. A. Motahari, A. K. Khandani, "Signal space cooperative communication," *IEEE Trans. Wireless Comm*., Apr. 2010.

[3] O. Amin, R. Mesleh, S. Ikki, M. Ahmed, and O. Dobre, "Performance analysis of multiple relays cooperative systems with signal space diversity," *IEEE Trans. Veh. Technol*., Aug. 2015.

Novelty/Contributions

- Two-way relaying + Signal space diversity

  Good combination, because two end-sources exchange
  - Baseline: 2 symbols over 4 time-slots
  - Proposed: 4 symbols over 3 time-slots

  Adapt SSD signaling for two-way relaying (TDBC)

- Obtained E2E error probability for arbitrary 2D constellations (as a function of SNR), which accounts for all non-uniform rectilinear constellation caused by constellation rotation. This allows
  - choosing the best rotation angle as a function of SNR.
  - the joint optimization of rotation angle, and transmit powers of all nodes.

System Model (1/4)

- Original data symbols are rotated by a certain angle before being transmitted, and then the end-sources and the relay cooperate for transmitting in-phase and quadrature components of two consecutive rotated symbols.

$s_1^A = \Re\{s_1^A\} + j\Im\{s_1^A\}$ First symbol (belongs to the rotated constellation)

$s_2^A = \Re\{s_2^A\} + j\Im\{s_2^A\}$ Second symbol (belongs to the rotated constellation)

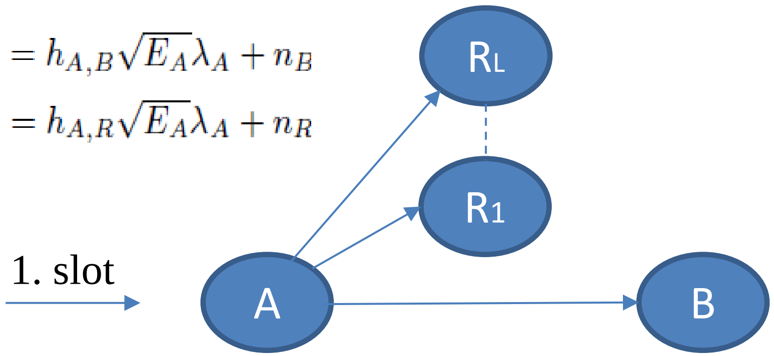
$s_1^A ; s_2^A \in \chi$

$\lambda_A = \Re\{s_1^A\} + j\Im\{s_2^A\}$ The new constellation point that will be sent from source A (belongs to the expanded constellation), $\Lambda = \Re\{\chi\} \times \Im\{\chi\}$

In the first time slot:

$$y_{A\to B} = h_{A,B}\sqrt{E_A}\lambda_A + n_B$$

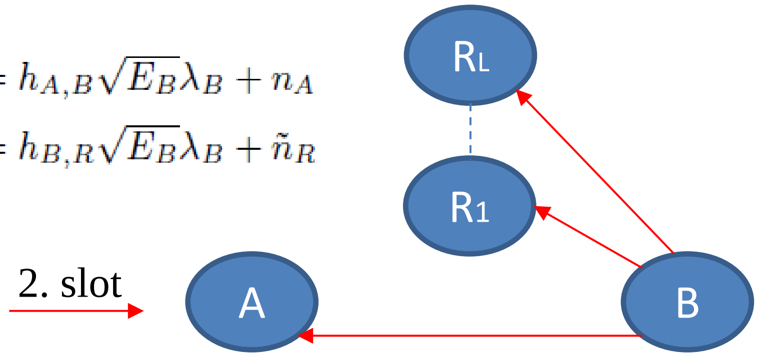
$$y_{A\to R} = h_{A,R}\sqrt{E_A}\lambda_A + n_R$$



In the second time slot:

$$y_{B\to A} = h_{A,B}\sqrt{E_B}\lambda_B + n_A$$

$$y_{B\to R} = h_{B,R}\sqrt{E_B}\lambda_B + \tilde{n}_R$$



System Model (2/4)

$$\lambda_R = \Re\{s_2^A\} + j\Im\{s_1^A\} + \Re\{s_2^B\} + j\Im\{s_1^B\}$$

In the third time slot:

