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[Tutorial Lecture-3] Distributed Lossy Multi-terminal Communications over Fading MAC and Decision Making

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First of All….

Tutorial Rules:

- I don't like one-way speech-type seminar. I like interactive discussions.
- Stop me at anytime when you come across difficulties of any kinds in understanding, and ask me questions (I will speak as slowly as the time allows me to do).
- We are all living in the engineering community where we share the same atmosphere : we do not need formality! Let's call each other by the first name (Please call me "Tad")

Home

How my Tutorial Lecture goes as …..

1. Background (Very briefly: 5 min) Summary of Tutorial-1, -2

2. E2E Lossless (10 min, including background theory introduction)

   Mainly for Speech, Video, High Resolution Applications …

3. E2E Lossy (30 min, including background theory introduction)

   Mainly for IoT, Distributed Sensing, Edge Computing ….

4. Towards URLLC (15 min, Correlated Source MAC Transmission)

   4.1 E2E Lossless

   4.2 E2E Lossy

5. Decision Making (10 min, Connection to Distributed Hypothesis Testig)

Home

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Bretagne-Pays de la Loire
École Mines-Télécom

CWC Oulu

JAIST JAPAN ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY 1990

Copied from Abstract

Network Information Theory is an extension of Shannon's Information Theory to Networks. We believe that the key to the successful development of *generation-less* mobile wireless communication systems concepts should be to best-utilize the latest results of Network Information Theory in the most suitable forms, so as to satisfy network objectives and requirements in efficient way. As such, identifying the theoretical performance limits of such systems is of most crucial importance. This Tutorial follows the previous two tutorial lectures[1], [2] that the first presenter has provided previously in the IEICE RCS meetings and is the last talk of the lecturer series provide along with the concept described above.

It has been shown in the two previous tutorial lectures that the theoretical basis for analyzing the performance of End-to-End Lossless wireless cooperative communication networks is Lossless Distributed Multiterminal Source Coding in Network Information Theory; The distributed multi-terminal assumption is required because cooperative networks are assumed to have massive wireless devices.

⋮

1. Background

JAIST
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IMT Atlantique
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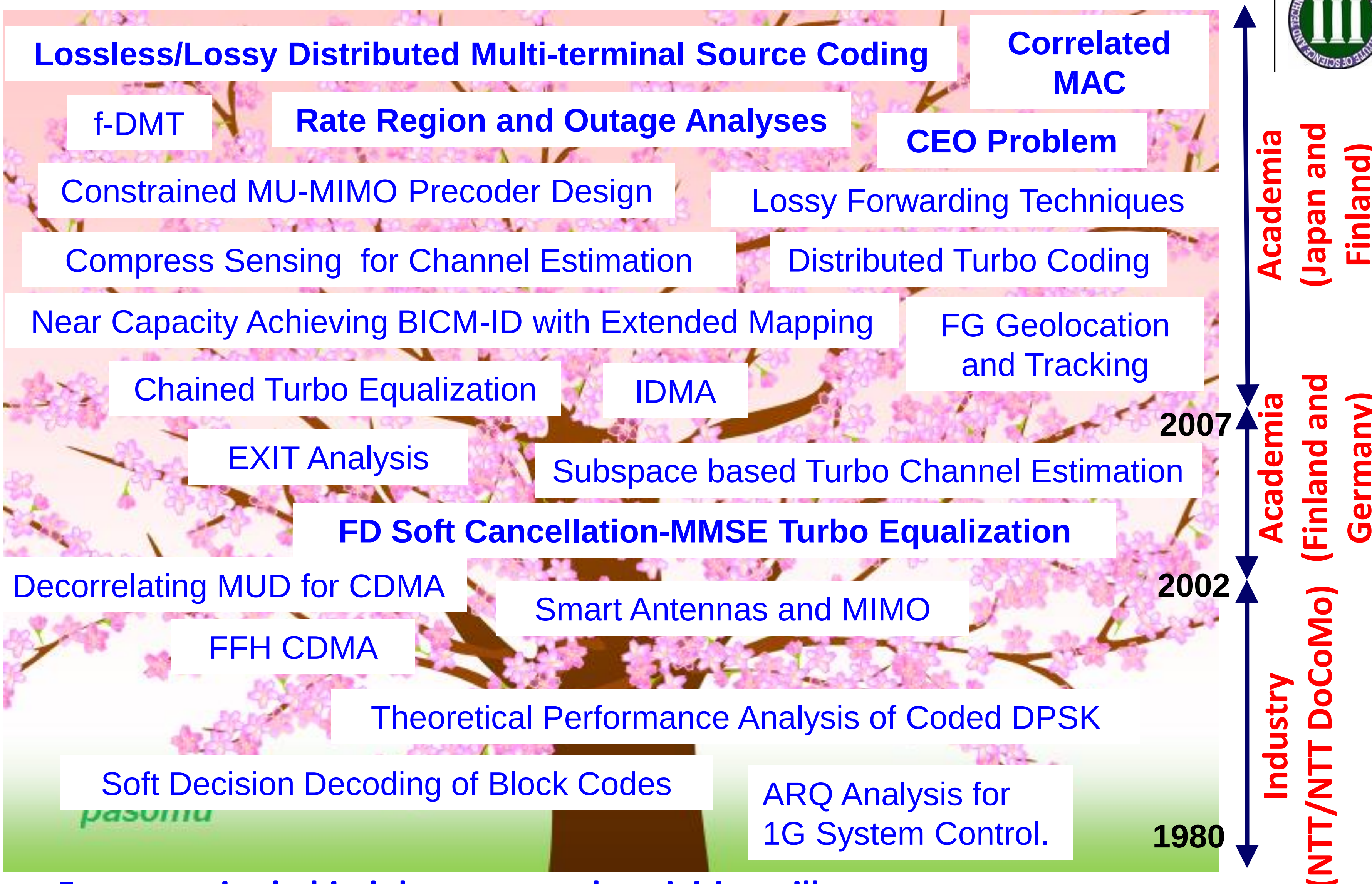
Sakura Not Yet bloom when I left JAIST in March 2021....

