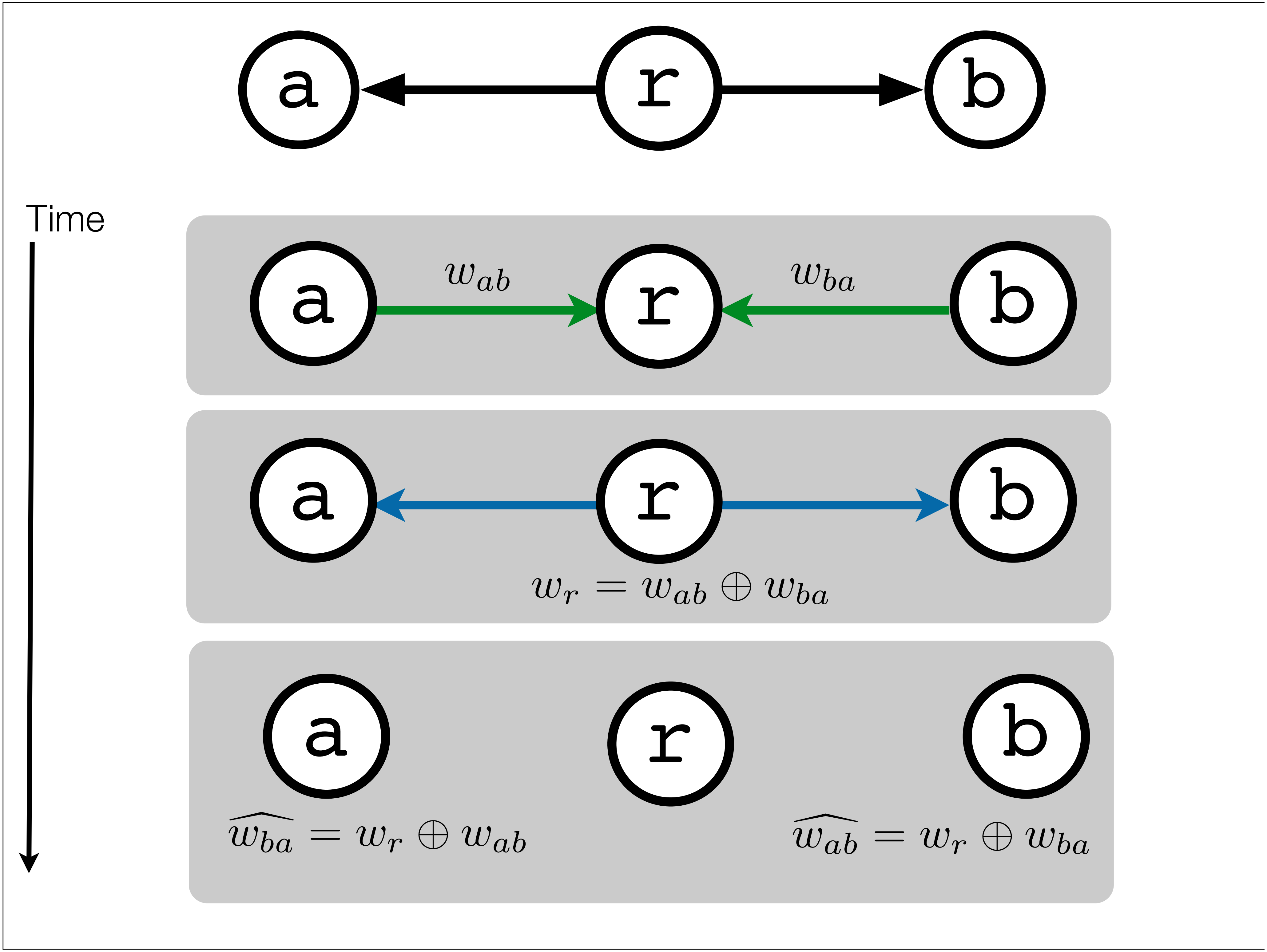
Capacity bounds on multi-pair two-way communication with a base-station aided by a relay

Sang Joon Kim, Harvard University
Besma Smida, Purdue University
Natasha Devroye, University of Illinois at Chicago



a
r
b
Time
w_{ab}
w_{ba}
$w_r = w_{ab} \oplus w_{ba}$
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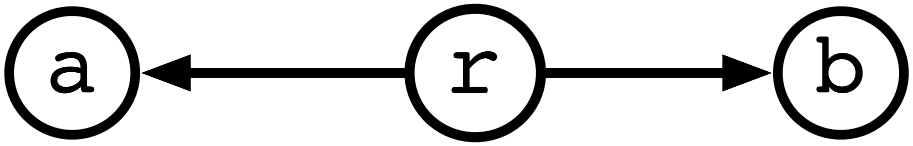
$\widehat{w_{ab}} = w_r \oplus w_{ba}$



(and extensions)

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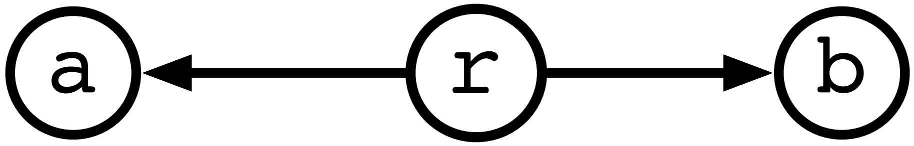

Channel model

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Direct link between terminal nodes

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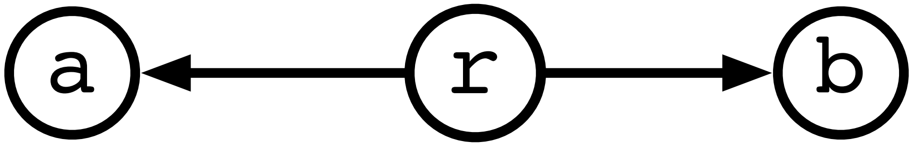

Relaying type

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Compress and forward

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Amplify and forward

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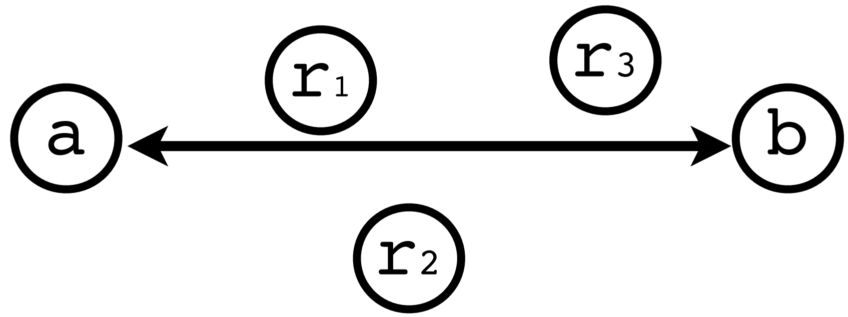
Extensions to multiple relays



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Extensions to multiple terminals

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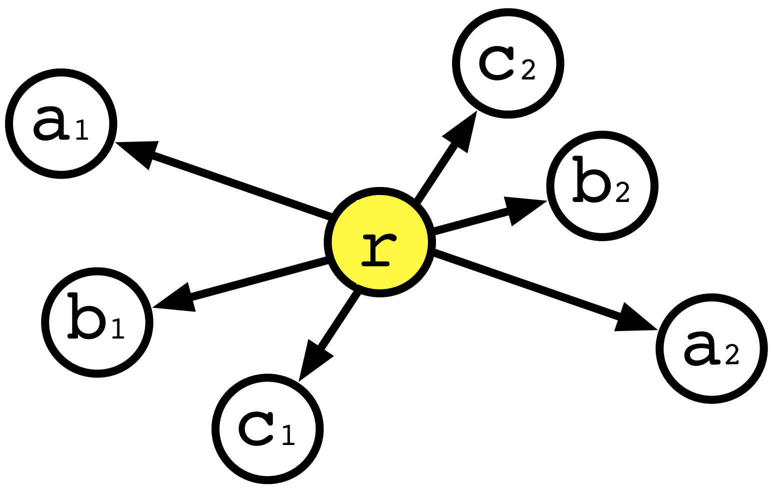

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and this work

Multiple terminals: multi-way

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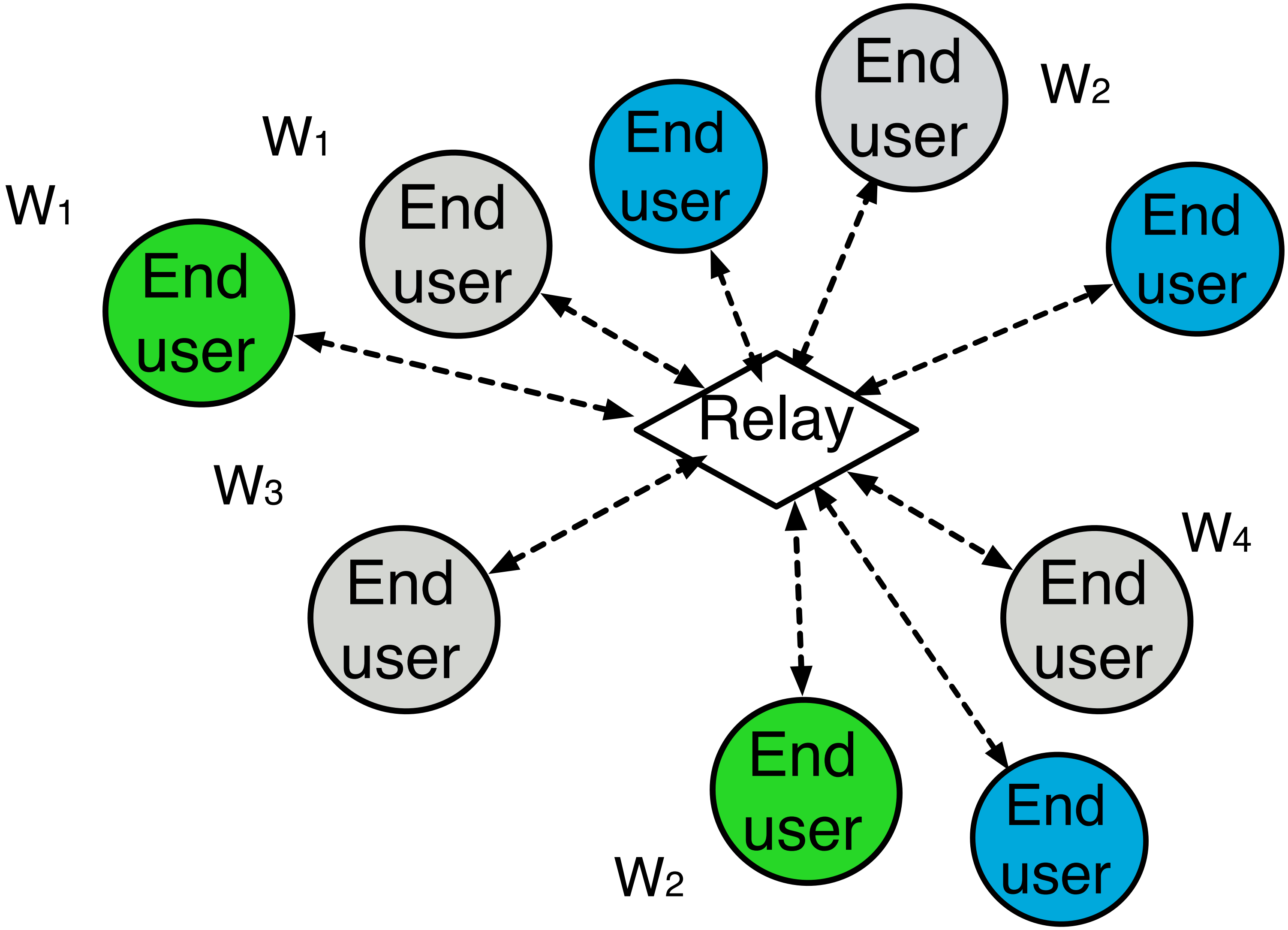

Multiple terminals: multiple two-way

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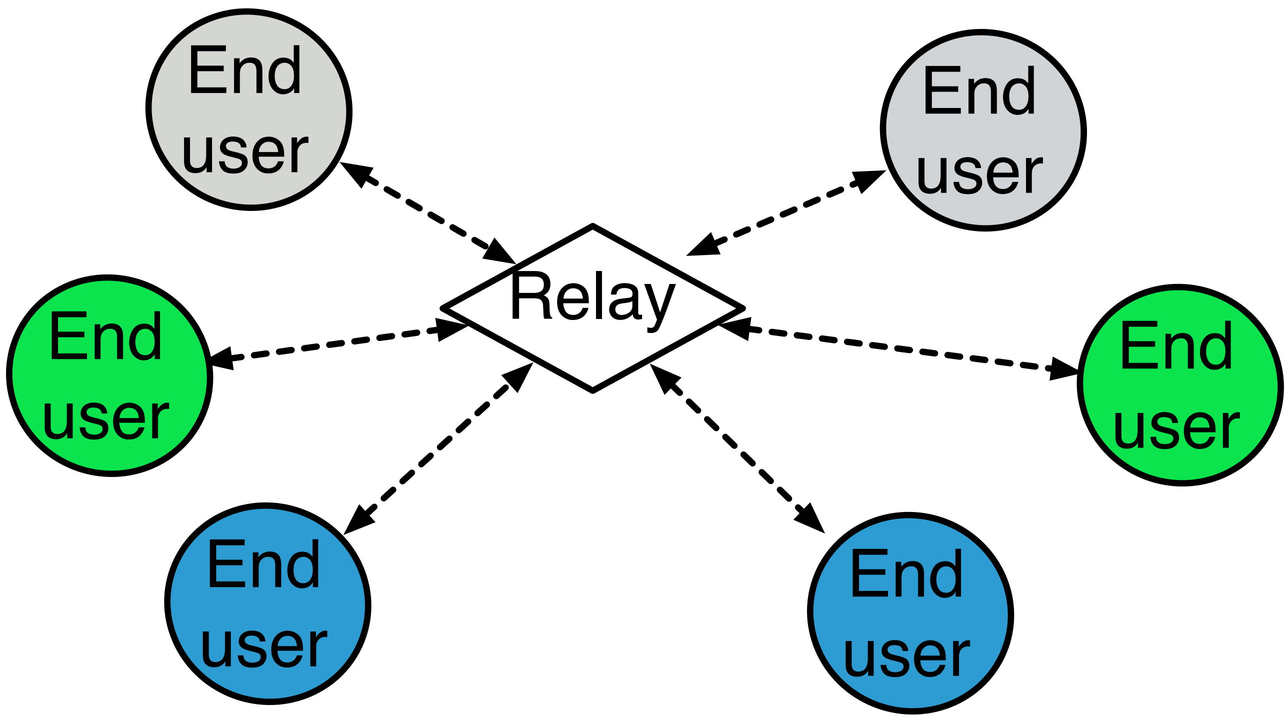