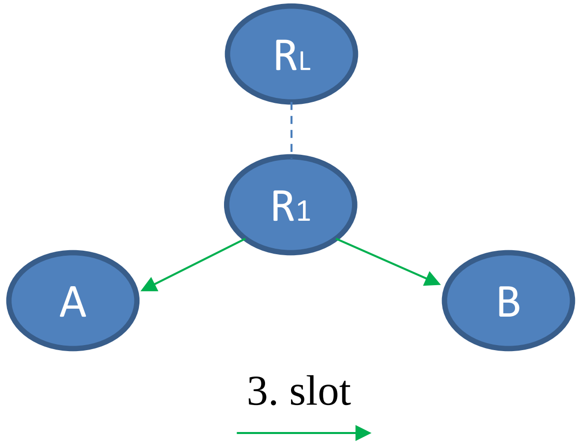
$$\hat{y}_{R\to A} = \sqrt{E_R} h_{A,R} \lambda_R + \tilde{n}_A$$

$$\hat{y}_{R\to B} = \sqrt{E_R} h_{B,R} \lambda_R + \tilde{n}_B$$

Since each node knows their data, the known parts will be removed:

$$y_{R\to A} = \sqrt{E_R} h_{A,R} \left[\Re\{s_2^B\} + j\Im\{s_1^B\} \right] + \tilde{n}_A$$

$$y_{R\to B} = \sqrt{E_R} h_{B,R} \left[\Re\{s_2^A\} + j\Im\{s_1^A\} \right] + \tilde{n}_B$$

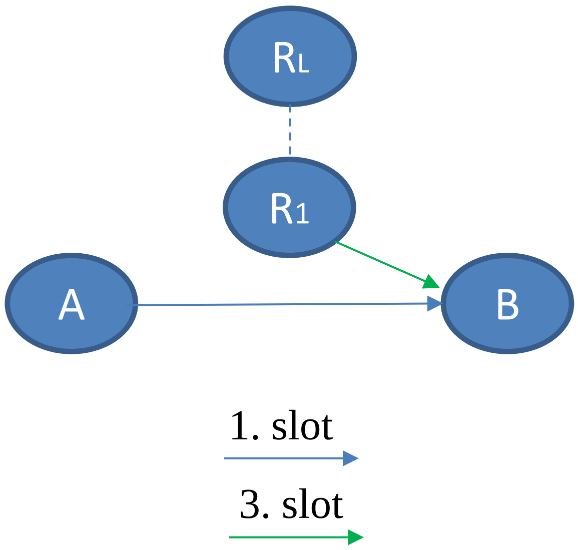


System Model (3/4)

Considering the direct and the cooperative links, the received signals at the end-source B:

$$y_{A\rightarrow B} = \sqrt{E_A} h_{A,B} \left[\Re\{s_1^A\} + j\Im\{s_2^A\}\right] + n_B$$

$$y_{R\rightarrow B} = \sqrt{E_R} h_{B,R} \left[\Re\{s_2^A\} + j\Im\{s_1^A\}\right] + \tilde{n}_B$$



To detect the original message, the end-source B reorders the received components:

$$r_1^{A\rightarrow B} = \Re\{h_{A,B}^* y_{A\rightarrow B}\} = \sqrt{E_A} |h_{A,B}|^2 \Re\{s_1^A\} + \hat{n}_{B_1}$$
$$r_2^{A\rightarrow B} = \Im\{h_{A,B}^* y_{A\rightarrow B}\} = \sqrt{E_A} |h_{A,B}|^2 \Im\{s_2^A\} + \hat{n}_{B_2}$$
$$r_3^{A\rightarrow B} = \Re\{h_{B,R}^* y_{R\rightarrow B}\} = \sqrt{E_R} |h_{B,R}|^2 \Re\{s_2^A\} + \hat{n}_{B_3}$$
$$r_4^{A\rightarrow B} = \Im\{h_{B,R}^* y_{R\rightarrow B}\} = \sqrt{E_R} |h_{B,R}|^2 \Im\{s_1^A\} + \hat{n}_{B_4}$$

