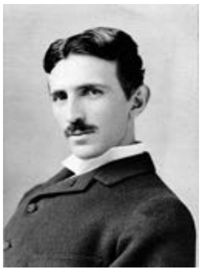
Fundamental Limits of Simultaneous Energy and Information Transmission

Selma Belhadj Amor and Samir M. Perlaza
Inria, Lyon, France

International Conference on Telecommunications (ICT)
Thessaloniki, Greece
May 17, 2016

Simultaneous Energy and Information Transmission: A Trade-Off??



When Tesla meets Shannon

Conflict $\Longrightarrow$ Trade-off between information and energy transmission rates

Example (Noiseless Transmission of a 4-PAM Signal in $\{-2, -1, 1, 2\}$)

- If no constraint is imposed on received energy rate $\longrightarrow$ can transmit 2 bits/ch.use
- If received energy rate is constrained to be
  - at maximum possible value $\longrightarrow$ can transmit 1 bit/ch.use
  - larger than a given value $\longrightarrow$ in some cases, can transmit 0 bits/ch.use

Outline

1 Point-to-point Information-Energy Trade-off

2 Multi-User Simultaneous Energy and Information Transmission

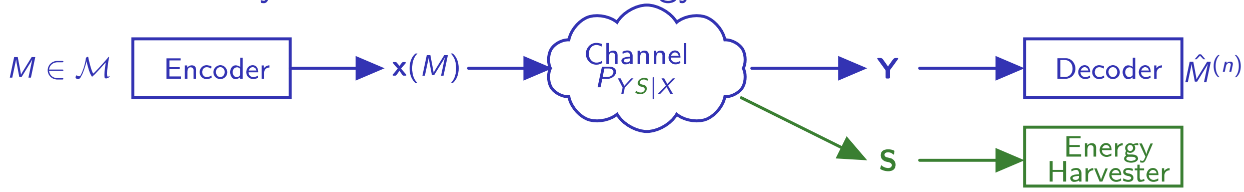
Discrete Memoryless Point-to-Point Channel

- Transmission blocklength n
- Finite input and output alphabets $\mathcal{X}$ and $\mathcal{Y}$
- Transition law $P_{Y|X}$ (memoryless)
- Transmitter sends message $M \in \mathcal{M} \triangleq \{1, 2, \ldots, 2^{nR}\}$
- Information rate R
- Decoder forms estimate $\hat{M}^{(n)}$

Probability of Error

$$P_{\text{error}}^{(n)}(R) \triangleq \Pr\left\{\hat{M}^{(n)} \neq M\right\}$$

Discrete Memoryless Channel with Energy Harvester



- Additional output alphabet $\mathcal{S}$; Transition law $P_{YS|X}$
- Energy function $\omega : \mathcal{S} \to \mathbb{R}_+$
- Harvested energy from $\mathbf{s} = (s_1, \ldots, s_n)$ is $\omega(\mathbf{s}) = \sum_{t=1}^{n} \omega(s_t)$
- Average energy rate (in energy-units per channel use) at the EH:

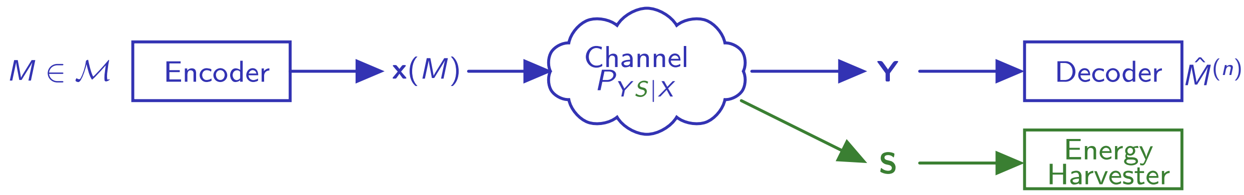
$$B^{(n)} \triangleq \frac{1}{n} \sum_{t=1}^{n} \omega(S_t).$$

- Minimum energy rate b at EH (in energy units per channel use)
- Energy rate B, with $b \leqslant B \leqslant B_{\max}$ ($B_{\max}$ is the maximum feasible energy rate)
- Guarantee $B^{(n)} \geqslant B$ with high probability

Probability of Energy Outage

$$P^{(n)}_{\text{outage}}(B) \triangleq \Pr\left\{B^{(n)} < B - \epsilon\right\}, \ \epsilon > 0 \text{ arbitrarily small}$$

Simultaneous Energy and Information Transmission (SEIT)



Objective of SEIT

Provide blocklength-n coding schemes such that:

(i) information transmission occurs at rate R with $P^{(n)}_{\text{error}}(R) \to 0$; and

(ii) energy transmission occurs at rate B with $P^{(n)}_{\text{outage}}(B) \to 0$ and $B \geq b$.

Under these conditions, the information-energy rate-pair (R, B) is achievable.

$\Rightarrow$ What is the fundamental limit on information rate for a given energy rate?

Information Capacity Under Minimum Energy Rate b

For each blocklength n, define the function $C^{(n)}(b)$ as follows:

$$C^{(n)}(b) \triangleq \max_{X^n : B^{(n)} \geqslant b} I(X^n; Y^n).$$

Definition: Information-Energy Capacity Function [Varshney'08]

The information-energy capacity function for a minimum energy rate b is defined as

$$C(b) \triangleq \limsup_{n \to \infty} \frac{1}{n} C^{(n)}(b).$$

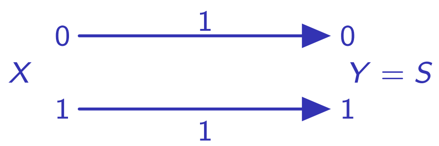
Theorem: Information Capacity Under Minimum Energy Rate [Varshney'08]

The supremum over all achievable information rates in the DMC under a minimum energy rate b in energy-units per channel use is given by $C(b)$ in bits/ch. use.