Multiple terminals: with base-station

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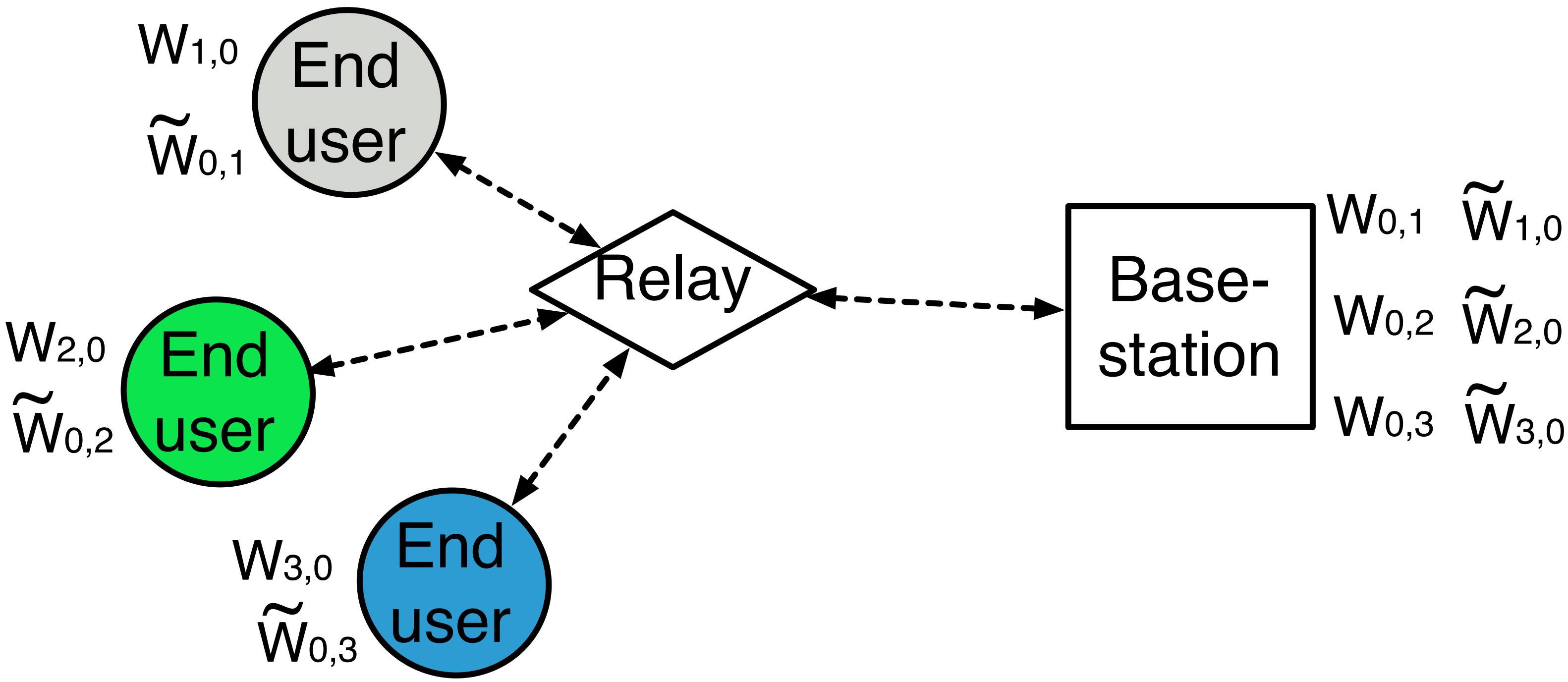

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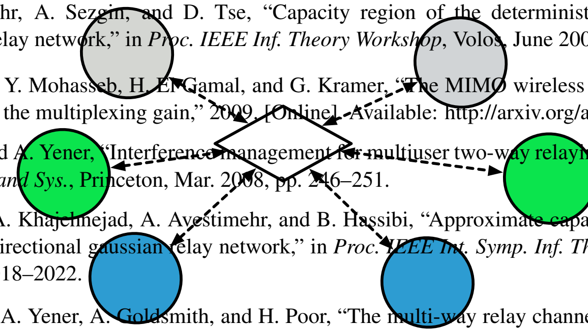

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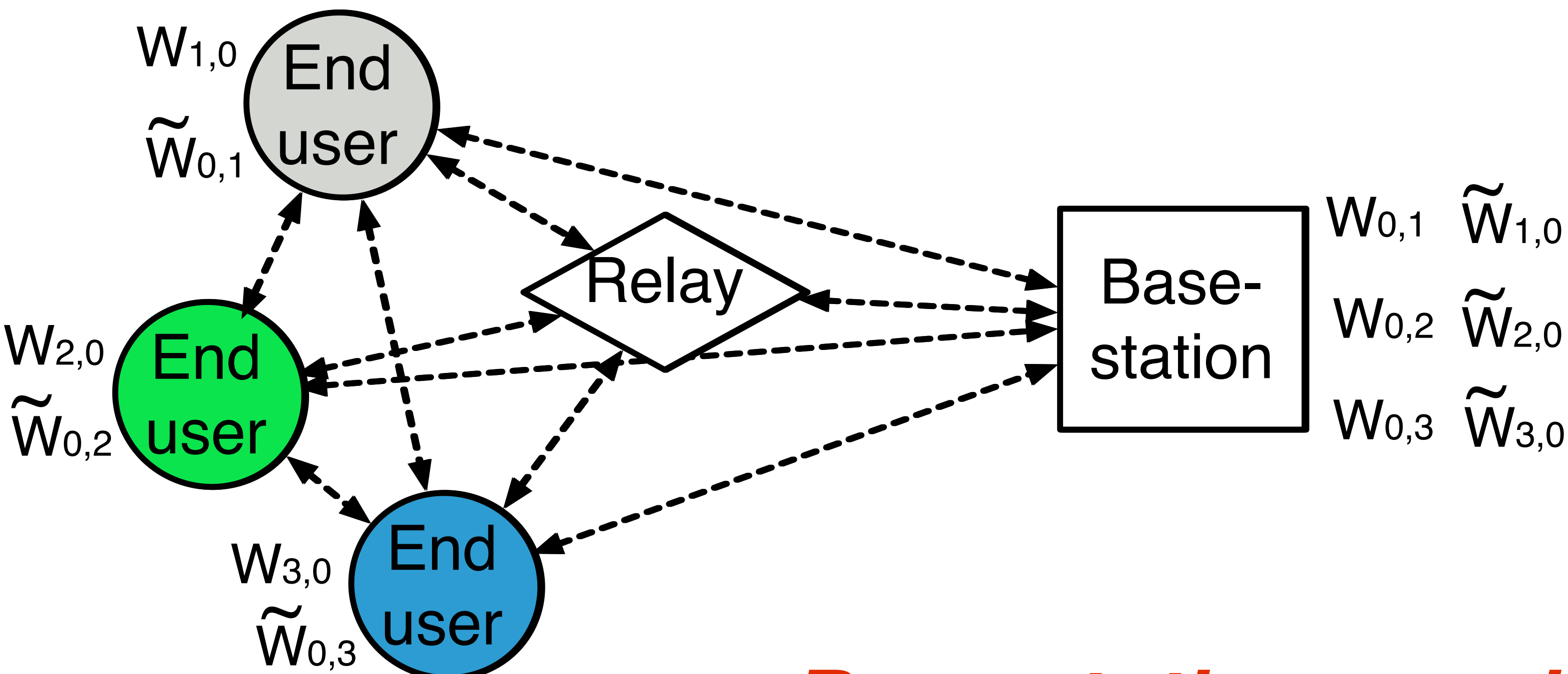
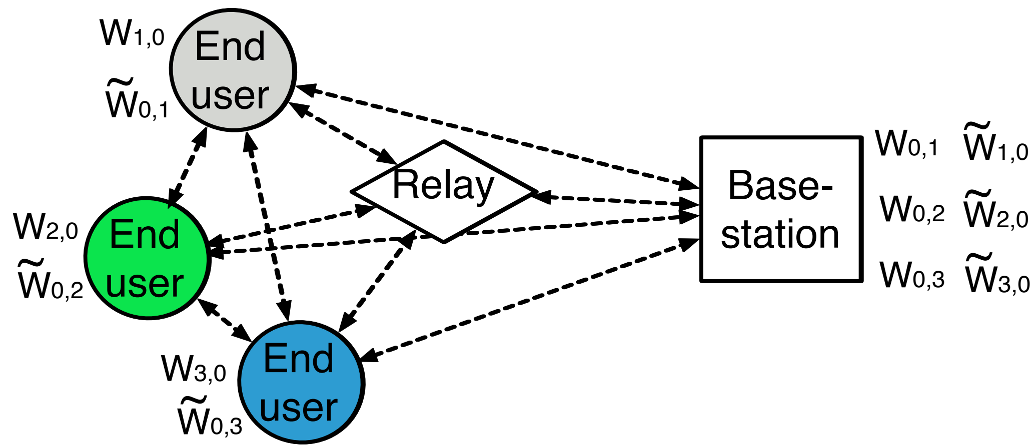
M. Chen and A. Yener, "Power allocation for F/TDMA multiuser two-way relay networks," *IEEE Trans. Wireless Comm.*, vol. 9, no. 2, pp. 546–551, 2010.



Base-station = node 0

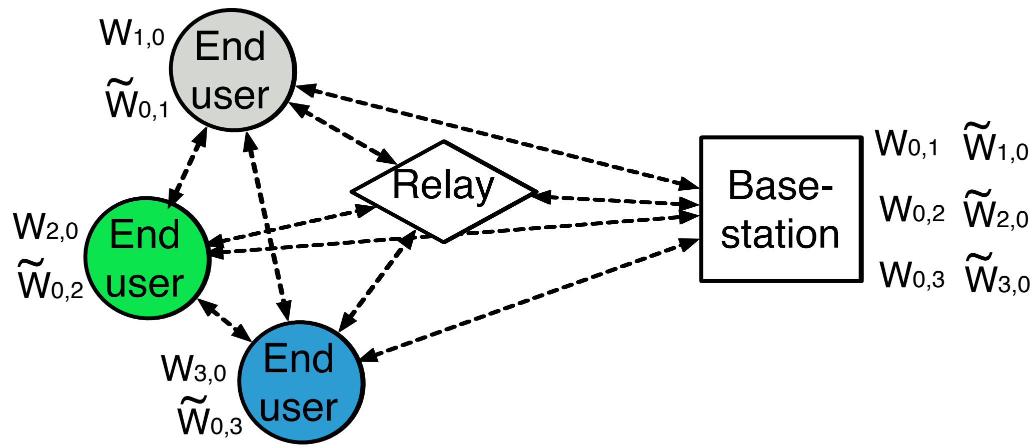
Arbitrary (m) number of end users

Contributions



- Achievable rate regions (DMC)
- Cut-set based outer bounds
- Numerical results for Gaussian channel

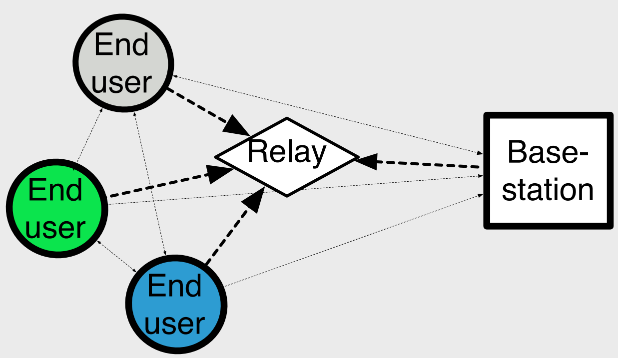
Channel assumptions



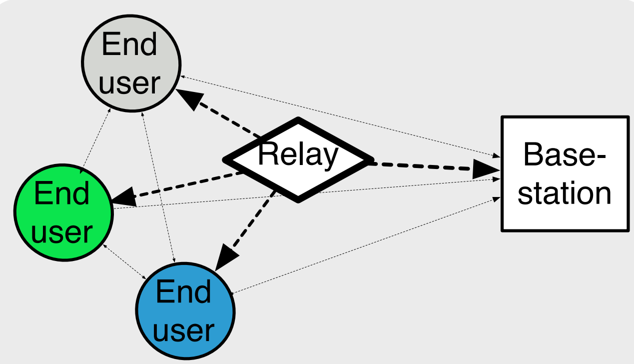
Half-duplex nodes

Decode + forward relay

"Protocols" = time "phases"