System Model (4/4)

Finally, the end-source B applies ML detector on the reordered signals to detect the end-source messages:

1.

$$\hat{s}_1^A = \arg\min_{s^A \in \chi} \Big[\Big| r_1^{A \to B} - \sqrt{E_A} |h_{A,B}|^2 \Re\{s^A\} \Big|^2 + \Big| r_4^{A \to B} - \sqrt{E_R} |h_{B,R}|^2 \Im\{s^A\} \Big|^2 \Big],$$

2.

$$\hat{s}_2^A = \arg\min_{s^A \in \chi} \Big[\Big| r_3^{A \to B} - \sqrt{E_R} |h_{B,R}|^2 \Re\{s^A\} \Big|^2 + \Big| r_2^{A \to B} - \sqrt{E_A} |h_{A,B}|^2 \Im\{s^A\} \Big|^2 \Big].$$

Error Rate Performance

End-to-End Average SER

1) $$\overline{P}_i(e) = P_{off} P_{direct}^{i\to j} + (1 - P_{off}) \overline{P}_i(e|R), \; i \neq j, \; j \in \{A, B\}$$

where

2) $$P_{off} = 1 - \left(1 - \overline{P}_{direct}^{A\to R}\right)\left(1 - \overline{P}_{direct}^{B\to R}\right)$$

(Difference of the l-th and k-th symbols in the expanded constellation)

$$L_{k,l}(y_{A\to B}) = \Re\left[y_{A\to B} c_{k,l}^*\right] + d_{k,l},$$
$$c_{k,l} = \Lambda(l) - \Lambda(k),$$
$$d_{k,l} = \frac{1}{2}\left[|\Lambda(k)|^2 - |\Lambda(l)|^2\right].$$

3) $$\overline{P}_{direct}^{A\to B} = \mathbb{E}_{\gamma_B}\left[P_{direct}^{A\to B}(\gamma_B)\right]$$
$$= \int_0^\infty P_{direct}^{A\to B}(\gamma_B) f_{\gamma_B}(\gamma_B) d\gamma_B$$
$$= \sum_{k=0}^{M^2-1} \sum_{\substack{l=0 \\ l\neq k}}^{M^2-1} \sum_{t=1}^{T_l} \pm \int_0^\infty Q(a,b;\rho) f_{\gamma_B}(\gamma_B) d\gamma_B$$

$$a = \pm \bar{L}_{l,p_t}(\Lambda(k))\sqrt{2\gamma_B}, \; b = \pm \bar{L}_{l,p_{t+1}}(\Lambda(k))\sqrt{2\gamma_B}, \; \rho = \pm\Re\left[c_{l,p_t}, c_{l,p_t}^*\right]$$

$$f_{\gamma_B}(\gamma_B) = \frac{1}{\bar{\gamma}_B}\exp\left(-\frac{\gamma_B}{\bar{\gamma}_B}\right)$$

(Complementary CDF of a bivariate Gaussian variable)

4) $$\overline{P}_B(e|R) = \mathbb{E}_{\gamma_{coop}}\left[P_B(e|R)\right]$$
$$\approx \sum_{k=0}^{M-1} \sum_{\substack{l=0 \\ l\neq k}}^{M-1} \sum_{t=1}^{T_l} \pm \int_0^\infty Q(a,b;\rho) f_{\gamma_{coop}}(\gamma) d\gamma$$

$$f_{\gamma_{coop}}(\gamma) = \frac{\bar{\gamma}/\bar{\gamma}_{A,R}}{\bar{\gamma}_{R,B} - \bar{\gamma}}\left(\frac{\bar{\gamma}_{R,B}}{\bar{\gamma}_{A,B}}\left[\exp\left(\frac{-\gamma}{\bar{\gamma}_{A,B}}\right) - \exp\left(\frac{-\gamma}{\bar{\gamma}_{R,B}}\right)\right]\right)$$
$$- \frac{\bar{\gamma}}{\bar{\gamma}_{A,B} - \bar{\gamma}}\left(\frac{\bar{\gamma}_{R,B}}{\bar{\gamma}_{A,B}}\left[\exp\left(\frac{-\gamma}{\bar{\gamma}_{A,B}}\right) - \exp\left(\frac{-\gamma}{\bar{\gamma}_{R,B}}\right)\right]\right)$$
$$+ \frac{\bar{\gamma}/\bar{\gamma}_{R,B}}{\bar{\gamma}_{A,B} - \bar{\gamma}}\left[\exp\left(\frac{-\gamma}{\bar{\gamma}_{A,B}}\right) - \exp\left(\frac{-\gamma}{\bar{\gamma}}\right)\right],$$