Can you enjoy Sakura in your nearby park in Indonesia and/or Malaysia?

Tree of Tad's SISU: Wireless Communications



Funny stories behind those research activities will be addressed inSeminar-2

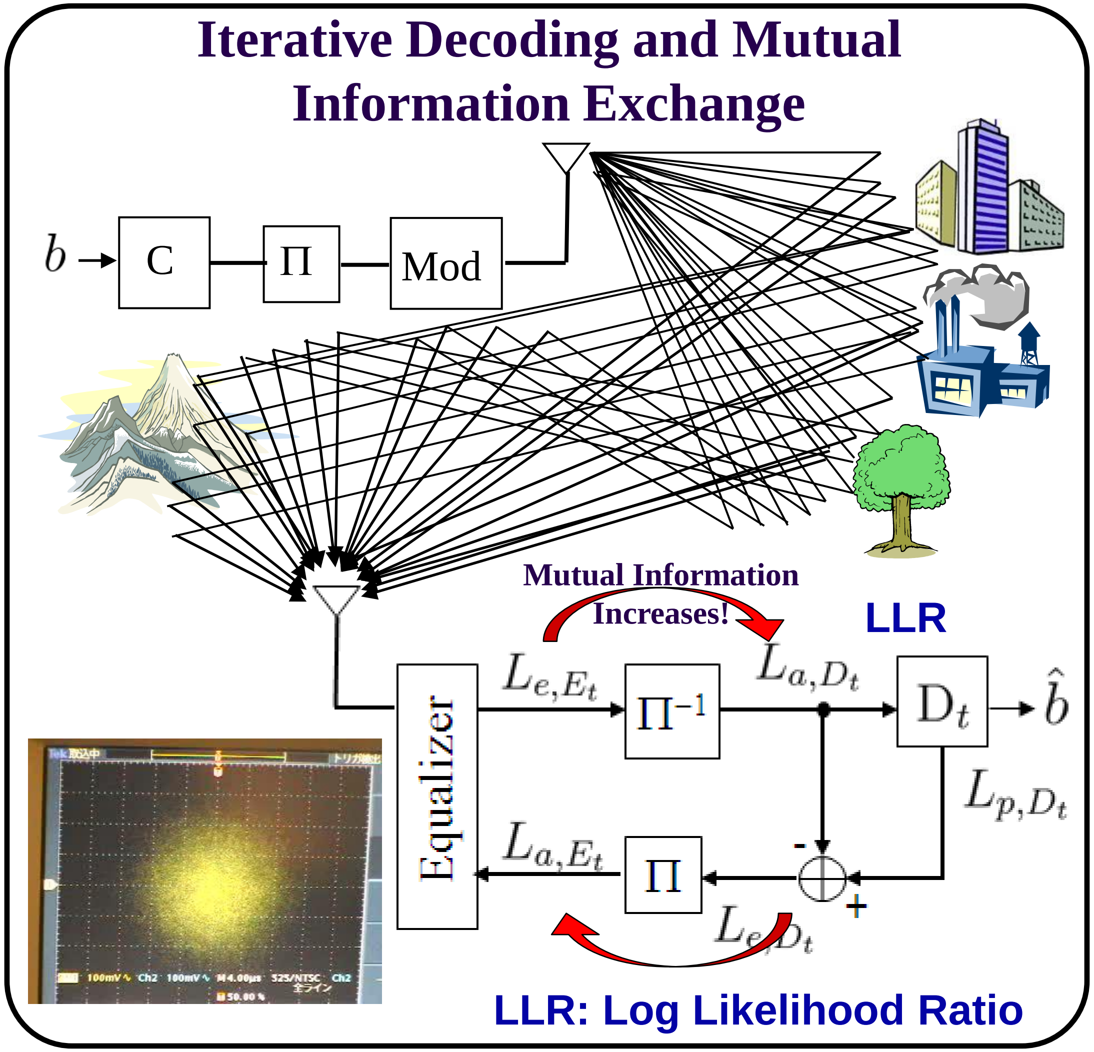
time

Almost 35 years ago!

Many Thanks to PhD Graduates

Prof. Kimmo Kansanen Prof. Xiaobo Zhou Dr. Xin He Dr. Meng Cheng
Prof. Ade Irawan Dr. Shen Qian Dr. Pen Shun Lu Dr. Nenad Veselinovic
Dr. Lin Wensheng Prof. Reza Kahar Dr. Jiguang He Dr. Juha Karjalainen