L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE International Symposium on Information Theory*, Jul. 2008, pp. 1612–1616.

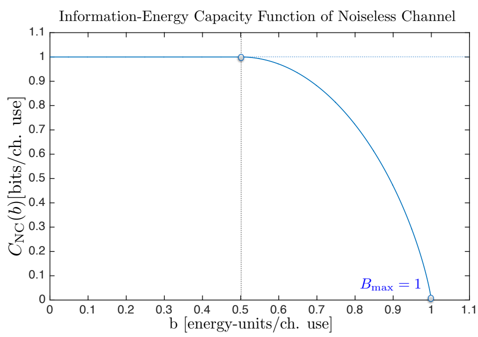
Example: Noiseless binary channel

- $S = Y$
- $P(1|1) = P(0|0) = 1$ and $P(1|0) = P(1|0) = 0$
- Channel capacity: $C = 1$ bit/ch.use.
- Capacity-achieving dist: Ber($\frac{1}{2}$)
- Symbol 1 $\longrightarrow$ 1 energy-unit & Symbol 0 $\longrightarrow$ 0 energy-unit
- Maximum energy: $B_{\max} = 1$ energy-units/ch.use (Symbol '1' always sent)



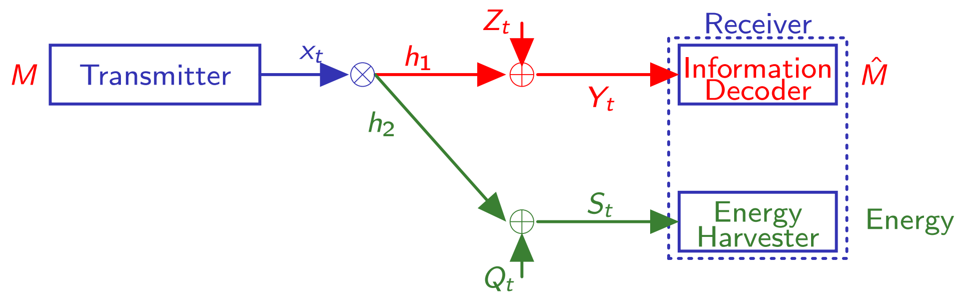
Information-Energy Capacity Function [Varshney'08]

$$C_{\text{NC}}(b) = \begin{cases} 1, & \text{if } 0 \leqslant b \leqslant \frac{1}{2}, \\ H_2(b), & \text{if } \frac{1}{2} \leqslant b \leqslant 1, \end{cases}$$



$\Rightarrow$ The more stringent the energy rate constraint is, the more the transmitter needs to switch over to using the most energetic symbol

Gaussian Memoryless Channel with Energy Harvester



$$\text{Information Decoder:} \quad Y_t = h_1 X_t + Z_t,$$
$$\text{Energy harvester:} \quad S_t = h_2 X_t + Q_t$$

- $X_t, Q_t, Z_t \in \mathbb{R}$;
- Constant channel coefs $h_1, h_2 \geqslant 0$ satisfying :

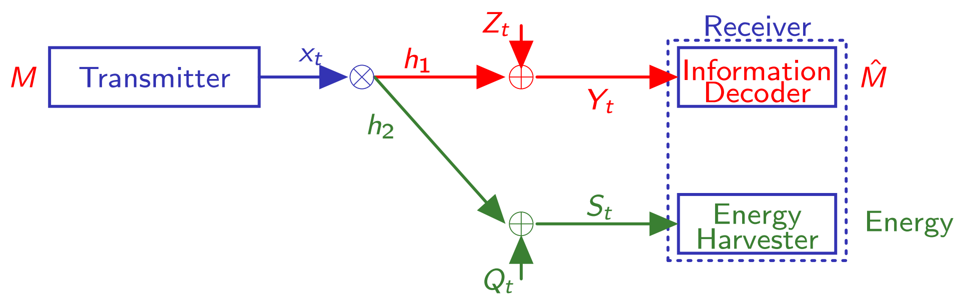
$$\|\mathbf{h}\|^2 \leqslant 1, \text{ with } \mathbf{h} \triangleq (h_1, h_2)^{\mathsf{T}} \quad \text{(energy conservation principle)}$$

- $\{Z_t\}, \{Q_t\}$ i.i.d. $\sim \mathcal{N}(0,1)$
- Input power constraints: $\frac{1}{n}\sum_{t=1}^{n} \mathrm{E}\left[X_t^2\right] \leqslant P$.
- Fully described by signal-to-noise ratios:

$$\mathrm{SNR}_i \triangleq |h_i|^2 P, \quad i \in \{1,2\}x.$$

- Output energy function: $\omega(s) \triangleq s^2$

Gaussian Memoryless Channel with Energy Harvester



- Capacity $\mathcal{C}(0,P) = \frac{1}{2}\log_2(1+\mathrm{SNR}_1)$
- Maximum energy rate $B_{\max} \triangleq 1 + \mathrm{SNR}_2$
- Optimal dist: $\mathcal{N}(0,P)$

Information-Energy Capacity Function $\mathcal{C}_{\mathrm{GC}}(b,P)$ [Belhadj Amor et al.'16]

For any $0 \leqslant b \leqslant 1 + \mathrm{SNR}_2$, the information-energy capacity function is

$$\mathcal{C}_{\mathrm{GC}}(b,P) = \max_{X:\mathrm{E}[X^2]\leqslant P \text{ and } \mathrm{E}[S^2]\geqslant b} I(X;Y) = \frac{1}{2}\log_2\left(1+\mathrm{SNR}_1\right) = \mathcal{C}(0,P).$$