[4] L. Szczecinski, H. Xu, X. Gao, and R. Bettancourt, "Efficient evaluation of BER for arbitrary modulation and signalling in fading channels," *IEEE Trans. Comm.*, vol. 55, no. 11, pp. 2061–2064, Nov. 2007.

Simulation Results (1/4)

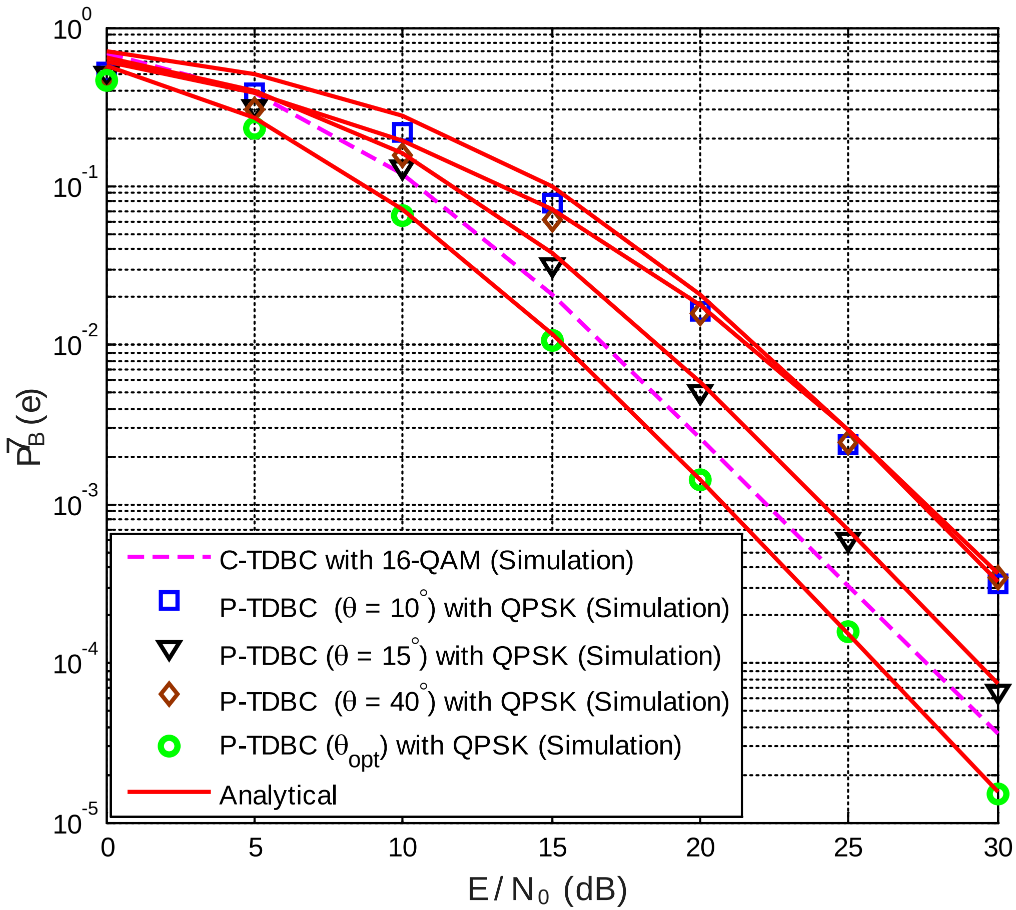


Fig. 1. SER performance of the proposed TDBC (P-TDBC) in compared to the conventional TDBC (C-TDBC) . ($E_A = E_B = E_R = E$)

$$\min_{\theta} \quad \overline{P}_i(e)$$
$$\text{subject to} \quad \theta \in (0^\circ,\ 45^\circ).$$