Prof. Yasuhiro Takano Dr. Valtteri Tervo ….. and many Master Course graduates from our lab, **as well as to** Prof. Anwar Khoirul, Prof. Norulhusna Ahmad and Prof. Mohd Azri Mohd Izhar, all having made a lot of good achievements!.

3G and 4G time   My spirit: We Shall change the world!



Nokia's Famous Research Reader said: "Recovery of the transmitted information is impossible, because equalization complexity is intractable!"
→ Researchers moved to CDMA to "escape from this problem".

3G is a Heat Source→ Global Warming!

My observation of the opinions in the world:
"No" to

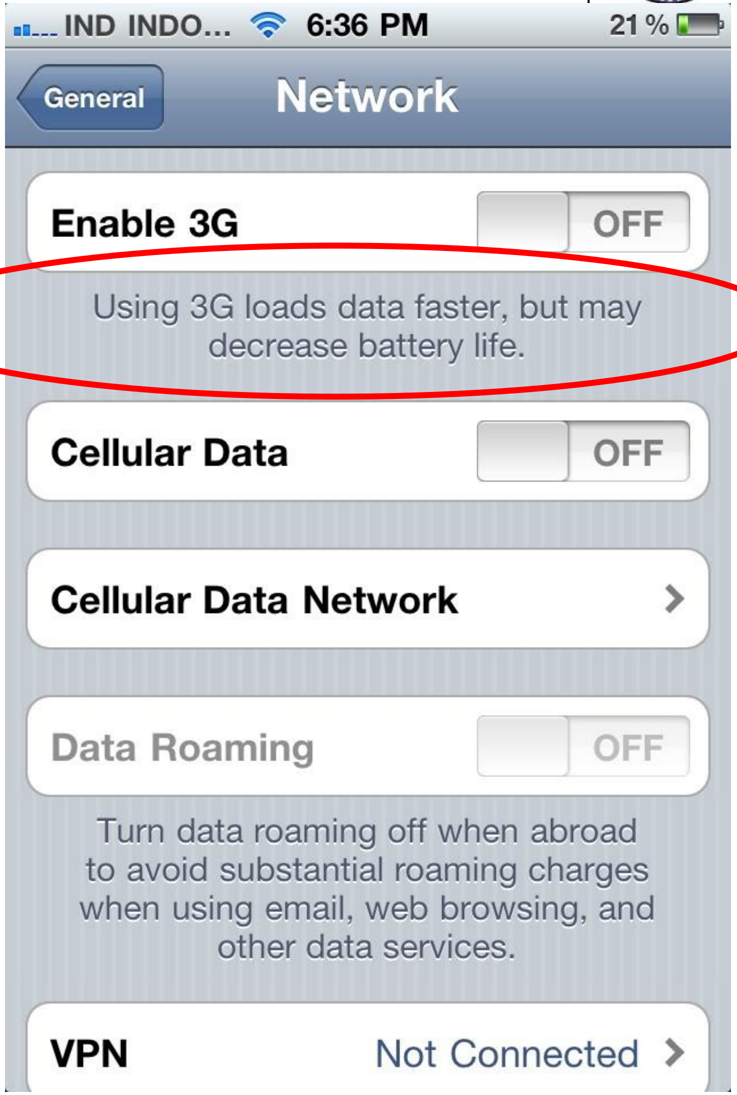
~~CDMA/OFDM~~

for Broadband Cellular Systems.