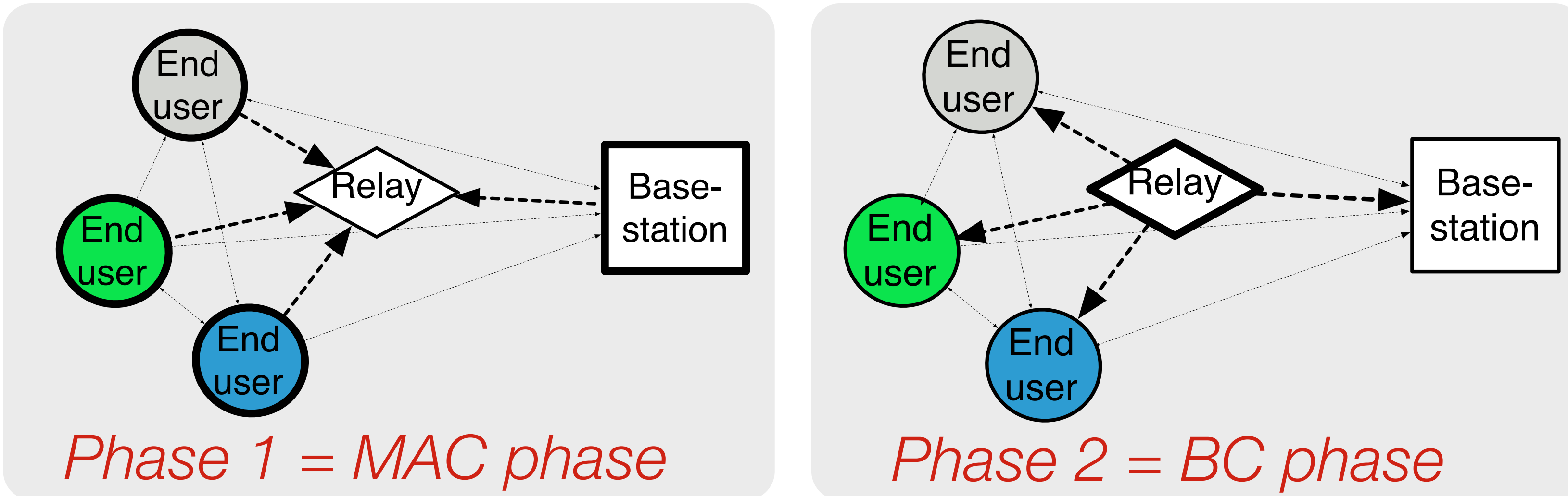


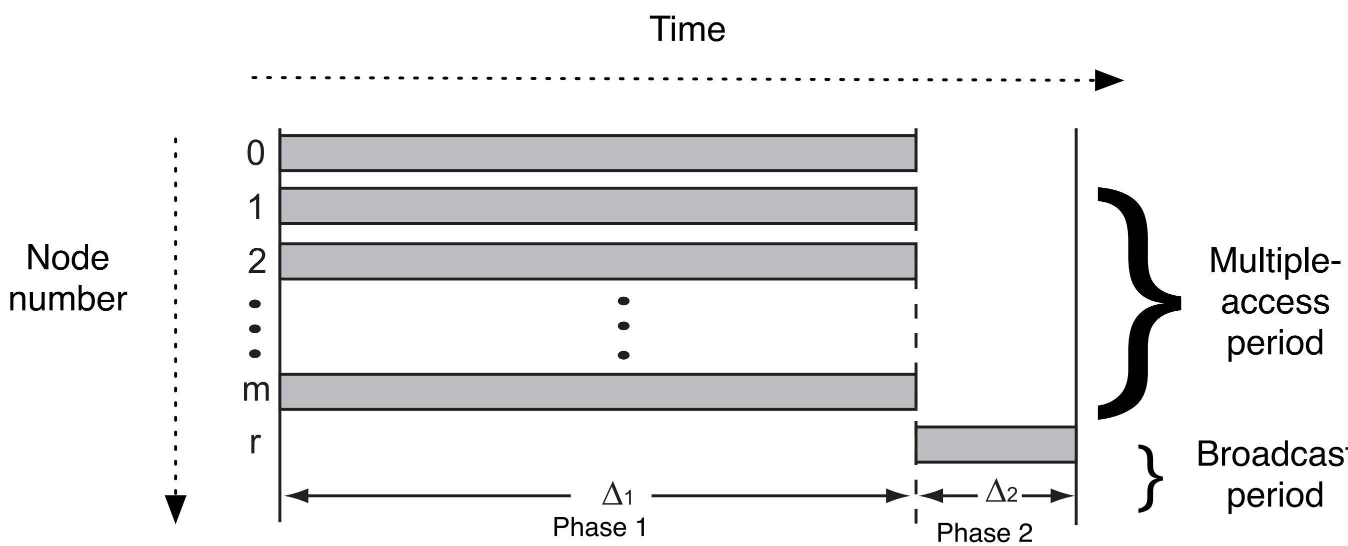
Phase 1 = MAC phase



Phase 2 = BC phase

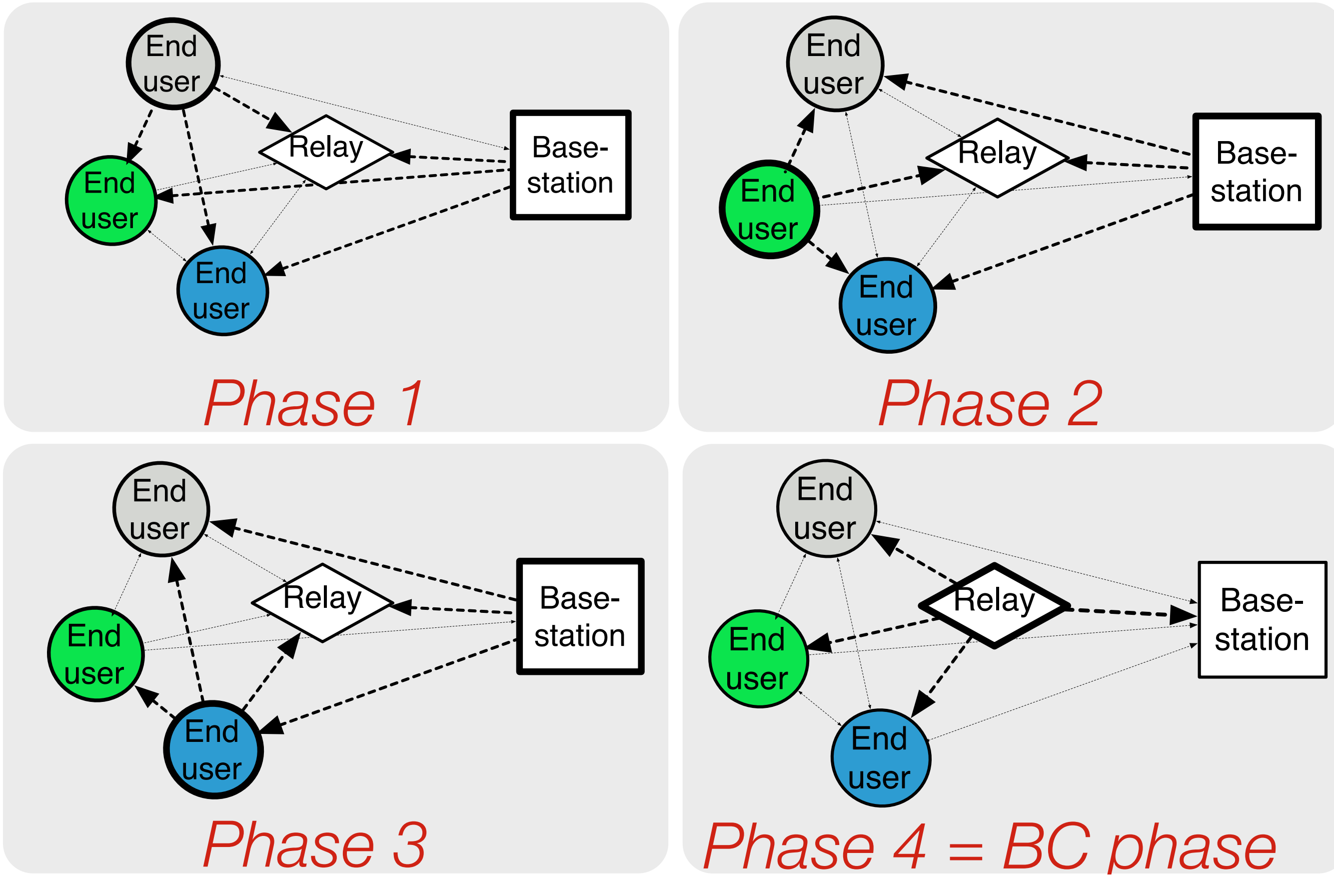
Protocol 1: FMABC (Full MAC then BC)

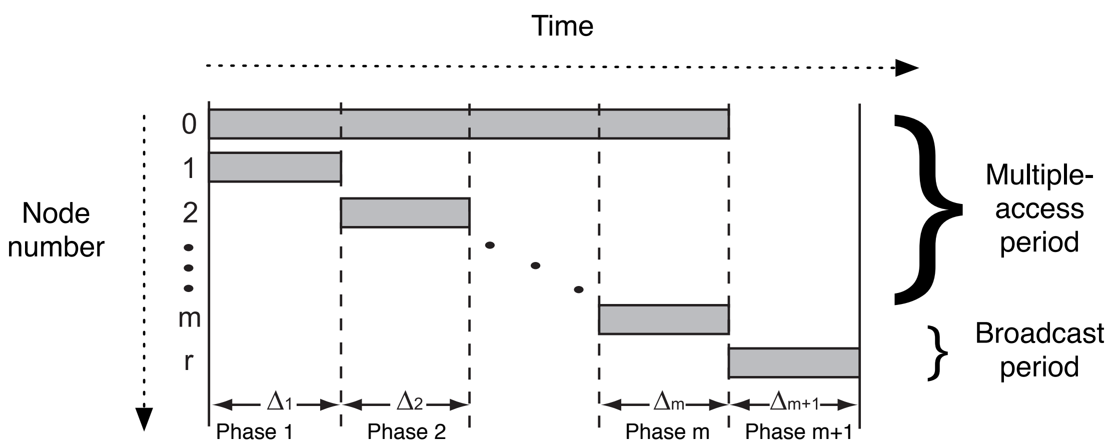




(a) FMABC protocol

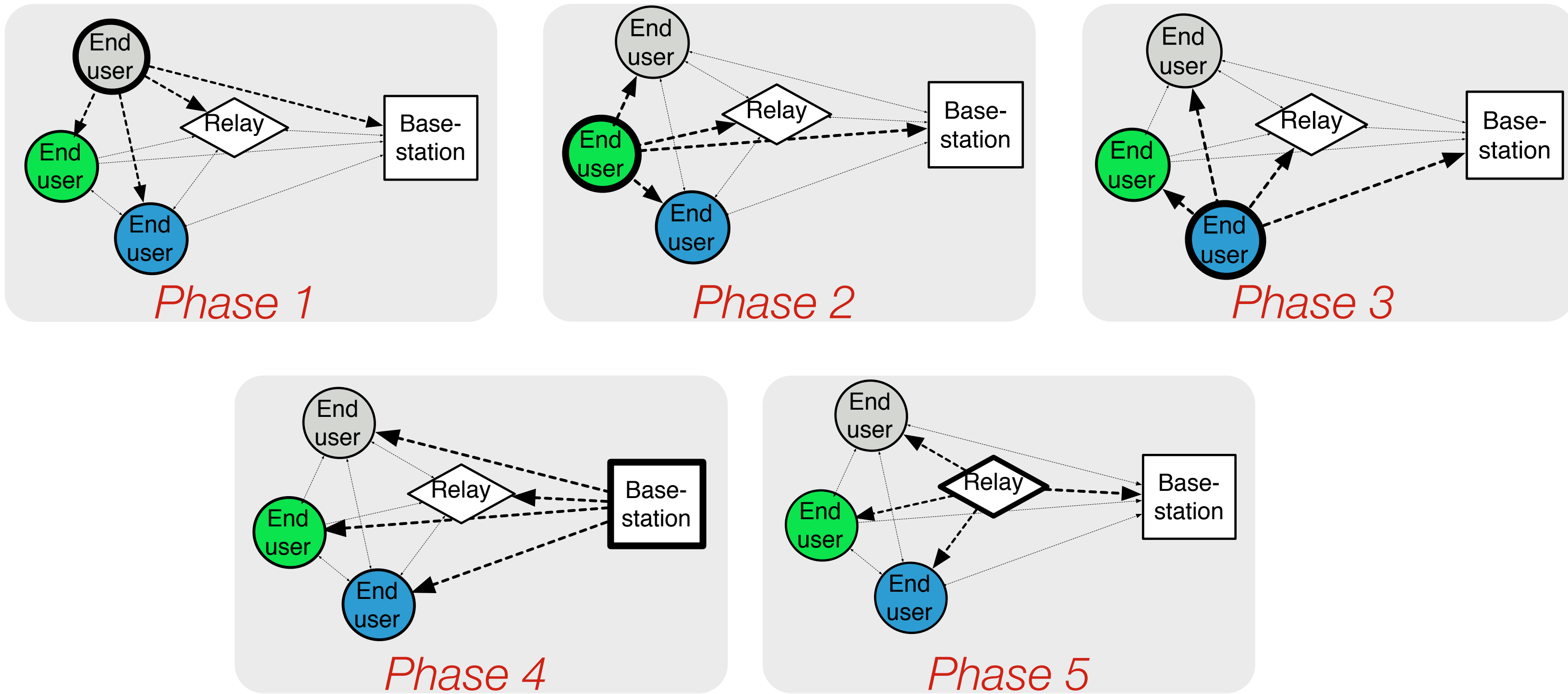
Protocol 2: PMABC (Partial MAC then BC)