THE OPTIMUM VALUES OF ROTATION ANGLE

E/N_0(dB)	0	5	10	15	20	25	30
θ_{opt}(deg)	34.96	30.28	28.52	27.91	27.66	27.56	27.53

Simulation Results (2/4)

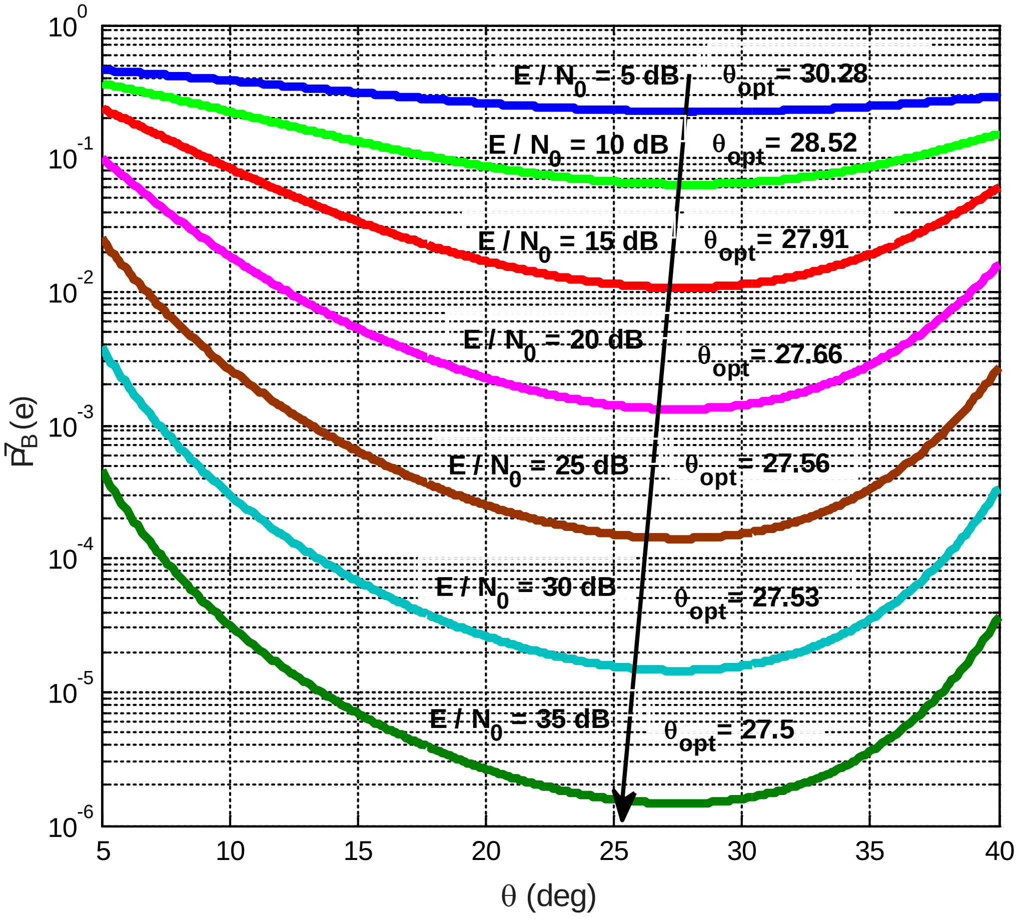


Fig. 2. The impact of different rotation angles on the system performance at the different SNR values.