For WiFi, OFDM is Ok because of small cell size.

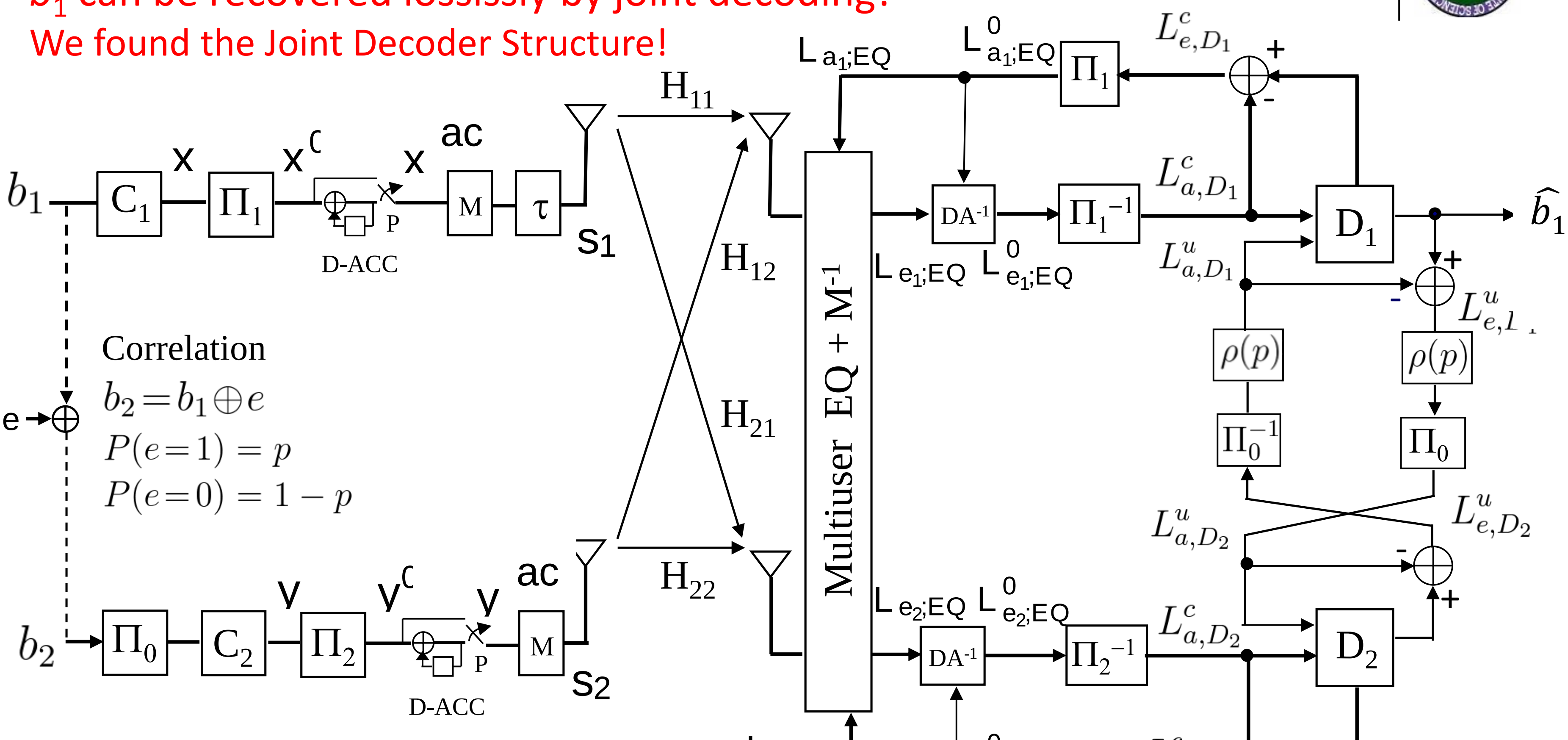
The simpler the better → Single Carrier!