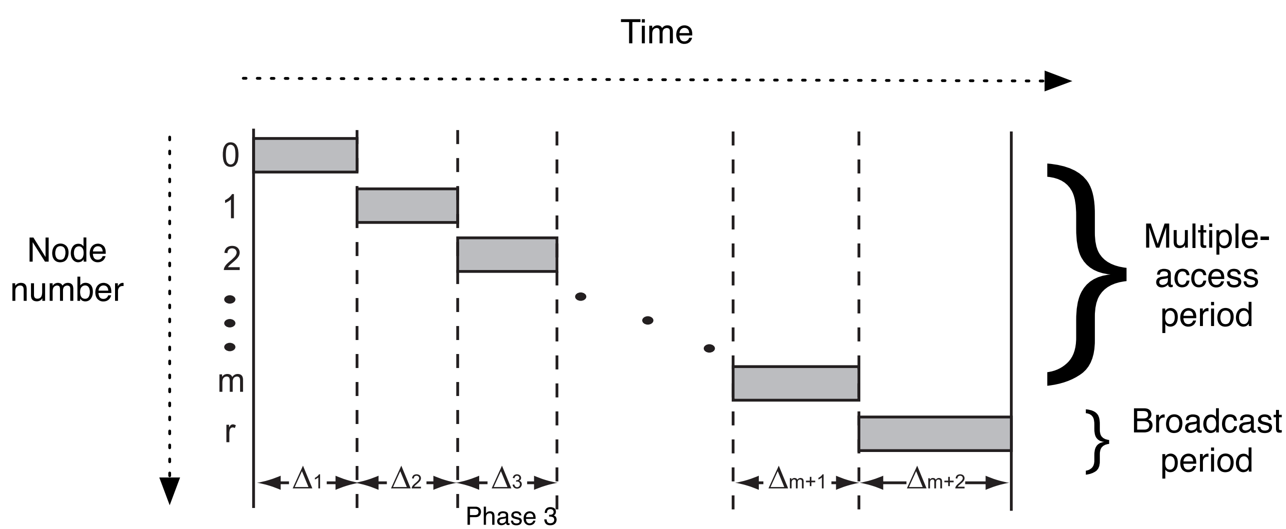




(b) PMABC protocol

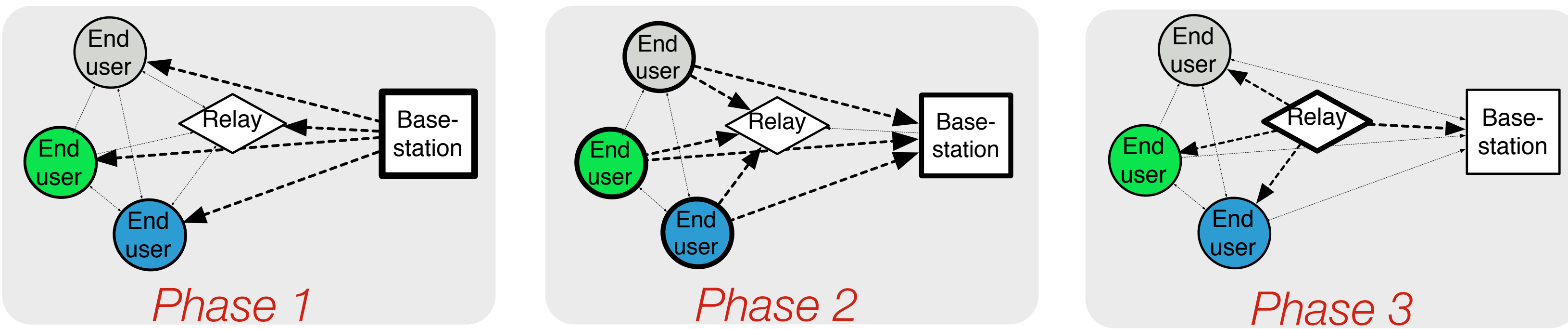
Protocol 3: FTDBC (Full Time Division then BC)

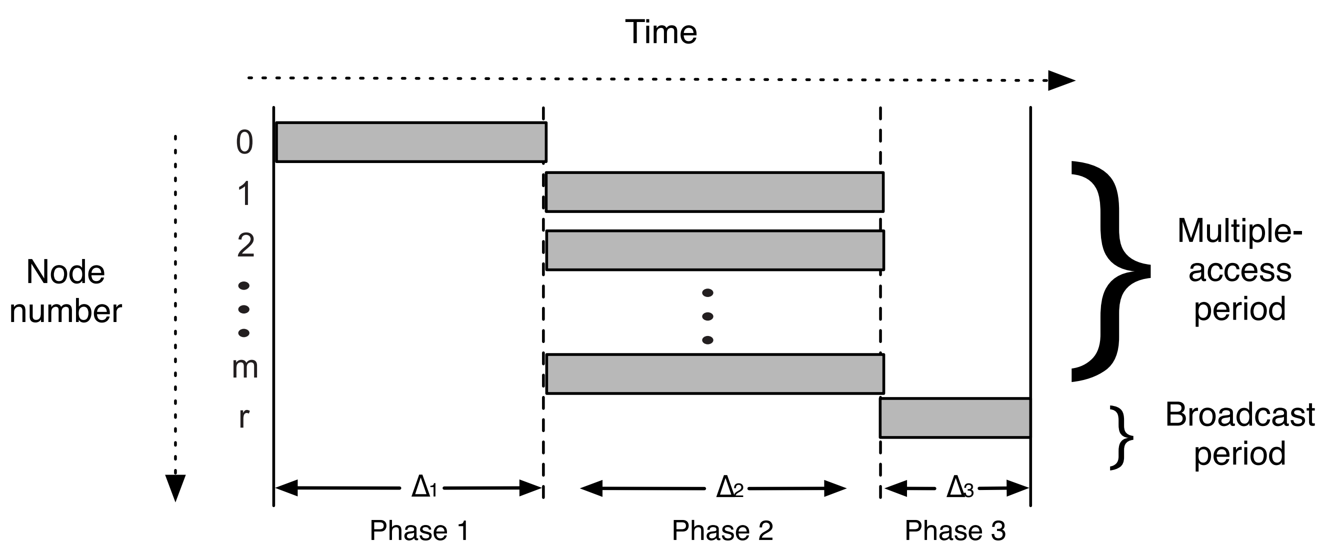




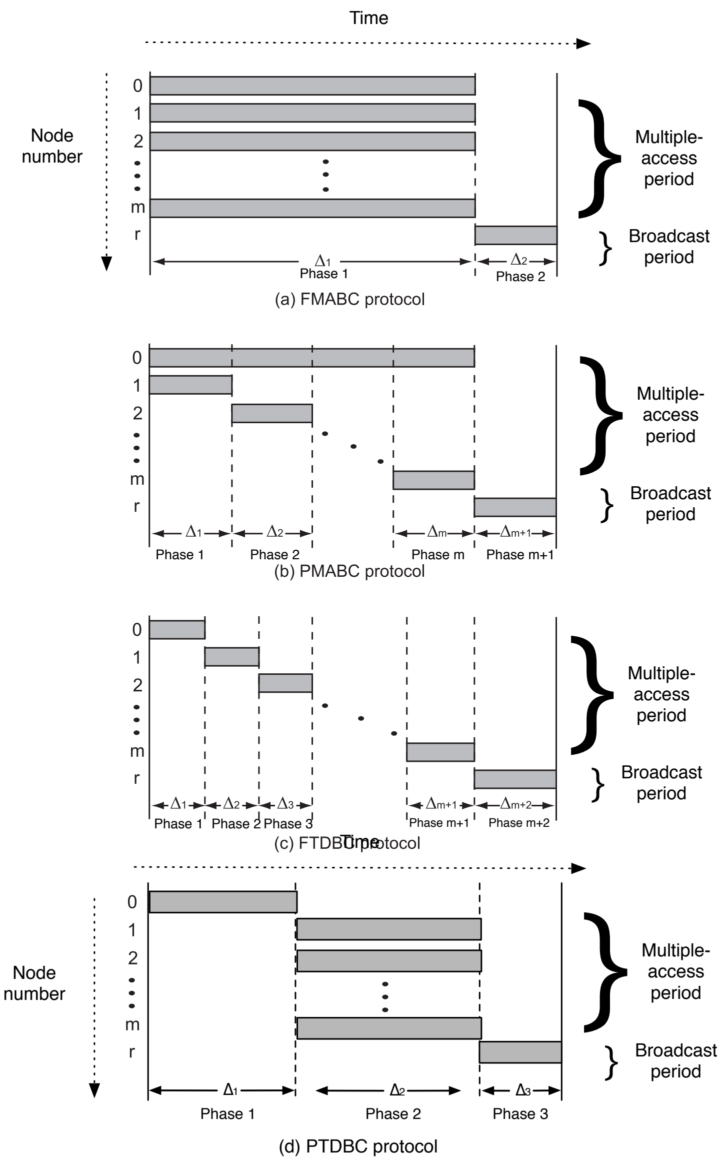
(c) FTDBC protocol

Protocol 4: PTDBC (Partial Time Division then BC)





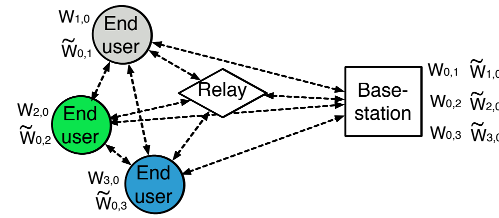
(d) PTDBC protocol

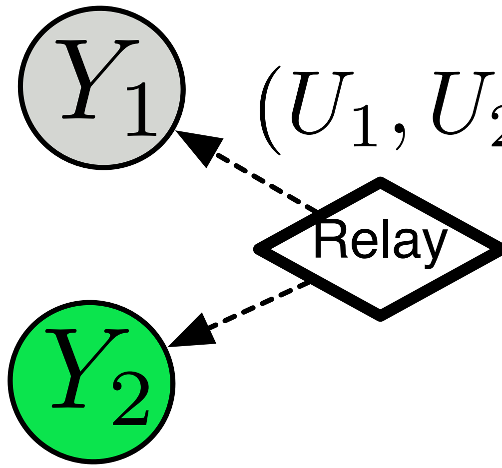


Which protocol is "better"?

1. Extended Marton's region for broadcasting
2. Per-flow network coding
3. Random-binning to exploit side-information
4. CF-based Terminal node cooperation

Marton's region





$$(U_1, U_2) - X$$

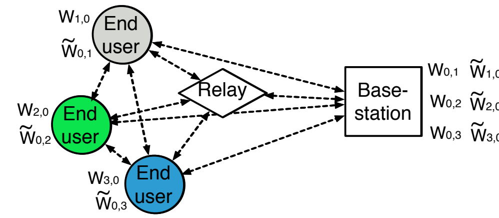
$$R_1 \leq I(U_1; Y_1)$$

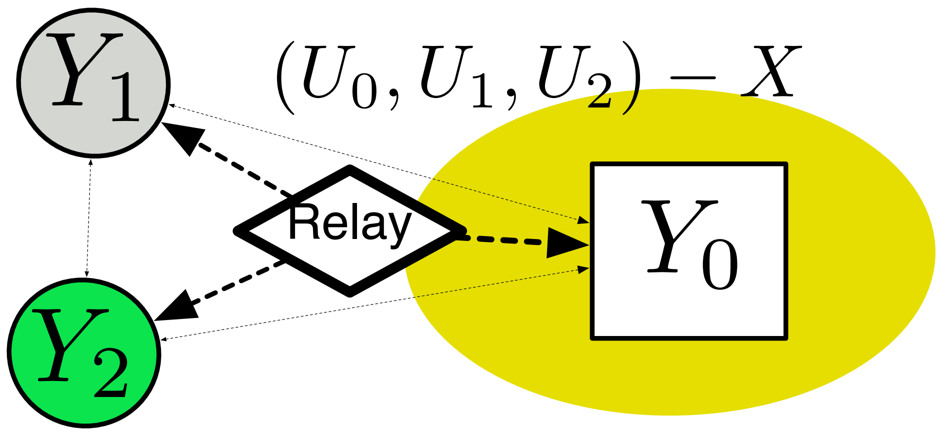
$$R_2 \leq I(U_2; Y_2)$$

$$R_1 + R_2 \leq I(U_1; Y_1) + I(U_2; Y_2) - I(U_1; U_2)$$

$$\text{over all joint distributions } p(u_1, u_2, x)$$

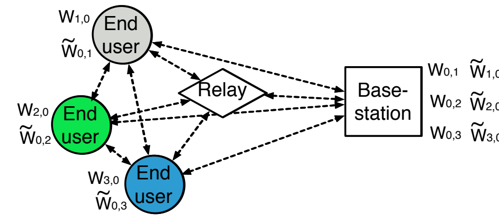
Extended Marton's in our notation





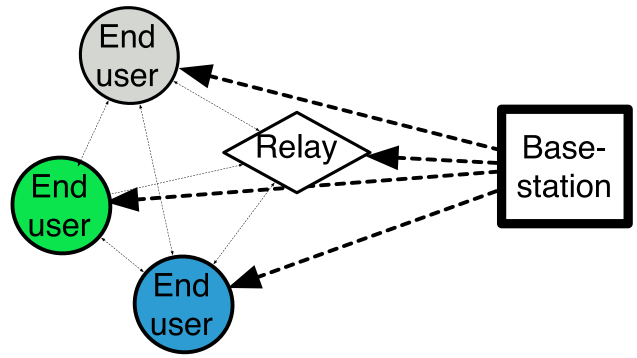
$$
\begin{aligned}
R_{0,1} &\leq I(U_1;Y_1) \\
R_{0,2} &\leq I(U_2;Y_2) \\
R_{1,0} + R_{2,0} &\leq I(U_0;Y_0) \\
R_{1,0} + R_{2,0} + R_{0,1} &\leq I(U_0;Y_0) + I(U_1;Y_1) - I(U_0;U_1) \\
R_{1,0} + R_{2,0} + R_{0,2} &\leq I(U_0;Y_0) + I(U_2;Y_2) - I(U_0;U_2) \\
R_{0,1} + R_{0,2} &\leq I(U_1;Y_1) + I(U_2;Y_2) - I(U_1;U_2) \\
R_{1,0} + R_{2,0} + R_{0,1} + R_{0,2} &\leq I(U_0;Y_0) + I(U_1;Y_1) + I(U_2;Y_2) - I(U_1;U_0) - I(U_2;U_1,U_0)
\end{aligned}
$$

over all joint distributions $p(u_0, u_1, u_2, x)$

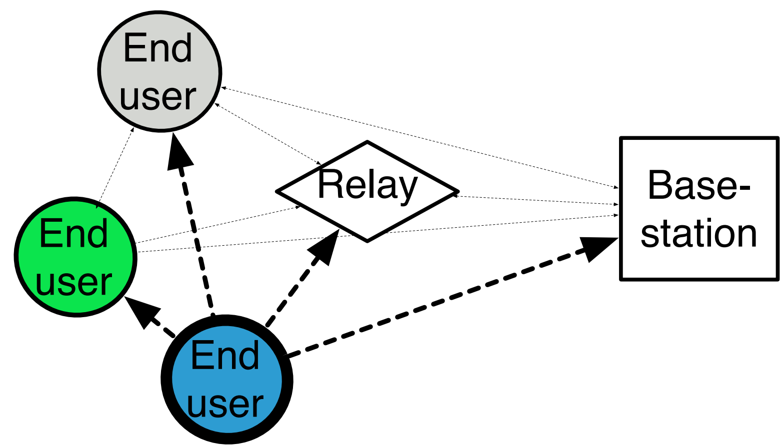


Use extended Marton's region at:

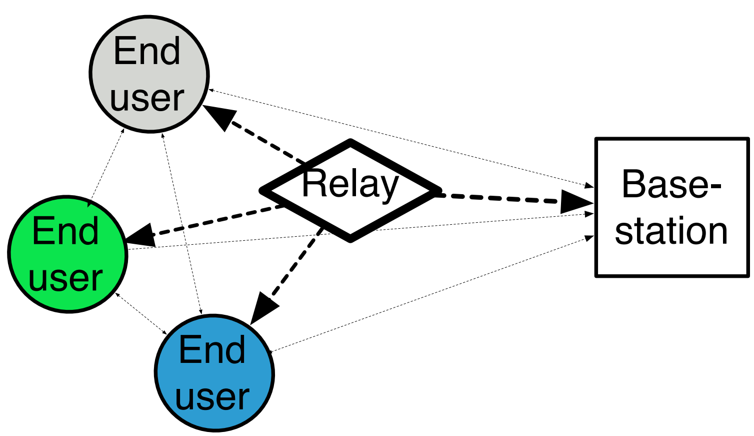
Base station

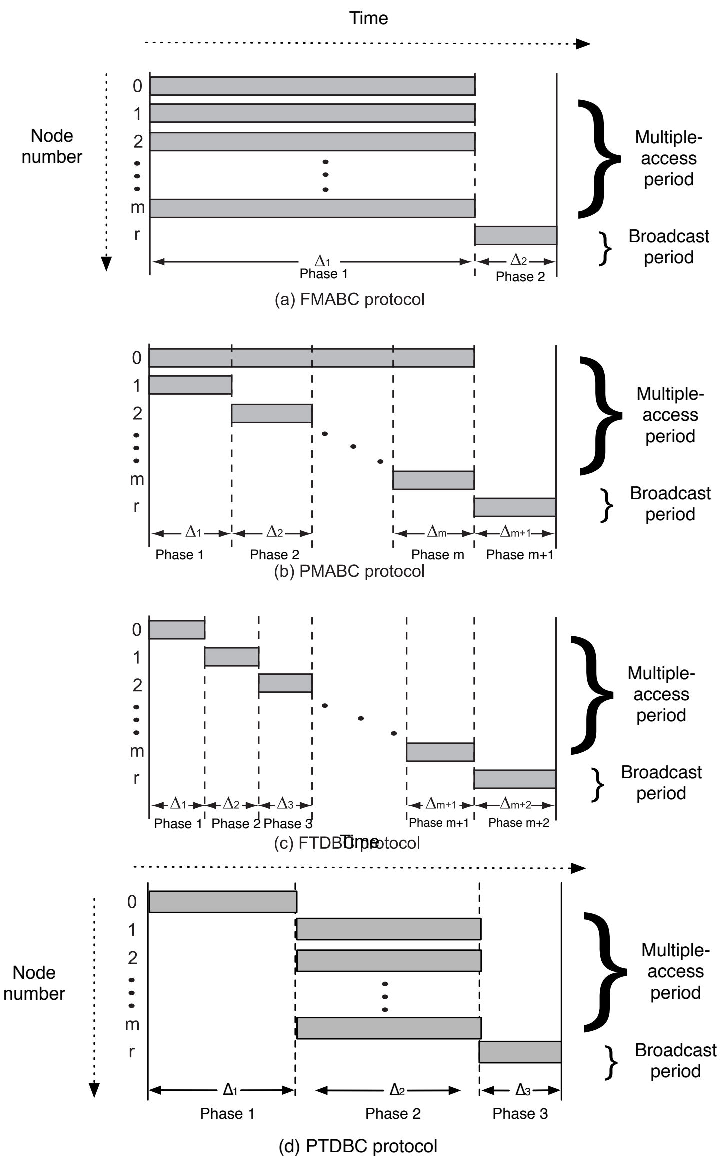


End user



Relay

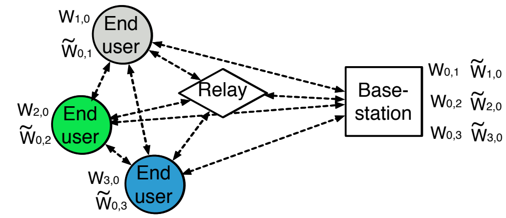


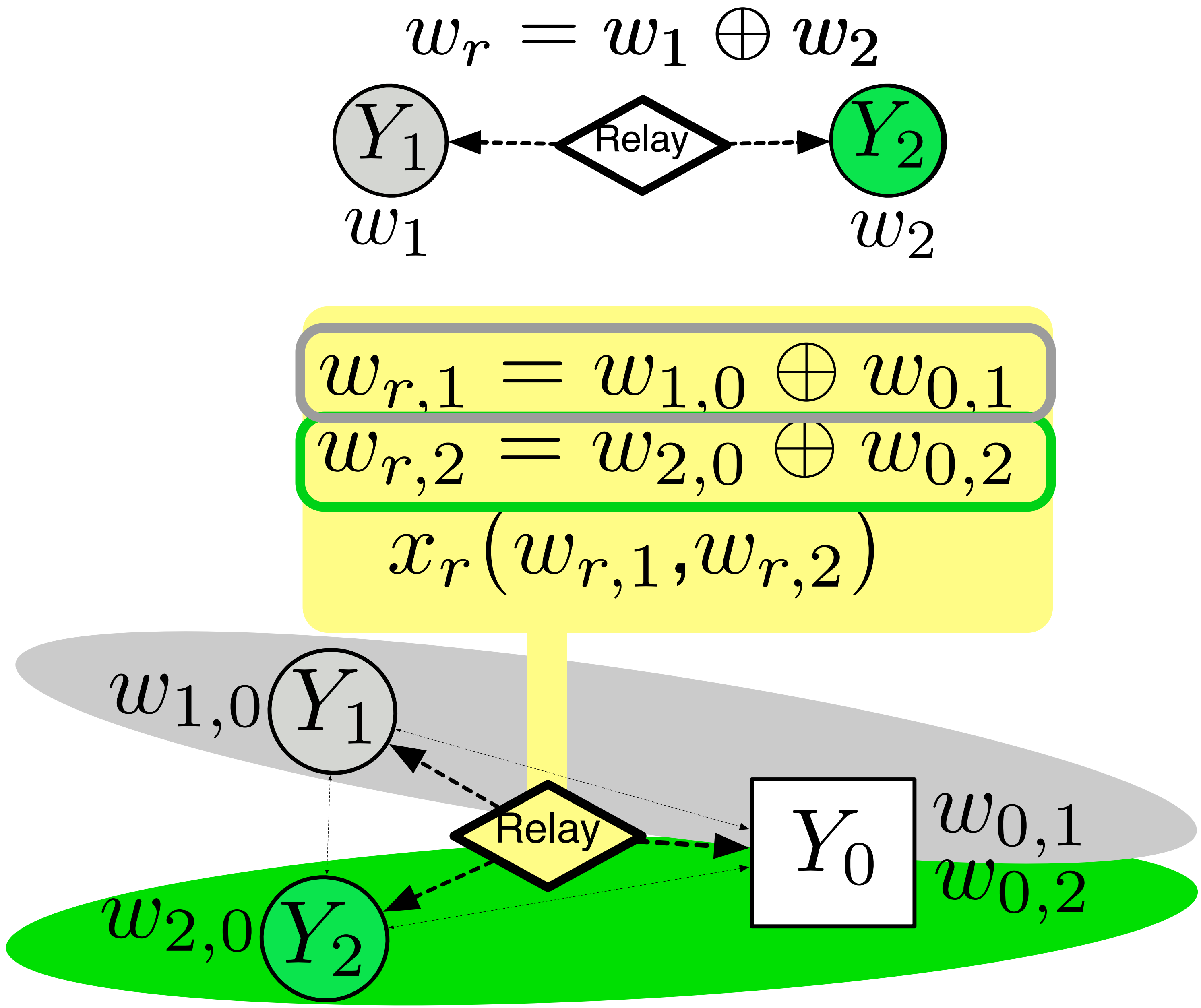


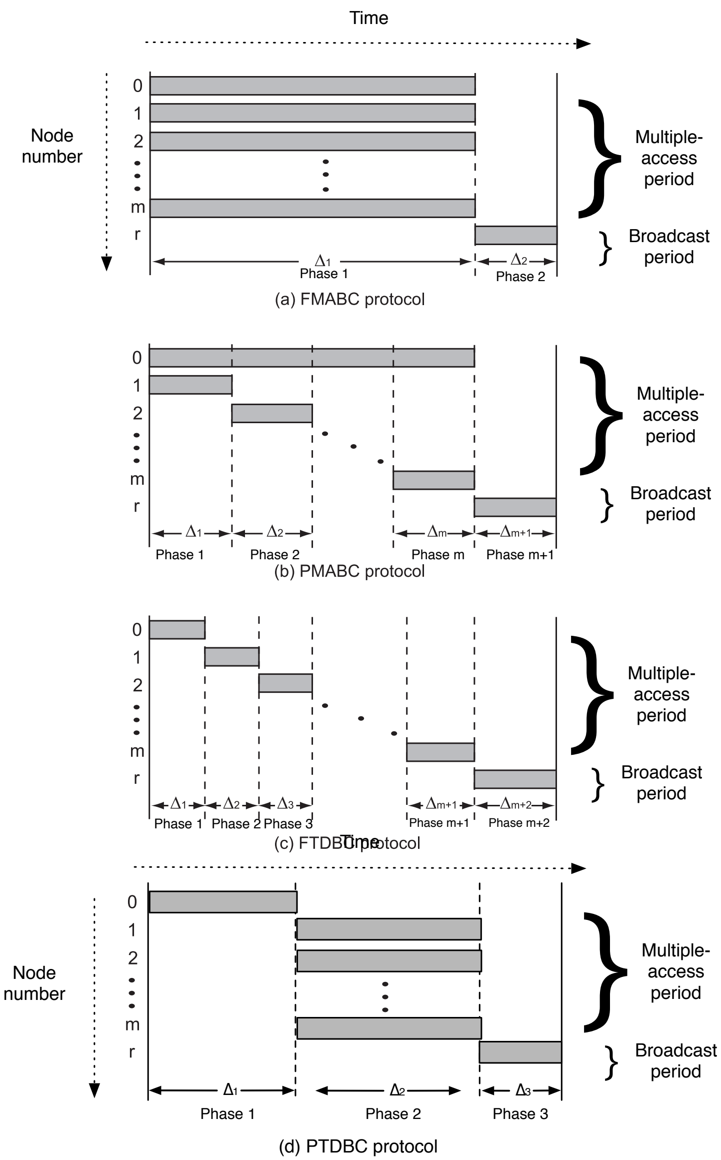
Which protocol is “better”?

1. Extended Marton’s region for broadcasting
2. Per-flow network coding
3. Random-binning to exploit side-information
4. CF-based Terminal node cooperation

Per-flow Network coding (N)



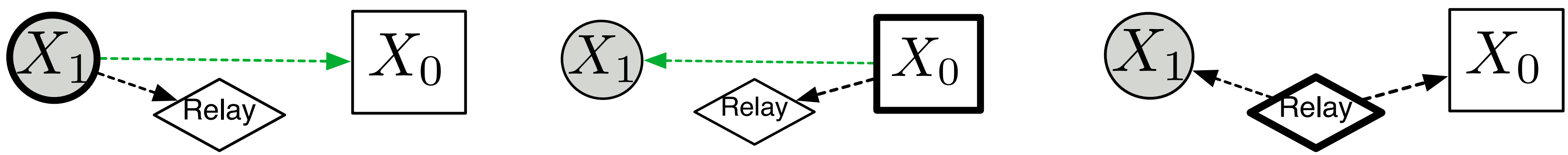




Which protocol is "better"?

1. Extended Marton's region for broadcasting
2. Per-flow network coding
3. Random-binning to exploit side-information
4. CF-based Terminal node cooperation

Random binning (R) for exploiting overheard information

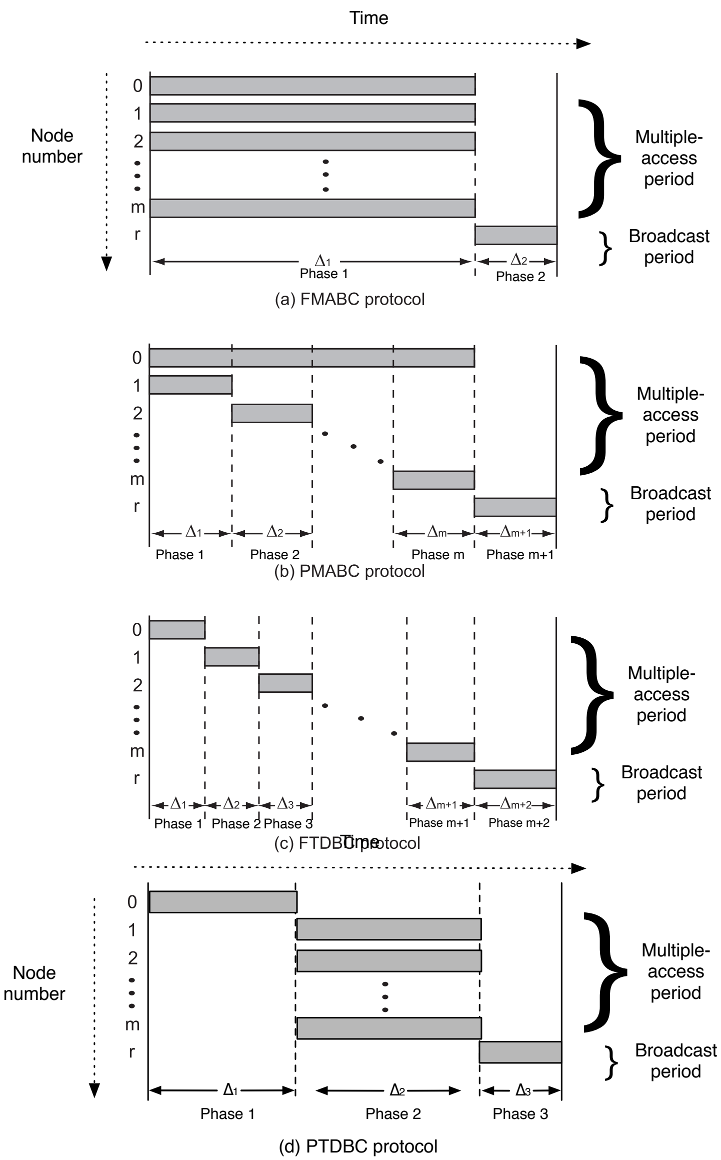


$$R_{1,0} \leq \Delta_1 I(X_1^{(1)}; Y_r^{(1)})$$

$$R_{1,0} \leq \Delta_1 I(X_1^{(1)}; Y_0^{(1)}) + \Delta_3 I(X_r^{(3)}; Y_0^{(3)})$$

$$R_{0,1} \leq \Delta_2 I(X_0^{(2)}; Y_r^{(2)})$$

$$R_{0,1} \leq \Delta_2 I(X_0^{(2)}; Y_1^{(2)}) + \Delta_3 I(X_r^{(3)}; Y_1^{(3)})$$

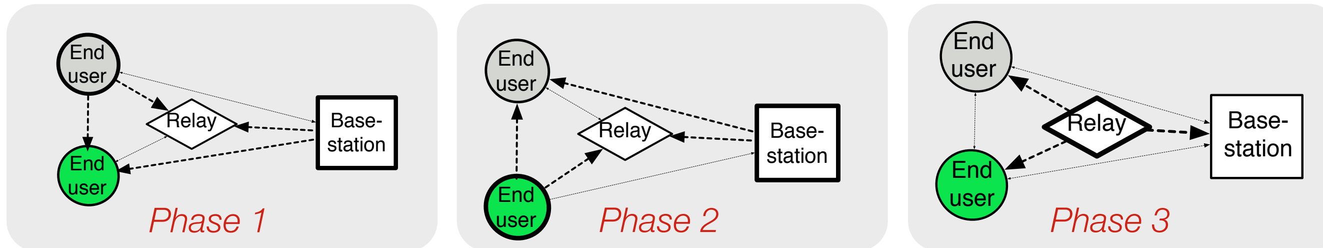


Which protocol is “better”?