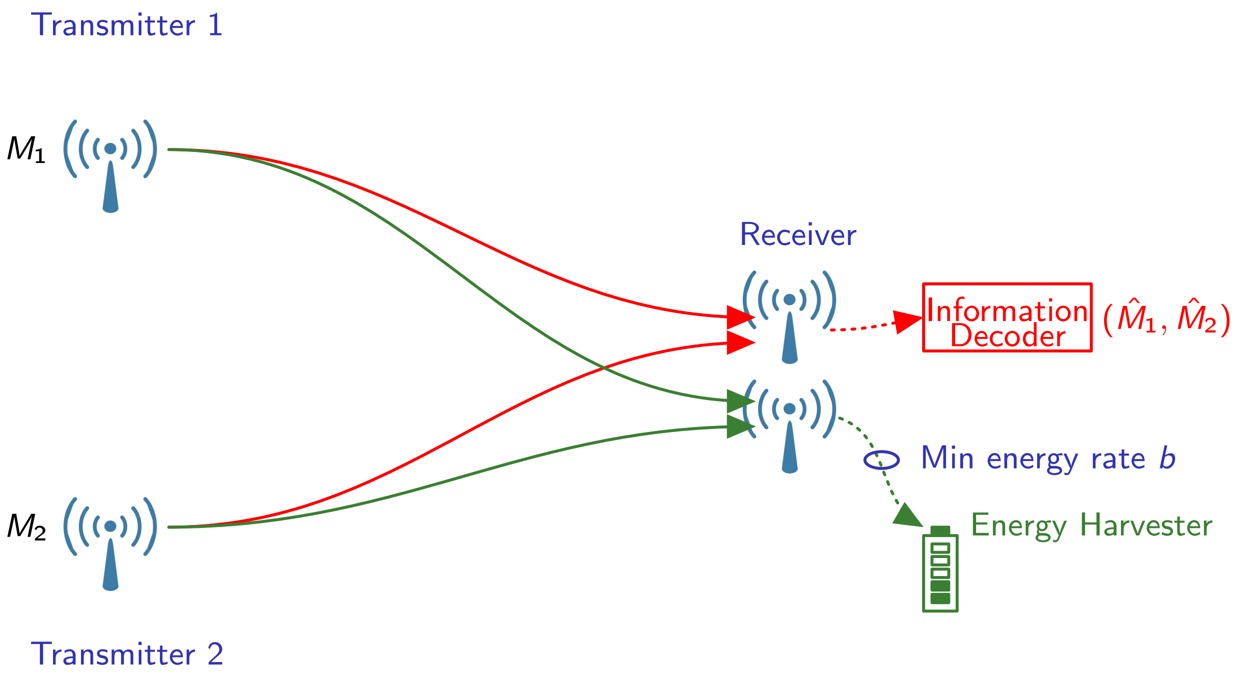
$\Longrightarrow$ For any feasible energy rate $0 \leqslant b \leqslant 1 + \mathrm{SNR}_2$ the information-optimal strategy is unchanged.

Outline

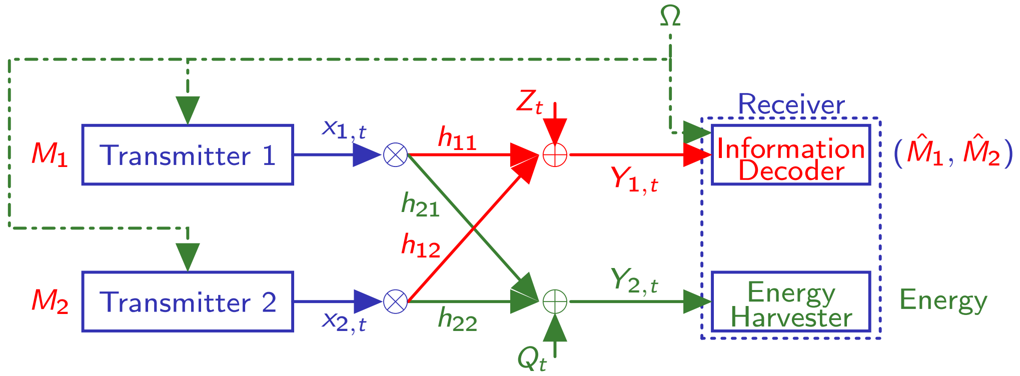
1 Point-to-point Information-Energy Trade-off

2 Multi-User Simultaneous Energy and Information Transmission

Multi-Access Channel With Minimum Energy Rate Constraint b



Gaussian Multiple Access Channel With Energy Harvester



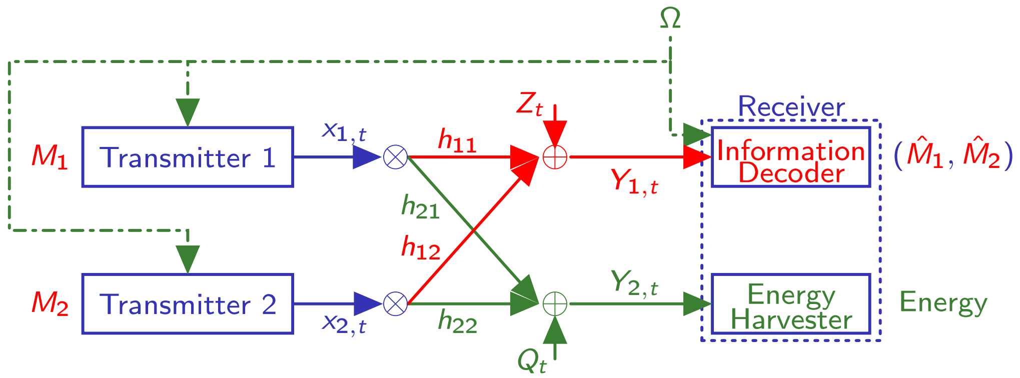
Information Decoder: $Y_{1,t} = h_{11}X_{1,t} + h_{12}X_{2,t} + Z_t$
Energy harvester: $Y_{2,t} = h_{21}X_{1,t} + h_{22}X_{2,t} + Q_t$