Prof. Gerhard Fettweis of Dresden University of Technology said in a Panel Session in 2010 VTC-Spring: "We have to apologize our mistake for 3G"



Joint Decoder Structure with LLR Update

Surprisingly, even with the bit flipping e between b_1 and b_2,
b_1 can be recovered loslssly by joint decoding!
We found the Joint Decoder Structure!



Probability Update (ρ(p))

$$P(x=0) = (1-p)P_o(x=0) + pP_o(x=1)$$

$$P(x=1) = (1-p)P_o(x=1) + pP_o(x=0)$$

$$\rho(p) = LLR_{update} = \ln\frac{(1-p)e^{L} + p}{(1-p) + pe^{L}}$$

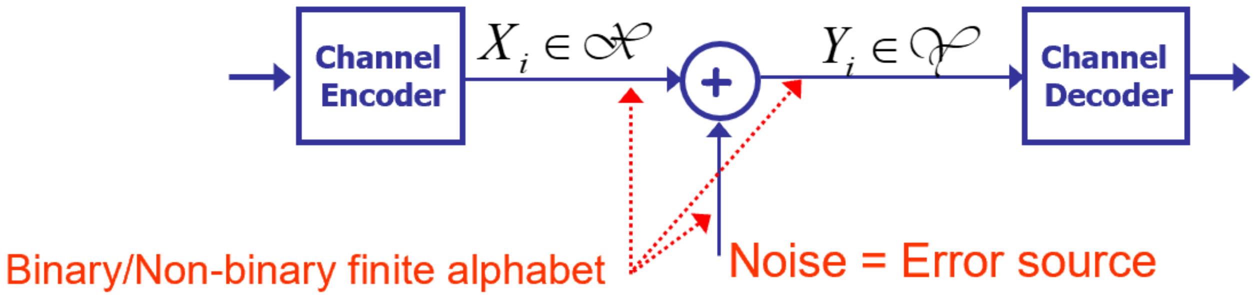
Home

- **We** developed Frequency Domain Turbo Equalization Algorithms for single carrier signalling: it requires computational complexity of only ”high school level math”!

- Convergence property analysis made significantly easy!

2. E2E Lossless

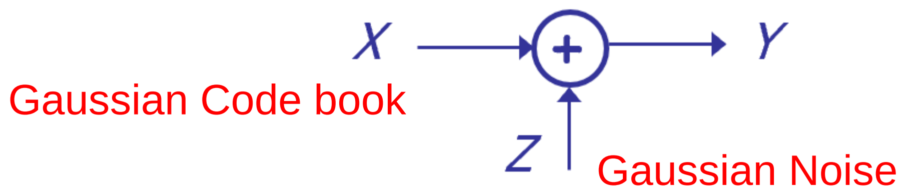
Quiz1: What is Channel's Maximum Capability in Point-to-Point case?



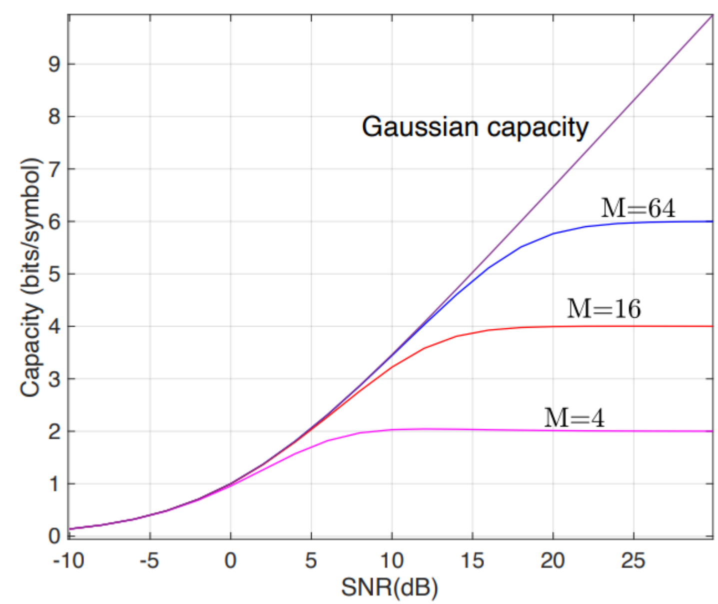
$$C = \max I(X;Y) \geq I(X;Y) \geq 0$$

$C \leq \log|\mathcal{X}|$ because $C = \max I(X;Y) \leq \max H(X) = \log|\mathcal{X}|$