1. Extended Marton’s region for broadcasting
2. Per-flow network coding
3. Random-binning to exploit side-information
4. CF-based Terminal node cooperation

Cooperation (C) between terminal nodes

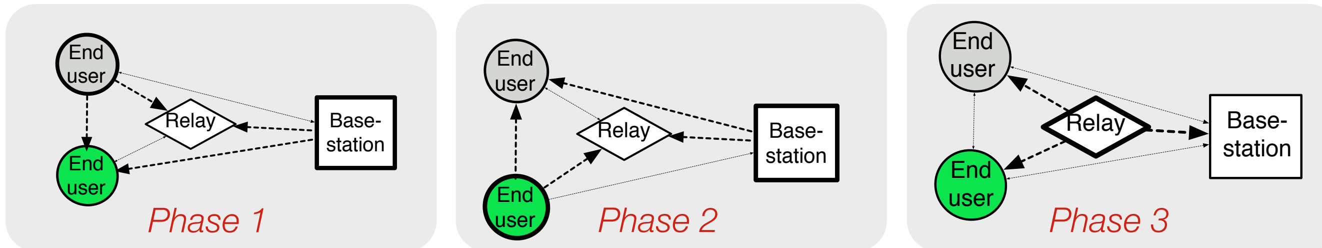
PMABC - NRC

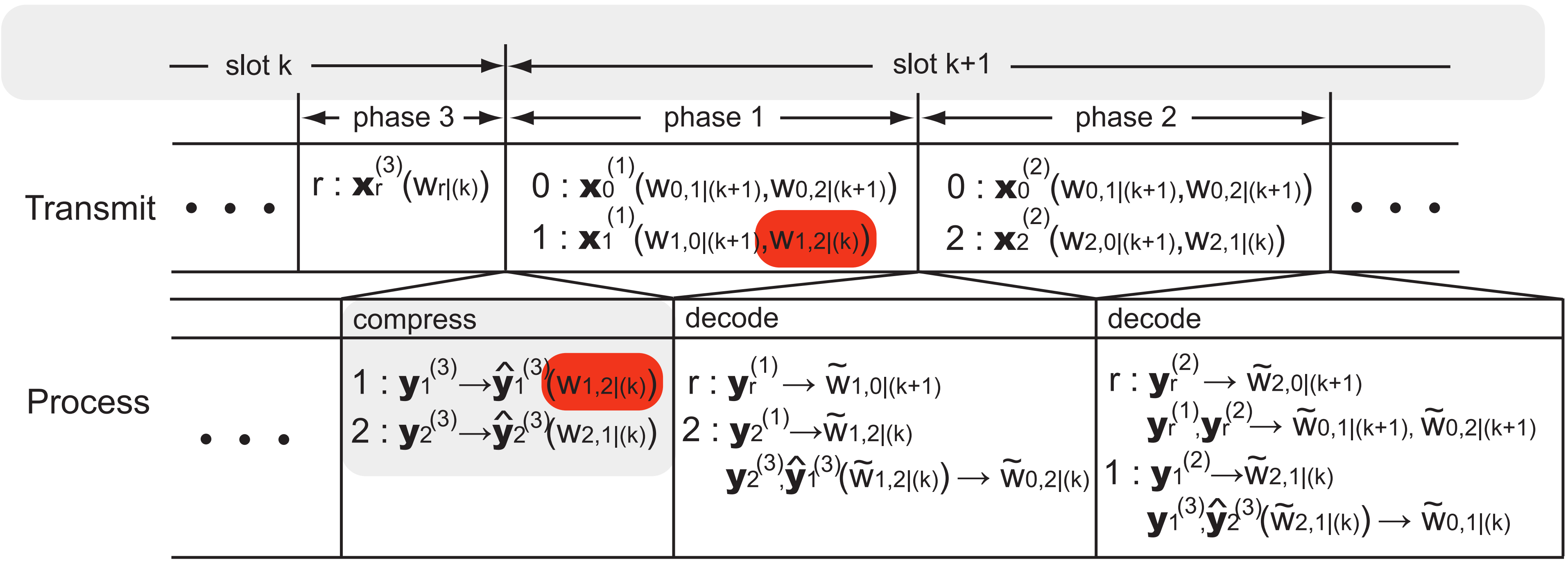


	slot k	slot k+1		
	phase 3	phase 1	phase 2	
Transmit • • •	r : $\mathbf{x}_r^{(3)}(w_{r\|(k)})$	0 : $\mathbf{x}_0^{(1)}(w_{0,1\|(k+1)}, w_{0,2\|(k+1)})$ 1 : $\mathbf{x}_1^{(1)}(w_{1,0\|(k+1)}, w_{1,2\|(k)})$	0 : $\mathbf{x}_0^{(2)}(w_{0,1\|(k+1)}, w_{0,2\|(k+1)})$ 2 : $\mathbf{x}_2^{(2)}(w_{2,0\|(k+1)}, w_{2,1\|(k)})$	• • •
	compress	decode	decode	
Process • • •	1 : $\mathbf{y}_1^{(3)} \rightarrow \hat{\mathbf{y}}_1^{(3)}(w_{1,2\|(k)})$ 2 : $\mathbf{y}_2^{(3)} \rightarrow \hat{\mathbf{y}}_2^{(3)}(w_{2,1\|(k)})$	r : $\mathbf{y}_r^{(1)} \longrightarrow \tilde{w}_{1,0\|(k+1)}$ 2 : $\mathbf{y}_2^{(1)} \rightarrow \tilde{w}_{1,2\|(k)}$ $\mathbf{y}_2^{(3)}, \hat{\mathbf{y}}_1^{(3)}(\tilde{w}_{1,2\|(k)}) \longrightarrow \tilde{w}_{0,2\|(k)}$	r : $\mathbf{y}_r^{(2)} \longrightarrow \tilde{w}_{2,0\|(k+1)}$ $\mathbf{y}_r^{(1)}, \mathbf{y}_r^{(2)} \longrightarrow \tilde{w}_{0,1\|(k+1)}, \tilde{w}_{0,2\|(k+1)}$ 1 : $\mathbf{y}_1^{(2)} \rightarrow \tilde{w}_{2,1\|(k)}$ $\mathbf{y}_1^{(3)}, \hat{\mathbf{y}}_2^{(3)}(\tilde{w}_{2,1\|(k)}) \longrightarrow \tilde{w}_{0,1\|(k)}$	