- n: blocklength
- $X_{1,t}, X_{2,t}, Q_t, Z_t \in \mathbb{R}$;
- Constant channel coefs $h_{11}, h_{12}, h_{21}, h_{22} \geqslant 0$ satisfying :

$$\forall j \in \{1,2\}, \|\mathbf{h}_j\|_2 \leq 1, \text{ with } \mathbf{h}_j \triangleq (h_{j1}, h_{j2})^{\mathsf{T}} \quad \text{(energy conservation principle)}$$

- $\{Z_t\}, \{Q_t\}$ i.i.d. $\sim \mathcal{N}(0,1)$
- Input power constraints: $P_i \triangleq \frac{1}{n}\sum_{t=1}^{n} \mathrm{E}\left[X_{i,t}^2\right] \leqslant P_{i,\max}, \quad i \in \{1,2\}$.
- Fully described by signal-to-noise ratios: $\mathrm{SNR}_{ji} \triangleq |h_{ji}|^2 P_{i,\max}, \quad (i,j) \in \{1,2\}^2$.

Information Transmission

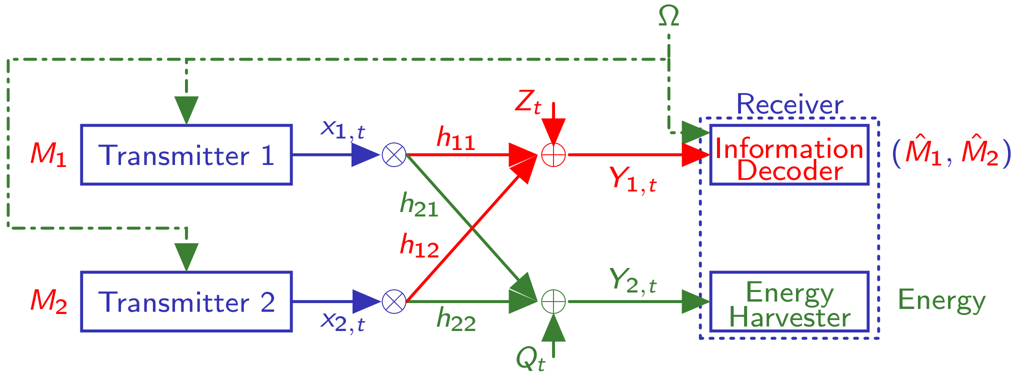


- Transmitters 1 and 2 send M_1 and M_2 to the information decoder
- Messages M_1 and M_2 independent ; $M_i \sim \mathcal{U}\{1, \dots, 2^{nR_i}\}$
- R_1 and R_2 are information transmission rates
- Common randomness Ω known to all terminals

Probability of Error

$$P_{\text{error}}^{(n)}(R_1, R_2) \triangleq \Pr\left\{(\hat{M}_1^{(n)}, \hat{M}_2^{(n)}) \neq (M_1, M_2)\right\}$$

Energy Transmission



- Minimum energy rate b at EH (in energy units per channel use) such that

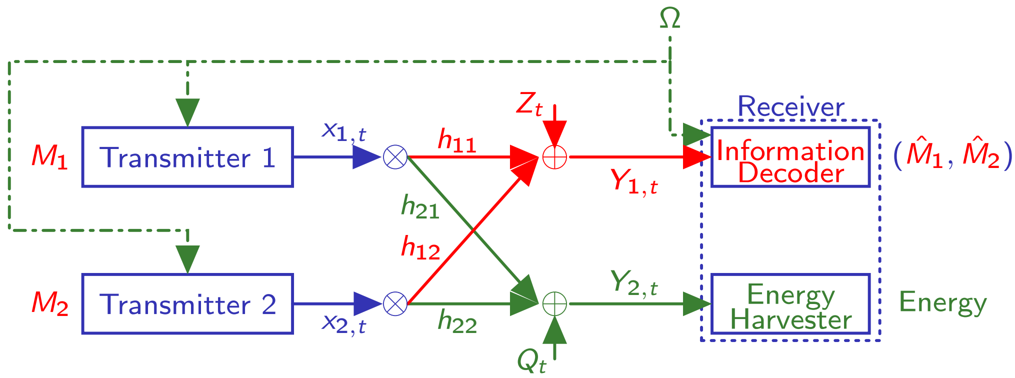
$$0 \leqslant b \leqslant 1 + \mathrm{SNR}_{21} + \mathrm{SNR}_{22} + 2\sqrt{\mathrm{SNR}_{21}\mathrm{SNR}_{22}}$$

- Average energy rate: $B^{(n)} \triangleq \frac{1}{n}\sum_{t=1}^{n} Y_{2,t}^2$
- B energy rate such that with $b \leqslant B \leqslant 1 + \mathrm{SNR}_{21} + \mathrm{SNR}_{22} + 2\sqrt{\mathrm{SNR}_{21}\mathrm{SNR}_{22}}$
- Guarantee $B^{(n)} \geqslant B$ with high probability

Probability of Energy Outage

$$P_{\text{outage}}^{(n)}(B) \triangleq \Pr\left\{B^{(n)} < B - \epsilon\right\}, \ \epsilon > 0 \text{ arbitrarily small}$$

Simultaneous Energy and Information Transmission (SEIT)



Objective of SEIT

Provide blocklength-n coding schemes such that:

(i) information transmission occurs at rates R_1 and R_2 with $P_{\text{error}}^{(n)}(R_1, R_2) \to 0$; and

(ii) energy transmission occurs at rate B with $P_{\text{outage}}^{(n)}(B) \to 0$ and $B \geq b$.