$C \leq \log|\mathcal{Y}|$ because $C = \max I(X;Y) \leq \max H(Y) = \log|\mathcal{Y}|$



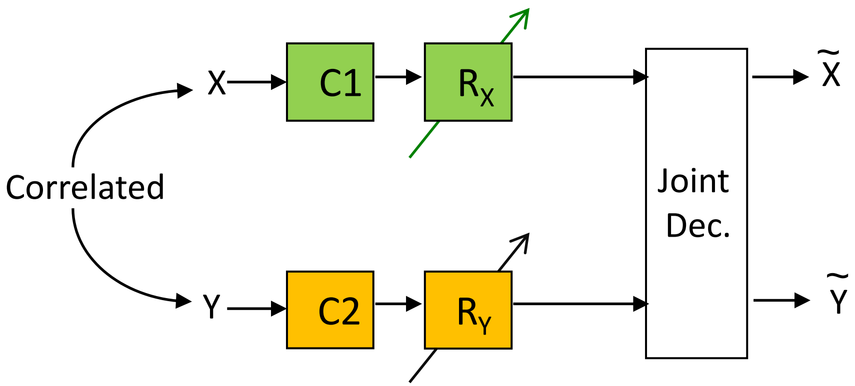
$$C = \max_{p(x):\ EX^2 \leq P} I(X;Y) = \log(1 + SNR)$$

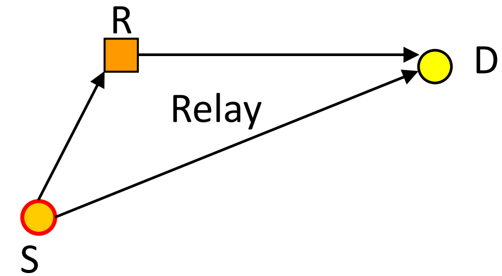


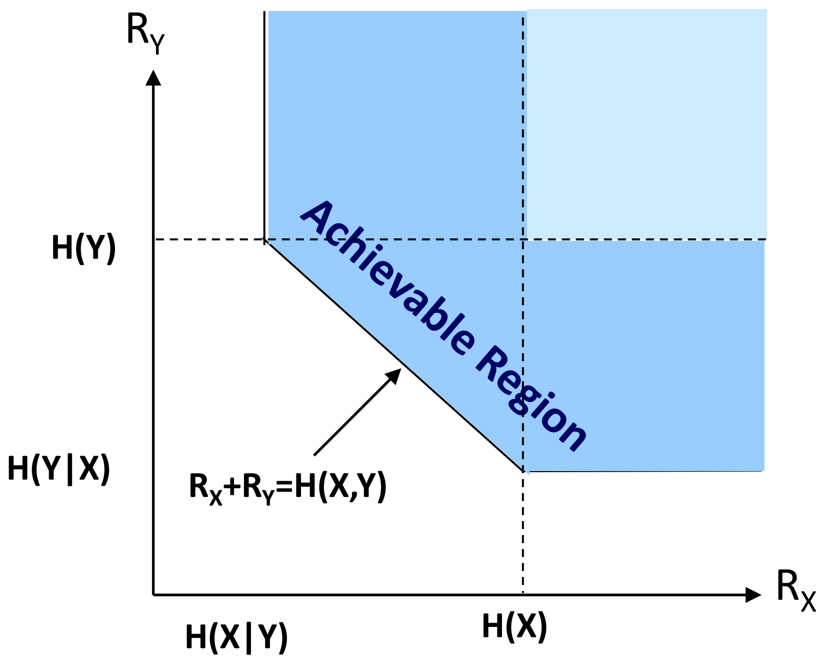
Slepian-Wolf Theorem

Quiz 2: What is Network's Maximum Capability?

"Capacity" is NOT the right word! Rate region is the right word!