Simulation Results (3/4)

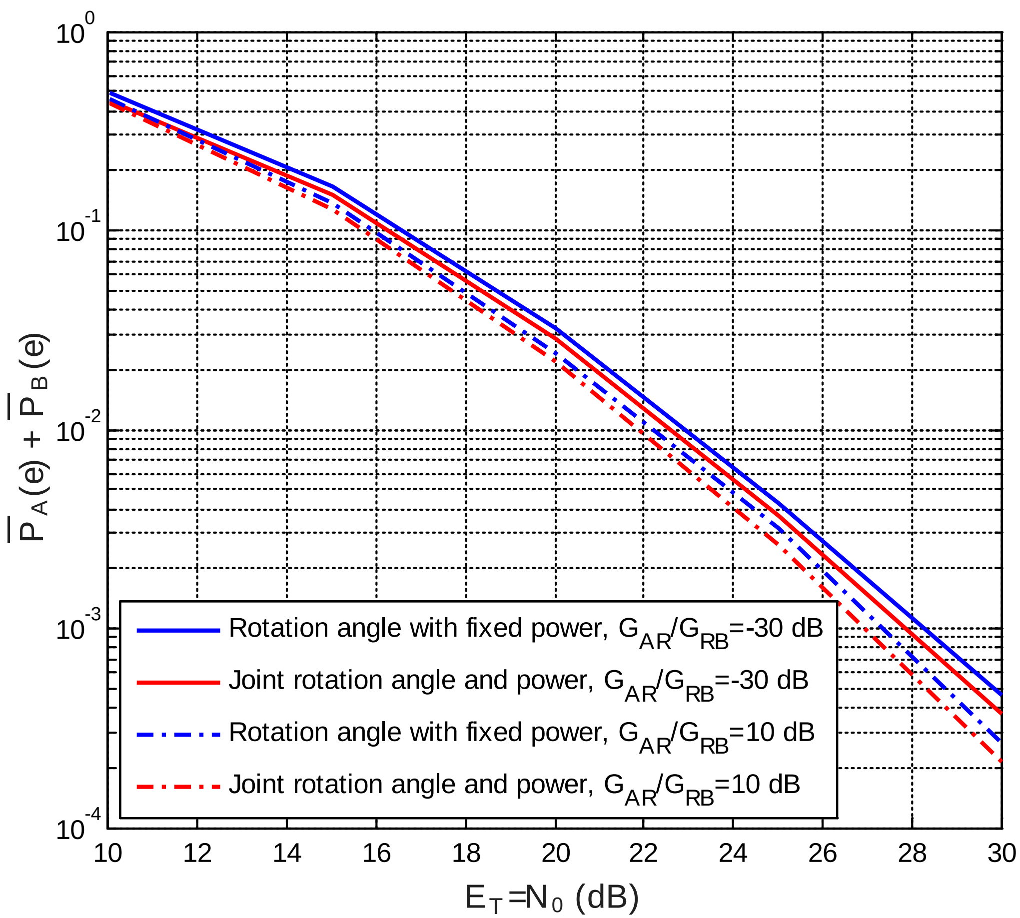
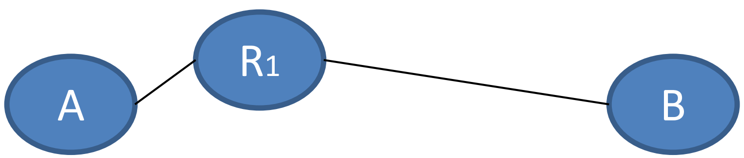


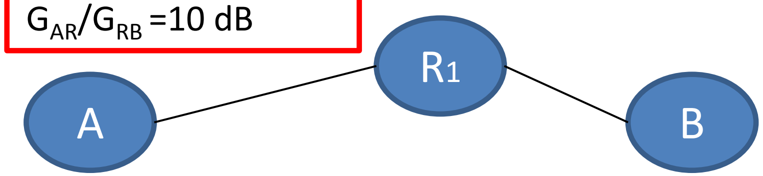
Fig. 3. Impact of joint optimization of rotation angle, and transmit powers at all nodes on the system performance. ($E_A + E_B + E_R = E_T$, $E^{max} = 0.8E_T$)

$$\begin{aligned} \min_{\theta,\, E_A,\, E_R,\, E_B} \quad & \overline{P}_i(e) \\ \text{subject to} \quad & E_A + E_B + E_R \le E_T, \\ & 0 < E_A,\ E_B,\ E_R \le E^{\max}, \\ & \theta \in (0^\circ,\ 45^\circ), \end{aligned}$$