Cooperation (C) between terminal nodes

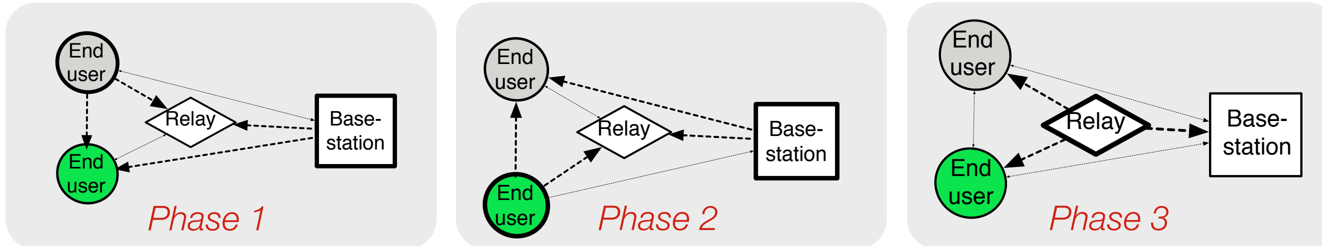
PMABC - NRC

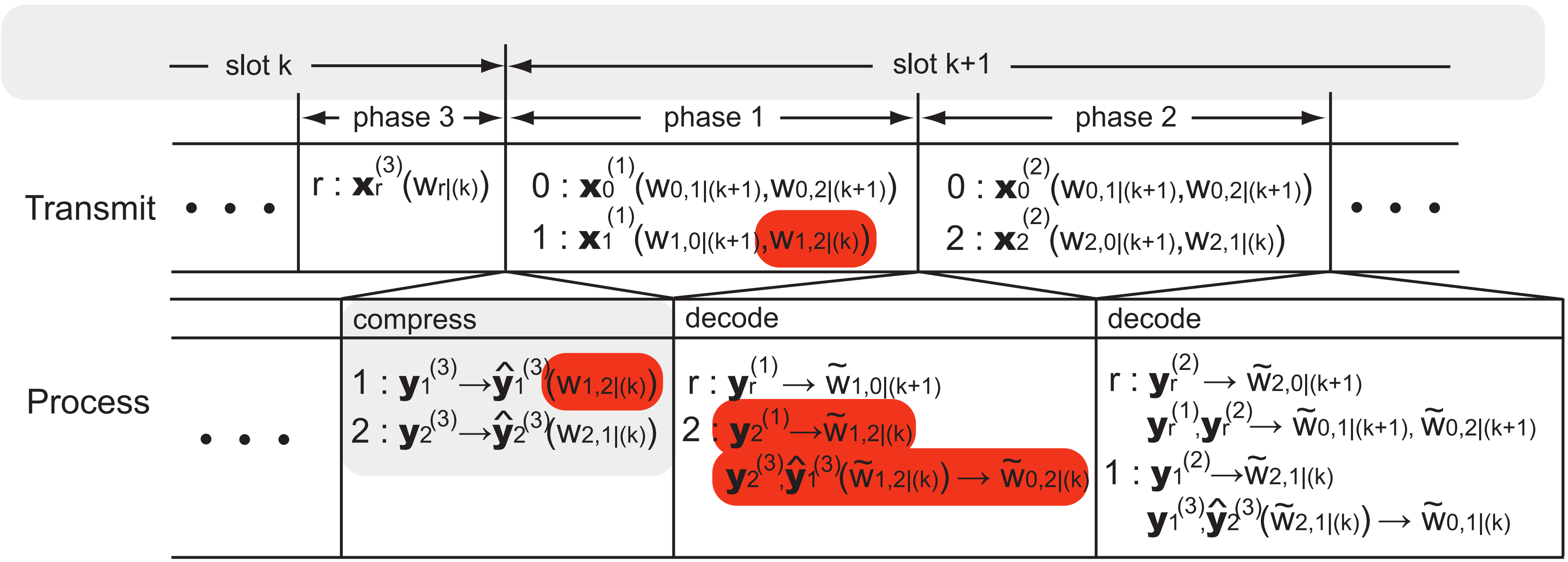




Cooperation (C) between terminal nodes

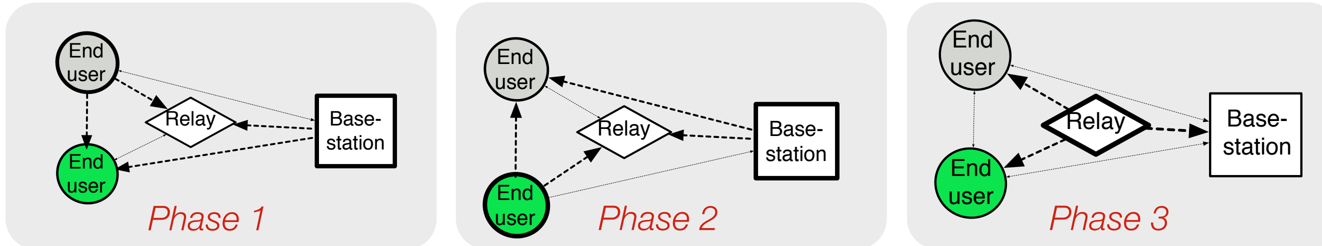
PMABC - NRC

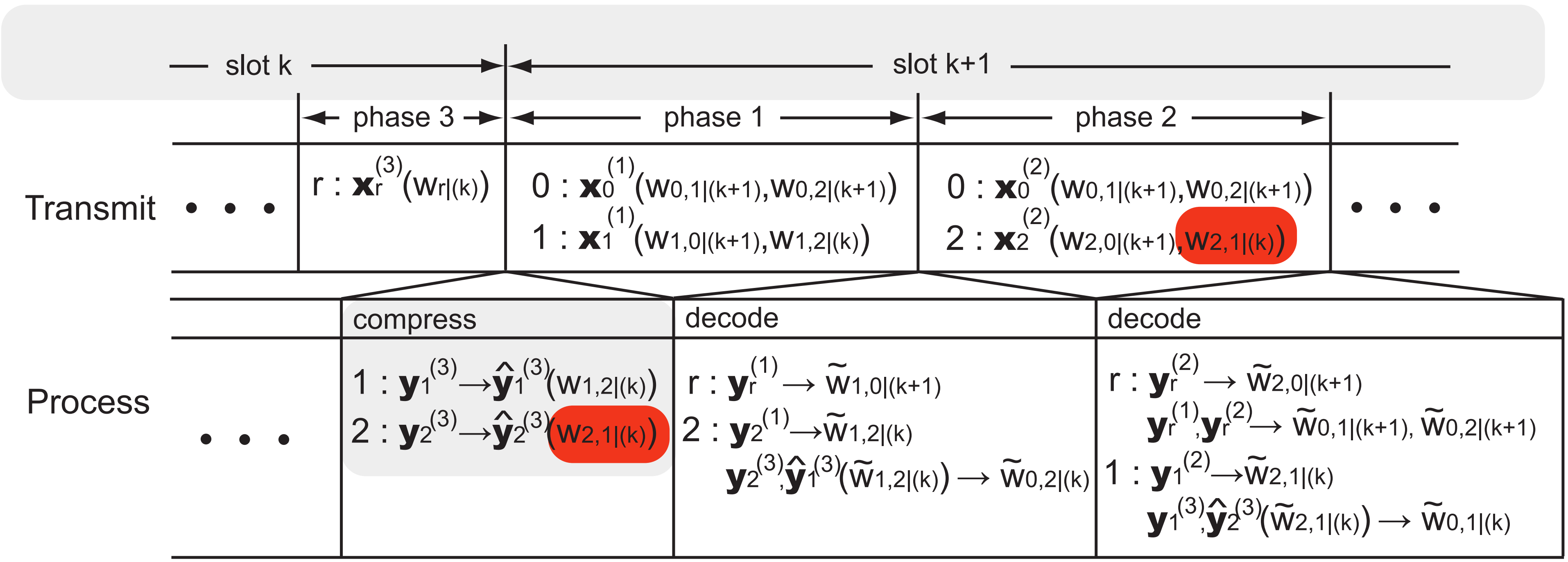




Cooperation (C) between terminal nodes

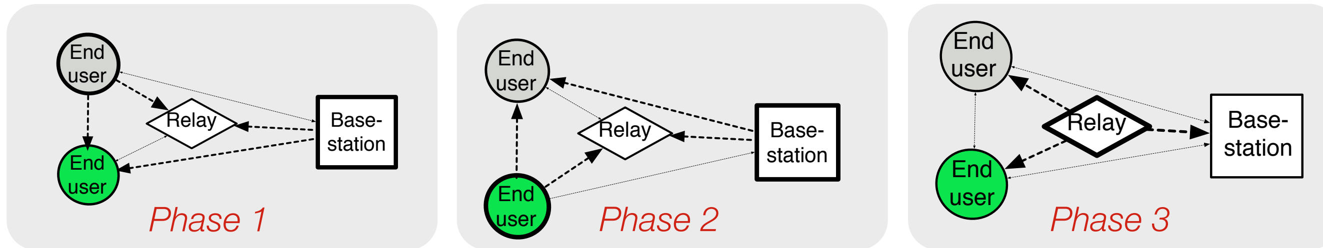
PMABC - NRC





Cooperation (C) between terminal nodes

PMABC - NRC



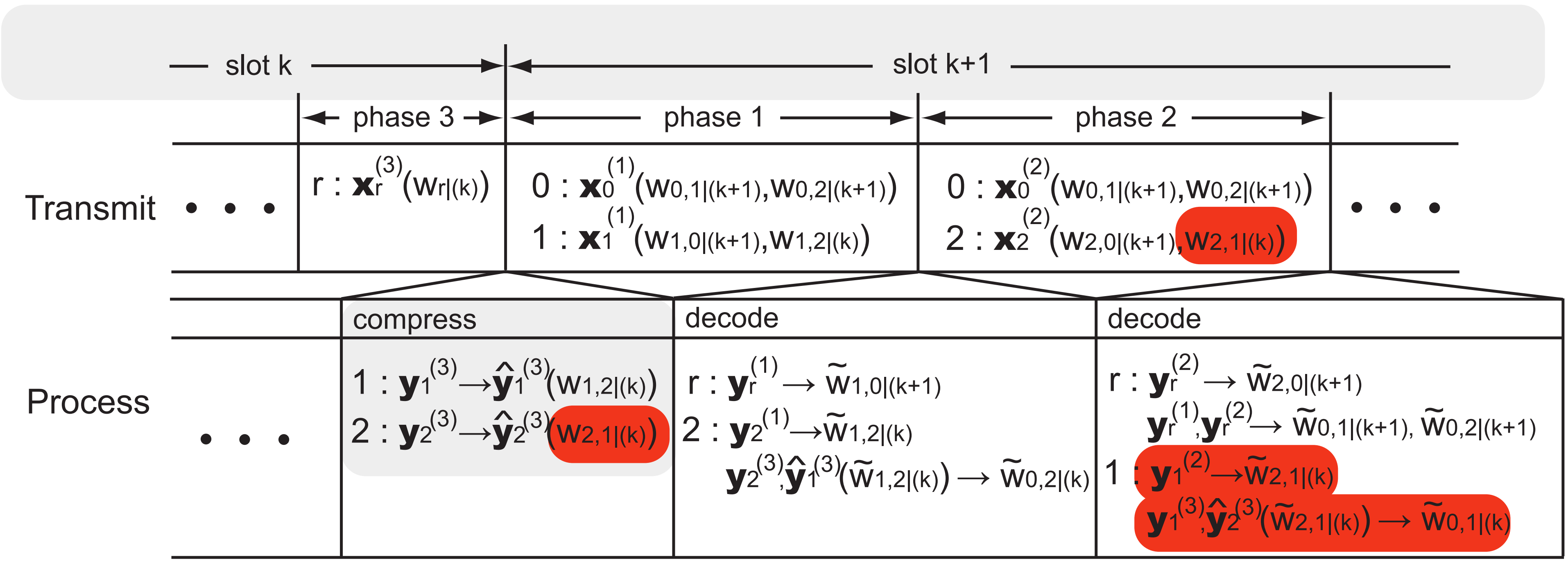


TABLE I

PROTOCOLS AND CODING SCHEMES

Protocol	Multiple Access	Marton's Broadcast	Network coding	Random binning	User cooperation
Simplest	–	–	–	–	–
FMABC	X	X	–	–	–
FMABC-N	X	X	X	–	–
PMABC	X	X	–	–	–
PMABC-NR	X	X	X	X	–
PMABC-NRC	X	X	X	X	X
FTDBC	–	X	–	–	–
FTDBC-NR	–	X	X	X	–
FTDBC-NRC	–	X	X	X	X
PTDBC	X	X	–	–	–
PTDBC-NR	X	X	X	X	–

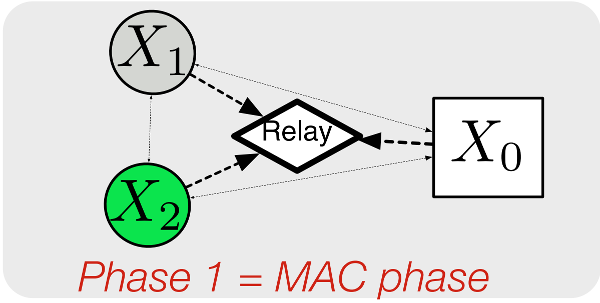
N = Network coding

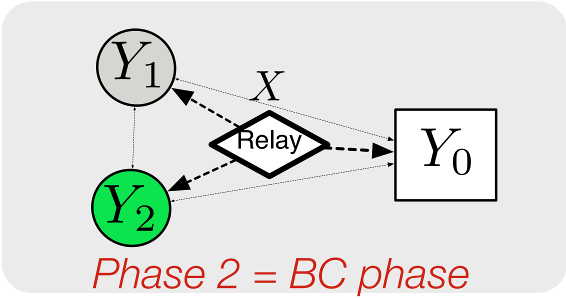
R = Random binning

C = Cooperation between terminals

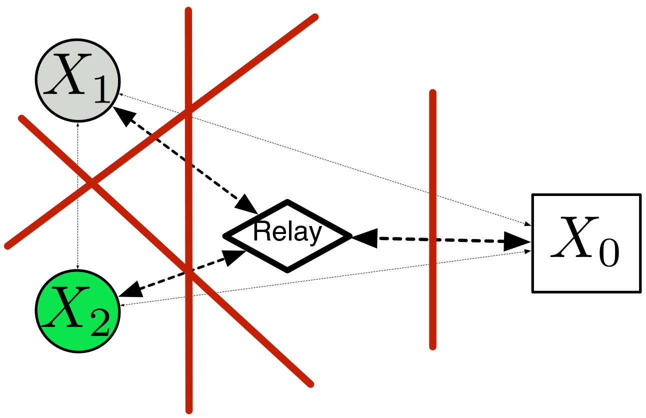
Outer bounds - half-duplex cut-set

FMABC

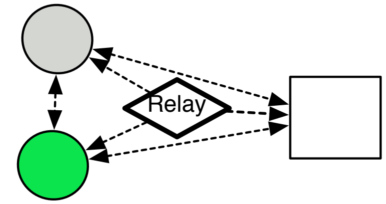




$$R_{0,1} + R_{0,2} \leq \Delta_1 I(X_0^{(1)}; Y_r^{(1)} | X_1^{(1)}, X_2^{(1)})$$
$$R_{1,0} + R_{2,0} \leq \Delta_2 I(X_r^{(2)}; Y_0^{(2)})$$
$$R_{1,0} \leq \Delta_1 I(X_1^{(1)}; Y_r^{(1)} | X_2^{(1)}, X_0^{(1)})$$
$$R_{2,0} \leq \Delta_1 I(X_2^{(1)}; Y_r^{(1)} | X_1^{(1)}, X_0^{(1)})$$
$$R_{1,0} + R_{2,0} \leq \Delta_1 I(X_1^{(1)}, X_2^{(1)}; Y_r^{(1)} | X_0^{(1)})$$
$$R_{0,1} \leq \Delta_2 I(X_r^{(2)}; Y_1^{(2)})$$
$$R_{0,2} \leq \Delta_2 I(X_r^{(2)}; Y_2^{(2)})$$
$$R_{0,1} + R_{0,2} \leq \Delta_2 I(X_r^{(2)}; Y_1^{(2)}, Y_2^{(2)})$$



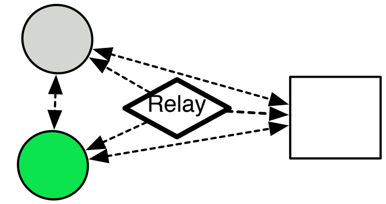
Simulations in Gaussian noise



$$\mathbf{Y}[k] = \mathbf{H}\mathbf{X}[k] + \mathbf{Z}[k]$$

$$\mathbf{H_1} = \begin{bmatrix} 0 & 0.3 & 0.05 & 1 \\ 0.3 & 0 & 1.5 & 1 \\ 0.05 & 1.5 & 0 & 0.2 \\ 1 & 1 & 0.2 & 0 \end{bmatrix} \quad \mathbf{H_2} = \begin{bmatrix} 0 & 0.9 & 0.4 & 1 \\ 0 & 0 & 0.02 & 1 \\ 0 & 0.02 & 0 & 0.5 \\ 1 & 1 & 0.5 & 0 \end{bmatrix}.$$

Simulations in Gaussian noise



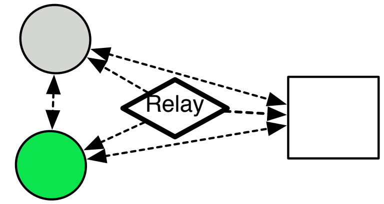
$$\mathbf{Y}[k] = \mathbf{H}\mathbf{X}[k] + \mathbf{Z}[k]$$

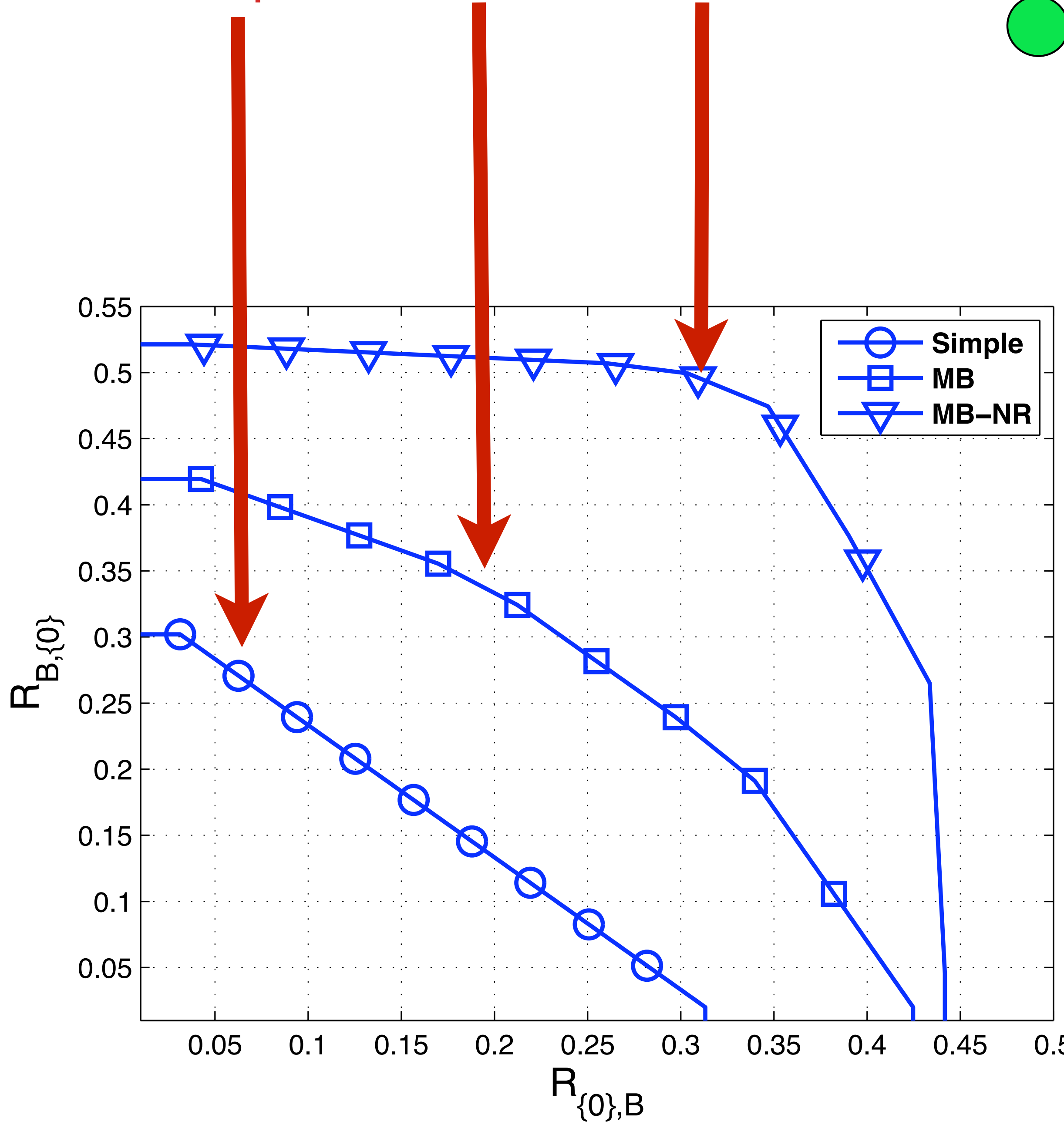
$$\mathbf{H_1} = \begin{bmatrix} 0 & 0.3 & 0.05 & 1 \\ 0.3 & 0 & 1.5 & 1 \\ 0.05 & 1.5 & 0 & 0.2 \\ 1 & 1 & 0.2 & 0 \end{bmatrix} \quad \mathbf{H_2} = \begin{bmatrix} 0 & 0.9 & 0.4 & 1 \\ 0 & 0 & 0.02 & 1 \\ 0 & 0.02 & 0 & 0.5 \\ 1 & 1 & 0.5 & 0 \end{bmatrix}.$$