Under these conditions, the information-energy rate-triplet (R_1, R_2, B) is achievable in the G-MAC with minimum energy rate b.

⇒ What are the fundamental limits on achievable information-energy rate-triplets?

Information-Energy Capacity Region $\mathcal{E}_b(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$

[Belhadj Amor et al.'15]

Theorem: Information-Energy Capacity Region $\mathcal{E}_b(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$

$\mathcal{E}_b(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$ contains all (R_1, R_2, B) that satisfy

$$
\begin{aligned}
0 \leqslant & \quad R_1 & \leqslant \frac{1}{2}\log_2\left(1+\beta_1\,\mathrm{SNR}_{11}\right),\\
0 \leqslant & \quad R_2 & \leqslant \frac{1}{2}\log_2\left(1+\beta_2\,\mathrm{SNR}_{12}\right),\\
0 \leqslant & R_1+R_2 & \leqslant \frac{1}{2}\log_2\left(1+\beta_1\,\mathrm{SNR}_{11}+\beta_2\,\mathrm{SNR}_{12}\right),\\
b \leqslant & \quad B & \leqslant 1+\mathrm{SNR}_{21}+\mathrm{SNR}_{22}+2\sqrt{(1-\beta_1)\mathrm{SNR}_{21}(1-\beta_2)\mathrm{SNR}_{22}},
\end{aligned}
$$

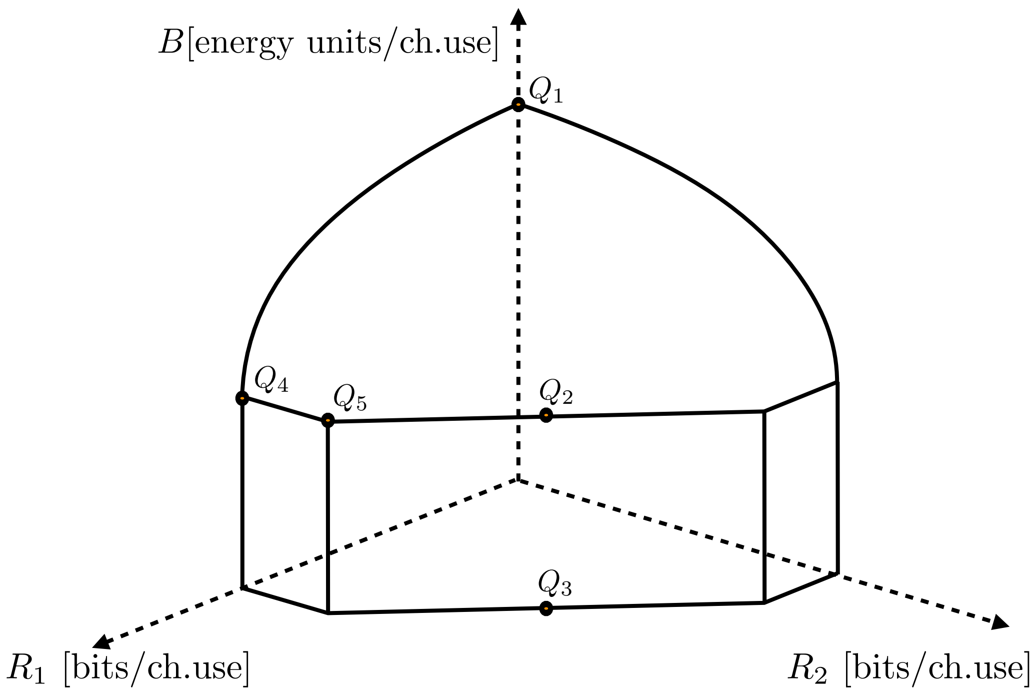
with $(\beta_1, \beta_2) \in [0,1]^2$.

- β_i : power-splitting coefficient at transmitter i
- $\beta_i P_{i,\max}$ to transmit information-carrying (IC) component ([Cover'75] and [Wyner'76])
- $(1-\beta_i)P_{i,\max}$ to transmit energy-carrying (EC) component (common randomness)

S. B., S. M. Perlaza, I. Krikidis and H. V. Poor. "Feedback enhances simultaneous wireless information and energy transmission in multiple access channels", Technical Report, INRIA, No. 8804, Lyon, France, Nov., 2015.