G_{AR}/G_{RB} =-30 dB



G_{AR}/G_{RB} =10 dB



Simulation Results (4/4)

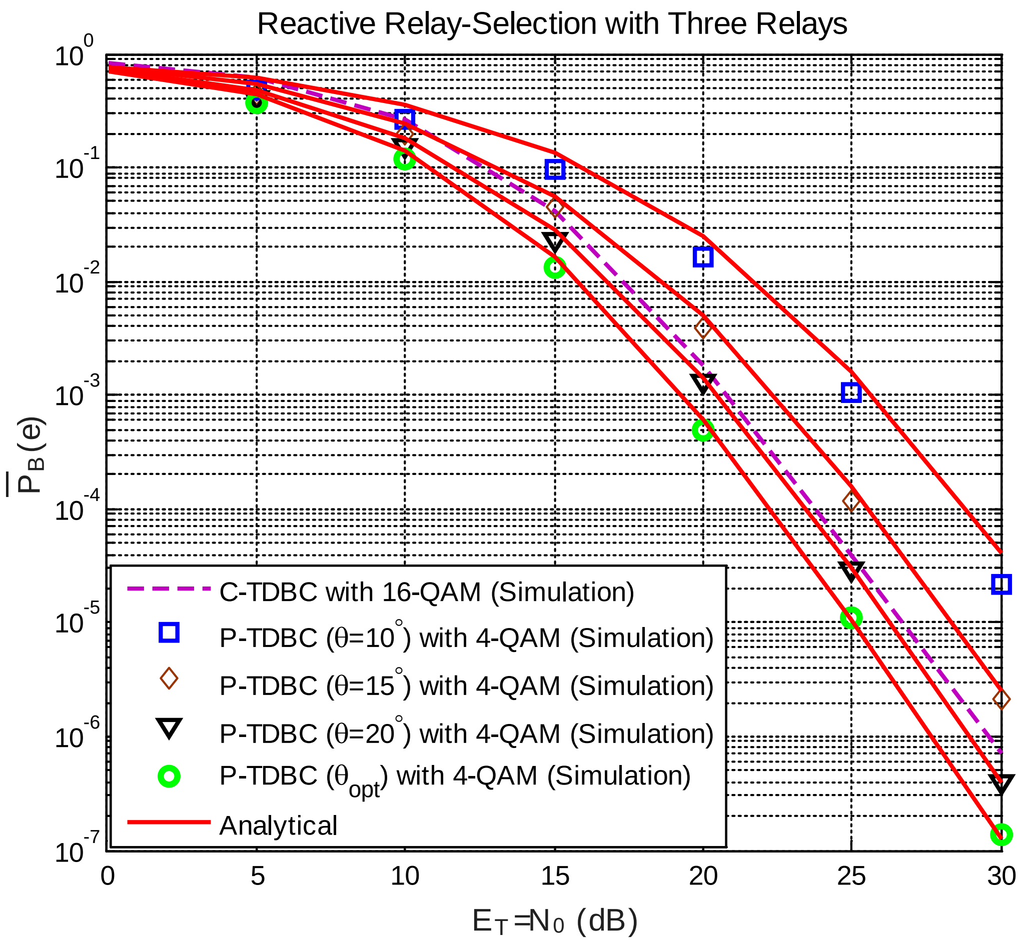


Fig. 4. SER performance of the proposed TDBC (P-TDBC) in compared to the conventional TDBC (C-TDBC) with reactive relay selection, when the number of relays is 3. ($E_A = E_B = E_R = E_T/3$)

Summary

- A signal space diversity-based TDBC protocol is proposed.
  - Higher spectral efficiency,
  - Higher spatial diversity.

- Error rate performance analysis with arbitrary constellation is obtained.

- Effect of rotation angle is investigated.

- Joint effect of rotation angle and power allocation is shown.

Future Works

- Imperfect channel estimation
- Impact of coding rate
- Cognitive radio

Thank you!

This work is supported in part by Huawei Canada Co., Ltd., and in part by the Ontario Ministry of Economic Development and Innovation's ORF-RE (Ontario Research Fund - Research Excellence) program.