Evaluate expressions assuming Gaussian input distributions and optimize over:

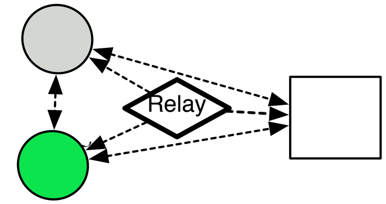
- phase durations
- correlation matrices of Marton binning RVs subject to power constraints
- compression parameters

Simple - MB - MB+NR





Network coding + random binning



FMABC

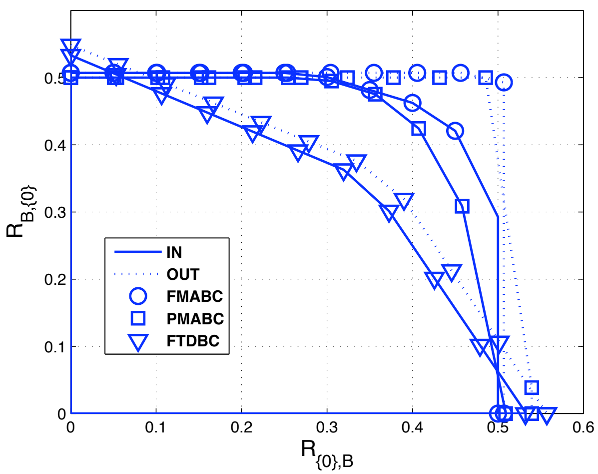


Fig. 7. Comparison with $P_0 = P_1 = P_2 = P_r = 0$ dB, $H = H_1$.

FMABC/ PMABC

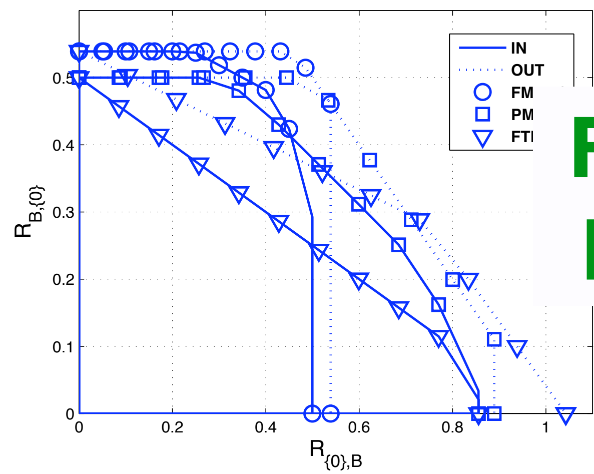


Fig. 8. Comparison with $P_0 = P_1 = P_2 = P_r = 0$ dB, $H = H_2$.

PMABC

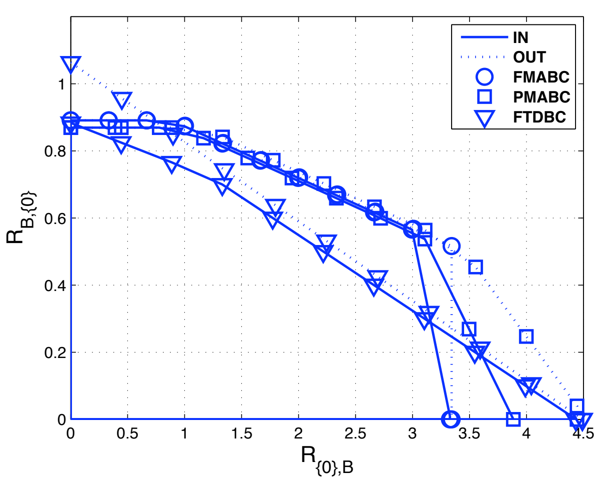


Fig. 9. Comparison with $P_0 = P_r = 20, P_1 = P_2 = 0$ dB, $H = H_1$.

FTDBC

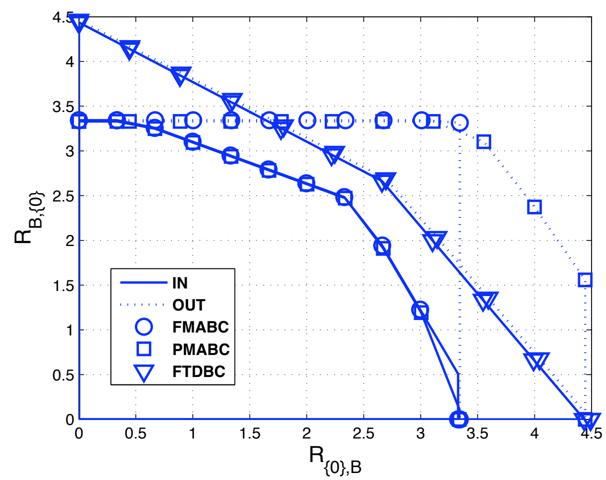
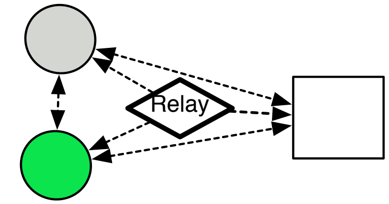
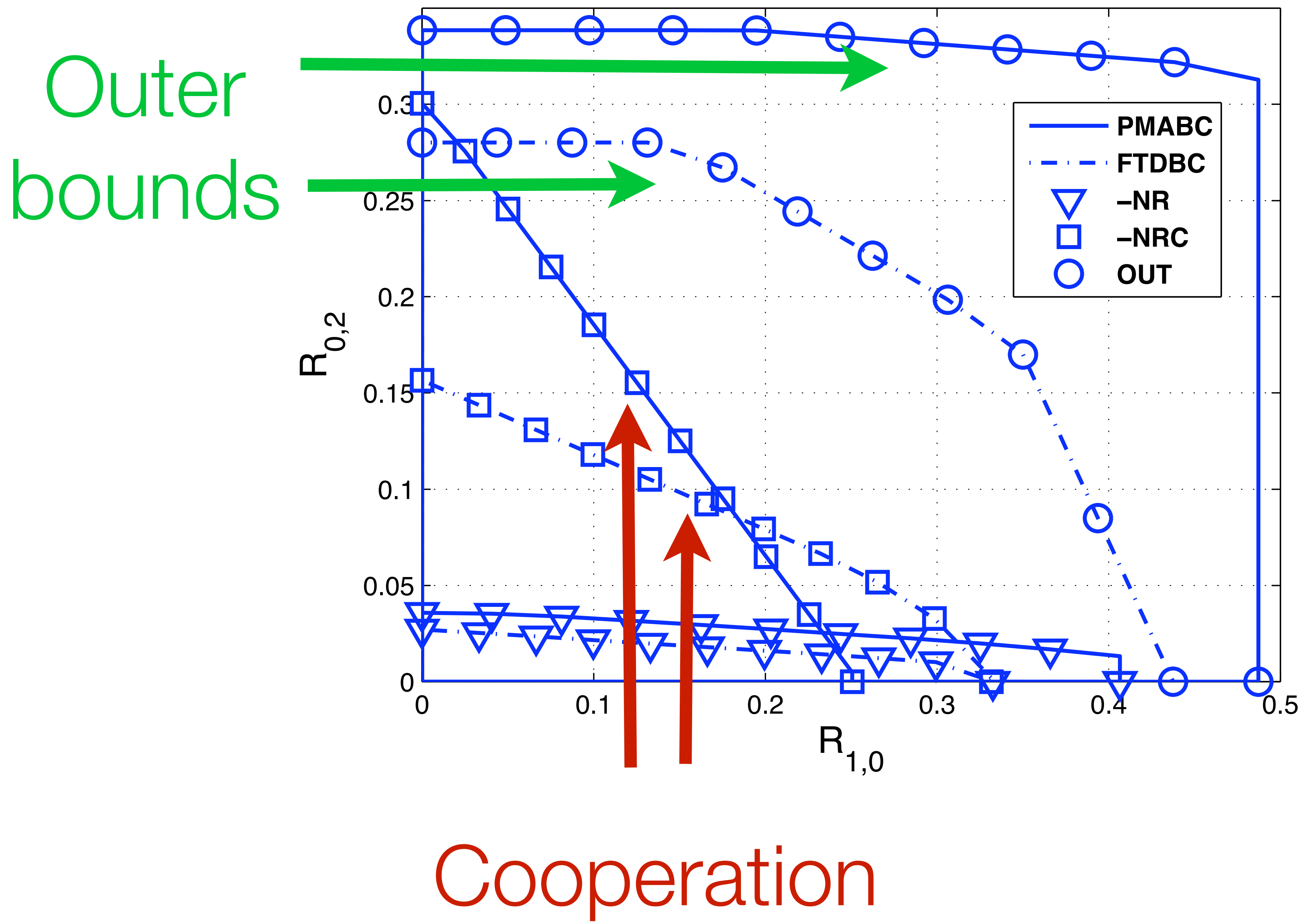


Fig. 10. Comparison with $P_0 = P_1 = P_2 = P_r = 20$ dB, $H = H_1$.


Relay


Outer bounds
Cooperation
PMABC
FTDBC
–NR
–NRC
OUT
R0,2
R1,0
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
0.5

Multiple terminals: with base-station

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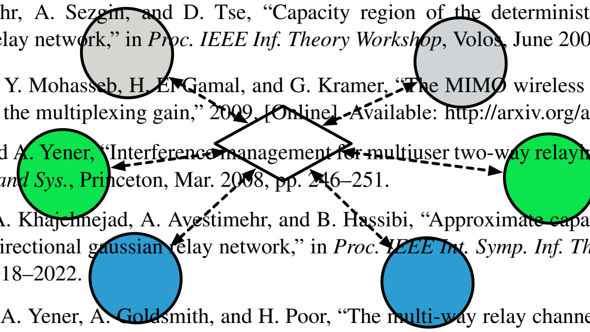

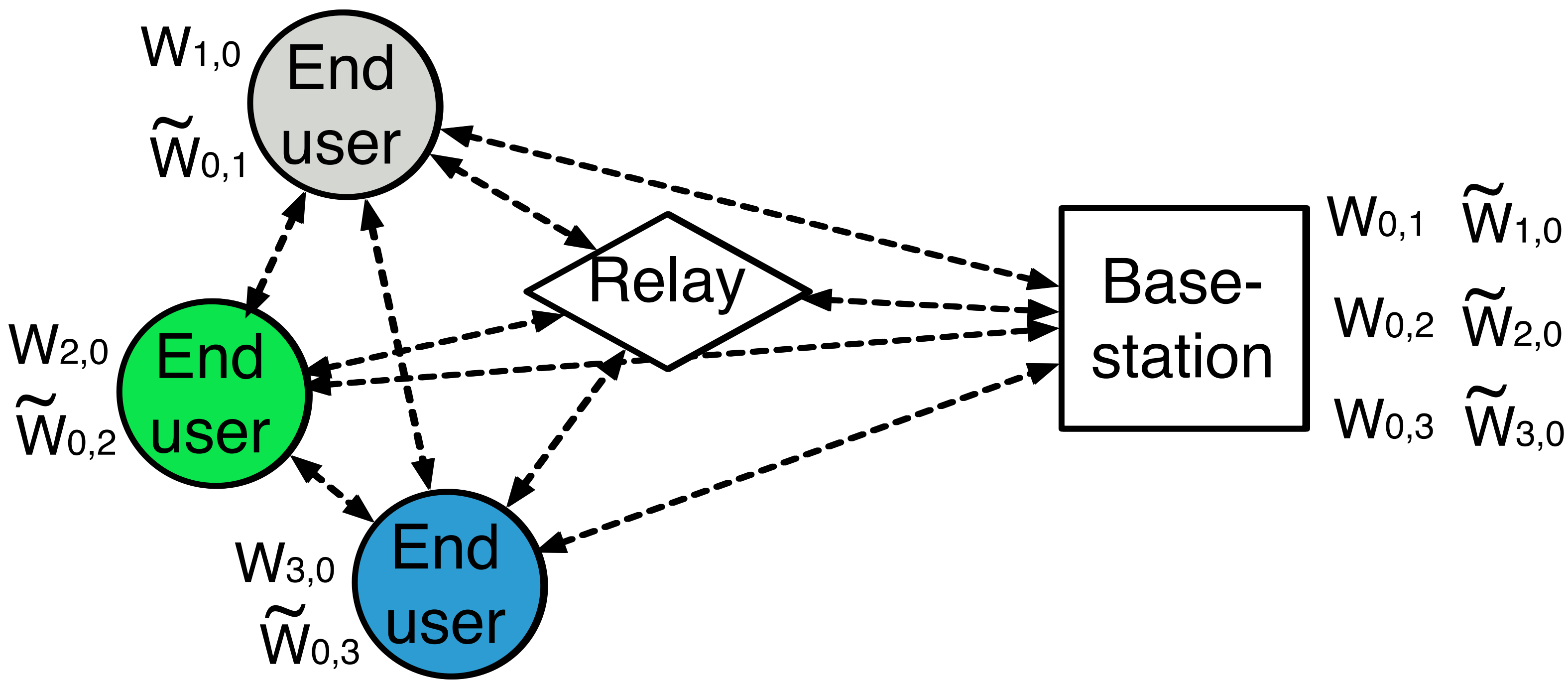

Arbitrary (m) number of end users

Questions?

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