3-D Representation of $\mathcal{E}_0(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$

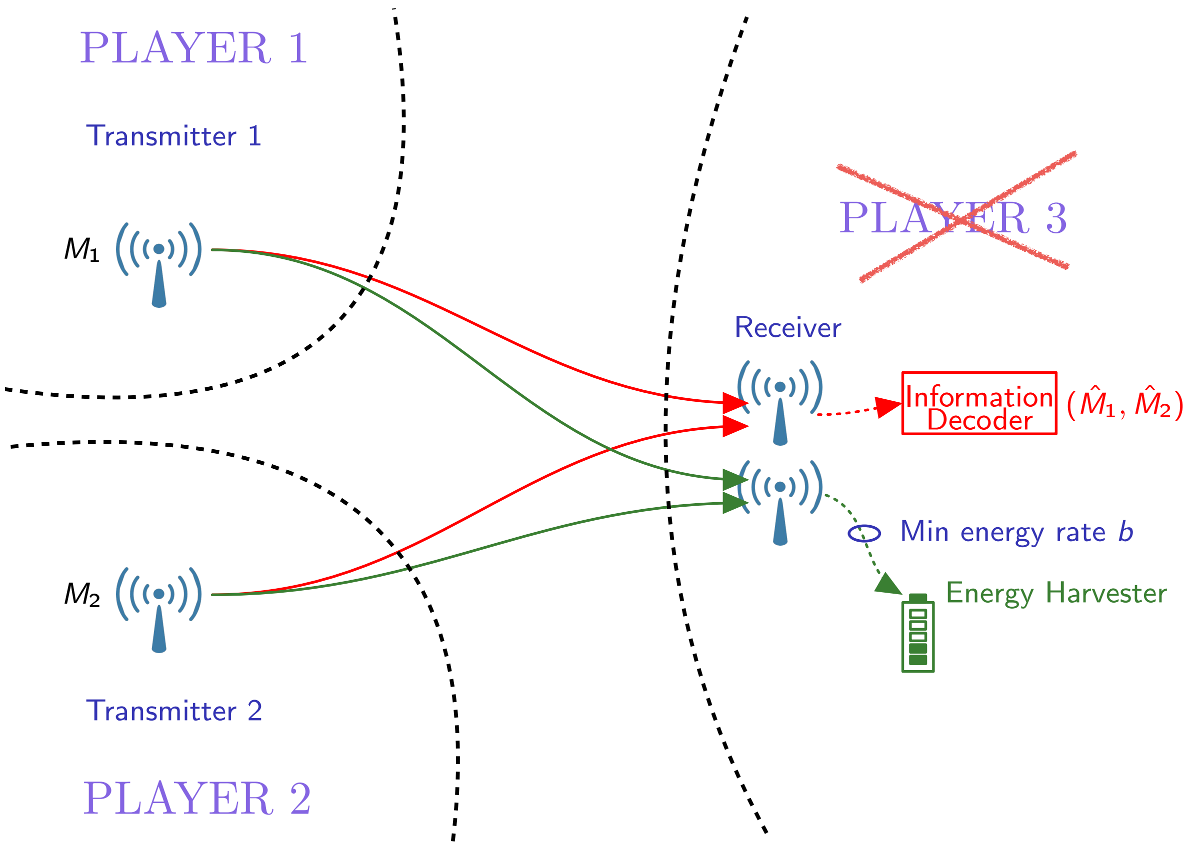
$\mathrm{SNR}_{11} = \mathrm{SNR}_{12} = \mathrm{SNR}_{21} = \mathrm{SNR}_{22} = 10$



Centralized Versus Decentralized SEIT

- Centralized:
  - A central controller determines a network operating point
  - Tx/Rx configuration or each component is imposed by controller
  - Central controller optimizes a network metric
  - → All $(R_1, R_2, B) \in \mathcal{E}_b(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$ are feasible operating points
- Decentralized:
  - Each component is autonomous
  - Each component determines its own Tx/Rx configuration
  - Each component optimizes an individual metric
  - → Only some $(R_1, R_2, B) \in \mathcal{E}_b(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$ are stable

Decentralized MAC with Minimum Energy Rate Constraint b



Game Formulation

Consider the following game in normal form:

$$\mathcal{G}(b) = \left(\mathcal{K}, \{\mathcal{A}_k\}_{k\in\mathcal{K}}, \{u_k\}_{k\in\mathcal{K}}\right)$$

- $b \in [0, 1 + \mathrm{SNR}_{21} + \mathrm{SNR}_{22} + 2\sqrt{\mathrm{SNR}_{21}\mathrm{SNR}_{22}}]$
- Set of players $\mathcal{K} = \{1, 2\}$
- Sets of actions $\mathcal{A}_1$ and $\mathcal{A}_2$
- Utility function $u_i : \mathcal{A}_1 \times \mathcal{A}_2 \rightarrow \mathbb{R}_+$ such that

$$u_i(s_1, s_2) = \begin{cases} R_i(s_1, s_2), & \text{if} \quad P_{\text{error}}^{(n)}(R_1, R_2) < \epsilon \text{ and } P_{\text{outage}}^{(n)}(b) < \delta \\ -1, & \quad\quad \text{otherwise,} \end{cases}$$

  where $\epsilon > 0$ and $\delta > 0$ are arbitrarily small.

Game Formulation

- A transmit configuration $s_i \in \mathcal{A}_i$ can be described in terms of:
  - Information rates R_i
  - Block-length n
  - Power-split β_i
  - Average input power P_i
  - Common randomness Ω
  - Channel input alphabet $\mathcal{X}_i$
  - Encoding functions $f_i^{(1)}, \ldots, f_i^{(n)}$, etc

- Receiver adopts a fixed decoding strategy

η-Nash Equilibrium (η-NE)

Definition (η-Nash Equilibrium)

Let $\eta \geqslant 0$. In the game $\mathcal{G}(b) = \left(\mathcal{K}, \{\mathcal{A}_k\}_{k\in\mathcal{K}}, \{u_k\}_{k\in\mathcal{K}}\right)$, an action profile (s_1^*, s_2^*) is an η-Nash equilibrium if for all $i \in \mathcal{K}$ and for all $s_i \in \mathcal{A}_i$, it holds that

$$u_i(s_i, s_j^*) \leqslant u_i(s_i^*, s_j^*) + \eta.$$

- If $\eta = 0$, we obtain the classical definition of Nash equilibrium.
- At any η-NE and for all $i \in \mathcal{K}$, player i cannot obtain a utility improvement bigger than η by changing its own action s_i (stability)

J. F. Nash, "Equilibrium points in n-person games," *Proc. of the National Academy of Sciences*, vol. 36, pp. 48–49, 1950.

η-Nash Equilibrium Region

Definition (η-Nash Equilibrium Region)

Let $\eta \geqslant 0$. An $(R_1, R_2, B) \in \mathcal{E}_b(\mathrm{SNR}_{11}, \mathrm{SNR}_{12}, \mathrm{SNR}_{21}, \mathrm{SNR}_{22})$ is said to be in the η-NE region of the game $\mathcal{G}(b) = \left(\mathcal{K}, \{\mathcal{A}_k\}_{k\in\mathcal{K}}, \{u_k\}_{k\in\mathcal{K}}\right)$ if there exists an action profile $(s_1^*, s_2^*) \in \mathcal{A}_1 \times \mathcal{A}_2$ that is an η-NE and the following holds:

$$u_1(s_1^*, s_2^*) = R_1 \text{ and } u_2(s_1^*, s_2^*) = R_2.$$

η-Nash Equilibrium Region with Single User Decoding (SUD)
[Belhadj Amor et al.'16]

Theorem: $\mathcal{N}_{\mathrm{SUD}}(b)$: η-Nash Equilibrium Region of $\mathcal{G}(b)$ with SUD

The set $\mathcal{N}_{\mathrm{SUD}}(b)$ contains all $(R_1, R_2, B) \in \mathcal{E}_b(\mathsf{SNR}_{11}, \mathsf{SNR}_{12}, \mathsf{SNR}_{21}, \mathsf{SNR}_{22})$ such that:

$$0 \leqslant R_1 = \frac{1}{2}\log_2\left(1 + \frac{\beta_1 \mathsf{SNR}_{11}}{1 + \beta_2 \mathsf{SNR}_{12}}\right),$$
$$0 \leqslant R_2 = \frac{1}{2}\log_2\left(1 + \frac{\beta_2 \mathsf{SNR}_{12}}{1 + \beta_1 \mathsf{SNR}_{11}}\right),$$
$$b \leqslant B \leqslant 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22} + 2\sqrt{(1-\beta_1)\mathsf{SNR}_{21}(1-\beta_2)\mathsf{SNR}_{22}},$$

where $\beta_1 = \beta_2 = 1$ when $b \in [0, 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22}]$ and (β_1, β_2) satisfy

$$b = 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22} + 2\sqrt{(1-\beta_1)\mathsf{SNR}_{21}(1-\beta_2)\mathsf{SNR}_{22}}$$

when $b \in (1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22}, 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22} + 2\sqrt{\mathsf{SNR}_{21}\mathsf{SNR}_{22}}]$.

η-Nash Equilibrium Region with Successive Interference Cancellation (SIC)
[Belhadj Amor et al.'16]

- $\mathrm{SIC}(i \to j)$: receiver uses SIC with decoding order: transmitter i before j.

Theorem: $\mathcal{N}_{\mathrm{SIC}(i\to j)}(b)$: η-Nash Equilibrium Region of $\mathcal{G}(b)$ with SIC($i \to j$)

The set $\mathcal{N}_{\mathrm{SIC}(i\to j)}(b)$ contains all $(R_1, R_2, B) \in \mathcal{E}_b(\mathsf{SNR}_{11}, \mathsf{SNR}_{12}, \mathsf{SNR}_{21}, \mathsf{SNR}_{22})$ such that:

$$0 \leqslant R_i = \frac{1}{2}\log_2\left(1 + \frac{\beta_i \mathsf{SNR}_{1i}}{1 + \beta_j \mathsf{SNR}_{1j}}\right),$$
$$0 \leqslant R_j = \frac{1}{2}\log_2\left(1 + \beta_j \mathsf{SNR}_{1j}\right),$$
$$b \leqslant B \leqslant 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22} + 2\sqrt{(1-\beta_1)\mathsf{SNR}_{21}(1-\beta_2)\mathsf{SNR}_{22}},$$

where $\beta_1 = \beta_2 = 1$ when $b \in [0, 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22}]$ and (β_1, β_2) satisfy

$$b = 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22} + 2\sqrt{(1-\beta_1)\mathsf{SNR}_{21}(1-\beta_2)\mathsf{SNR}_{22}}$$

when $b \in (1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22}, 1 + \mathsf{SNR}_{21} + \mathsf{SNR}_{22} + 2\sqrt{\mathsf{SNR}_{21}\mathsf{SNR}_{22}}]$.

η-Nash Equilibrium Region of $\mathcal{G}(b)$

[Belhadj Amor et al.'16]

- Any time-sharing combination between SUD, SIC($1 \to 2$), and SIC($2 \to 1$)

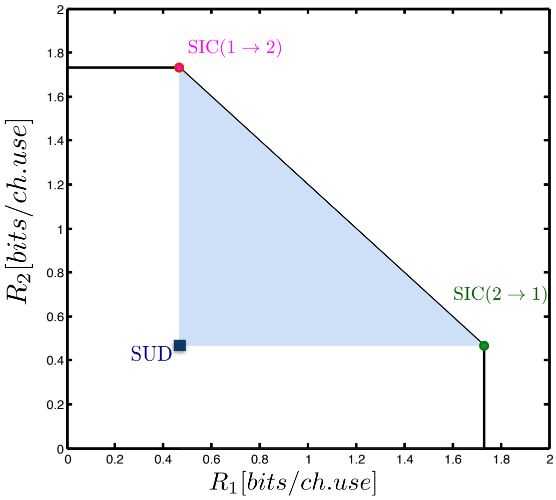
Theorem: $\mathcal{N}(b) \triangleq \eta$-Nash Equilibrium Region of $\mathcal{G}(b)$

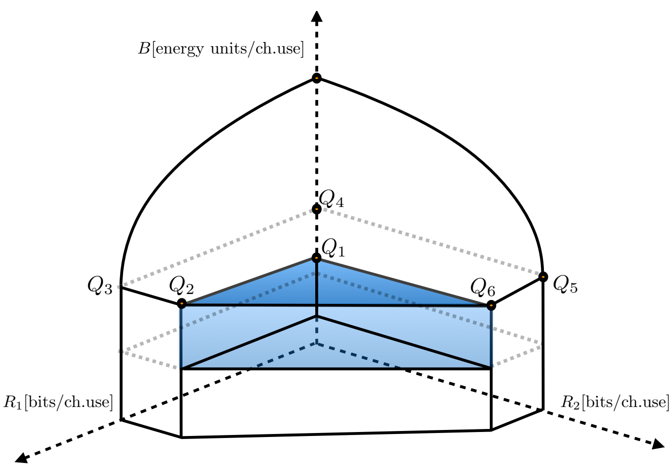
The set $\mathcal{N}(b)$ is defined as:

$$\mathcal{N}(b) = \text{Convex hull}\left(\mathcal{N}_{\mathrm{SUD}}(b) \cup \mathcal{N}_{\mathrm{SIC}(1\to 2)}(b) \cup \mathcal{N}_{\mathrm{SIC}(2\to 1)}(b)\right).$$

η-Nash Equilibrium Region for $b \leqslant 1 + \mathrm{SNR}_{21} + \mathrm{SNR}_{22}$

Projection over the plane R_1-R_2 for $\mathrm{SNR}_{11} = \mathrm{SNR}_{12} = \mathrm{SNR}_{21} = \mathrm{SNR}_{22} = 10$

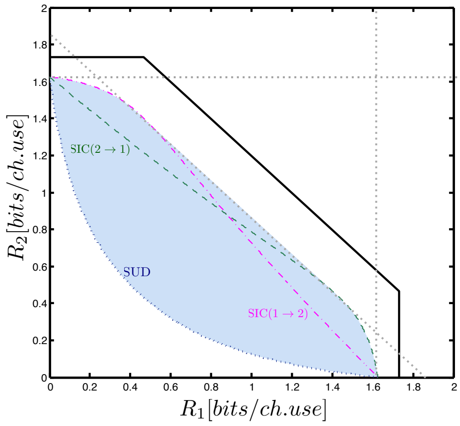


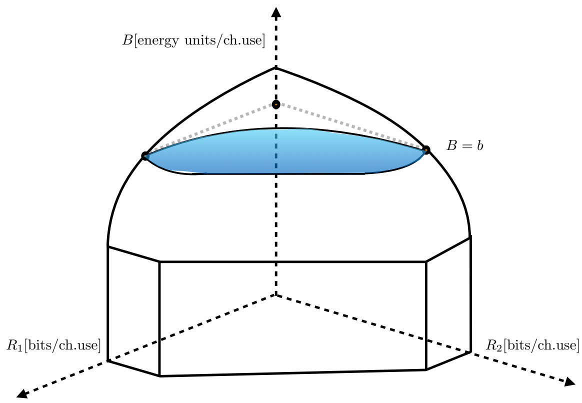


- Square point: Projection of $\mathcal{N}_{\mathrm{SUD}}(b)$
- Round points: Projection of $\mathcal{N}_{\mathrm{SIC}(i\to j)}(b)$
- Region inside solid lines: Projection of $\mathcal{E}_0(10, 10, 10, 10)$
- Blue region: Projection of convex hull of $\mathcal{N}_{\mathrm{SUD}}(b) \cup \mathcal{N}_{\mathrm{SIC}(1\to 2)}(b) \cup \mathcal{N}_{\mathrm{SIC}(2\to 1)}(b)$

η-Nash Equilibrium Region for $b = 0.7B_{\max} > 1 + \mathrm{SNR}_{21} + \mathrm{SNR}_{22}$.

Projection over the plane R_1-R_2 for $\mathrm{SNR}_{11} = \mathrm{SNR}_{12} = \mathrm{SNR}_{21} = \mathrm{SNR}_{22} = 10$





- Dotted line: Projection of $\mathcal{N}_{\mathrm{SUD}}(b)$
- Dashed line: Projection of $\mathcal{N}_{\mathrm{SIC}(i \to j)}(b)$
- Region inside solid lines: Projection of $\mathcal{E}_0(10, 10, 10, 10)$
- Blue region: Projection of convex hull of $\mathcal{N}_{\mathrm{SUD}}(b) \cup \mathcal{N}_{\mathrm{SIC}(1\to2)}(b) \cup \mathcal{N}_{\mathrm{SIC}(2\to1)}(b)$

Summary

- SEIT in point-to-point channels
  - Fundamental limits on information rate for a minimum energy rate b characterized by information-energy capacity function
  - Information-energy trade-off is not always observed!
- SEIT in multi-user channels
  - Centralized G-MAC with minimum energy rate constraint:
    - Fundamental limits characterized by information-energy capacity region
  - Decentralized G-MAC with minimum energy rate constraint
    - Fundamental limits characterized by η-NE information-energy region
    - There always exists an η-NE
    - There always exists a Pareto-optimal η-NE
- Open problems:
  - Extension to $K \geqslant 2$-users
  - Other Equilibria concepts (Stackelberg, Satisfaction, etc.)
  - SEIT in other multi-user channels (Broadcast channel, interference channel, etc)