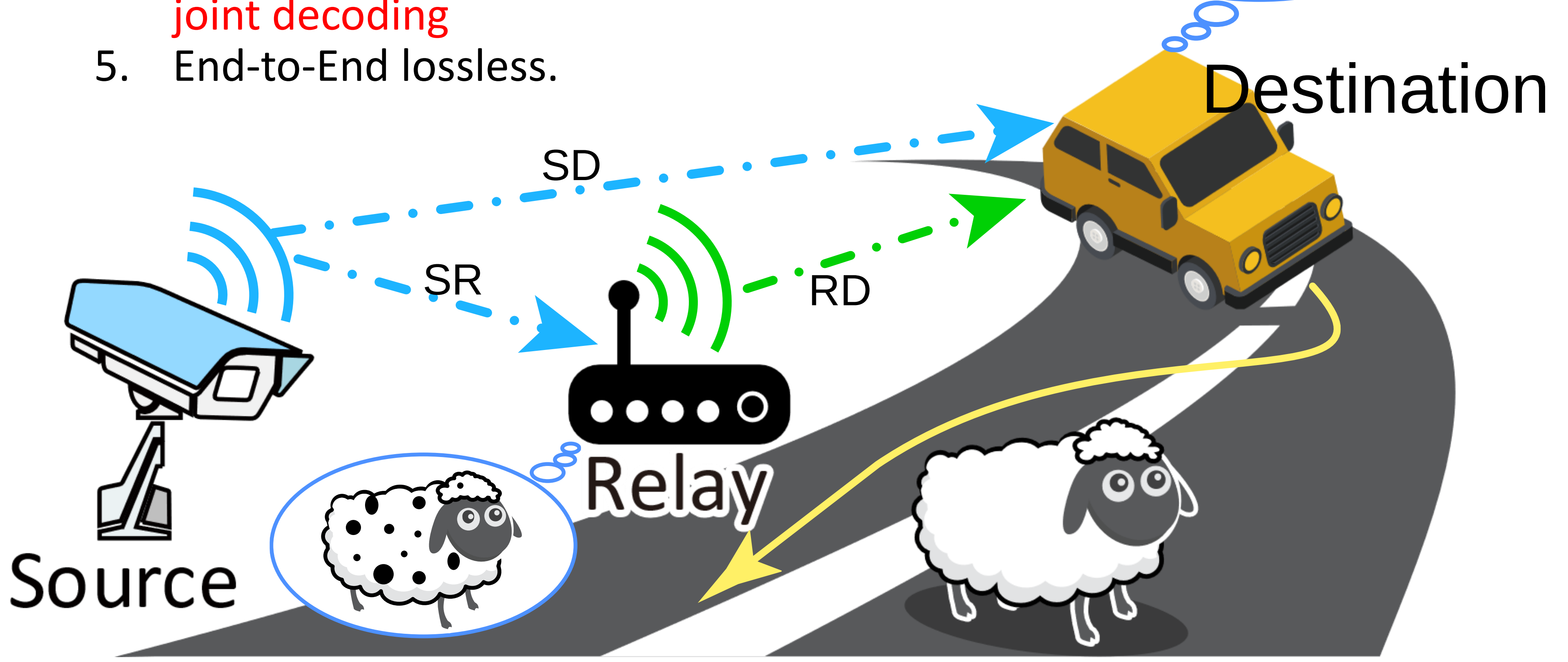


- Slepian-Wolf Theorem:

$$R_X \geq H(X|Y)$$
$$R_Y \geq H(Y|X)$$
$$R_X + R_Y \geq H(X,Y)$$

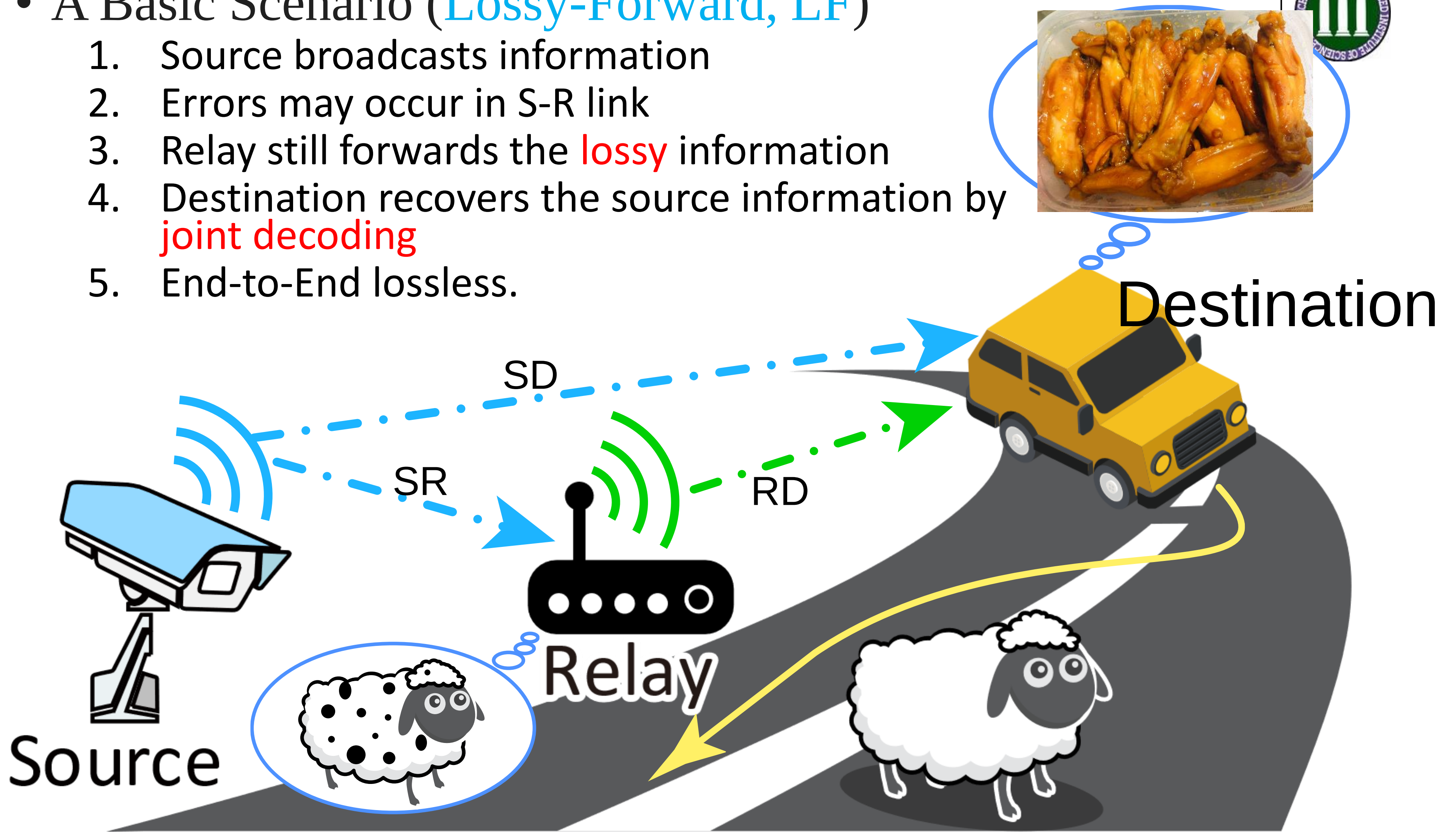
LF Works

- A Basic Scenario (Lossy-Forward, LF)
  1. Source broadcasts information
  2. Errors may occur in S-R link
  3. Relay still forwards the lossy information
  4. Destination recovers the source information by joint decoding
  5. End-to-End lossless.



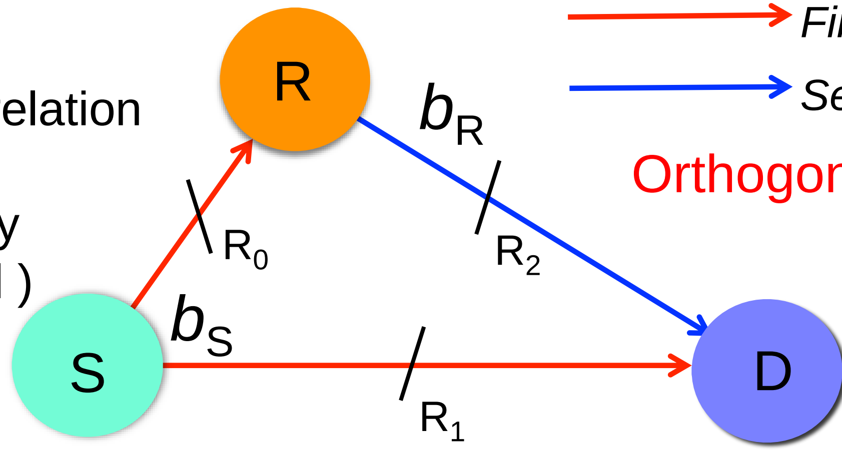
LF does not work: Outage!

- A Basic Scenario (Lossy-Forward, LF)
  1. Source broadcasts information
  2. Errors may occur in S-R link
  3. Relay still forwards the lossy information
  4. Destination recovers the source information by joint decoding
  5. End-to-End lossless.



Do we need to recover the relay information b_R?

Source-Relay Correlation (bit-flipping model equivalent to binary symmetric channel)

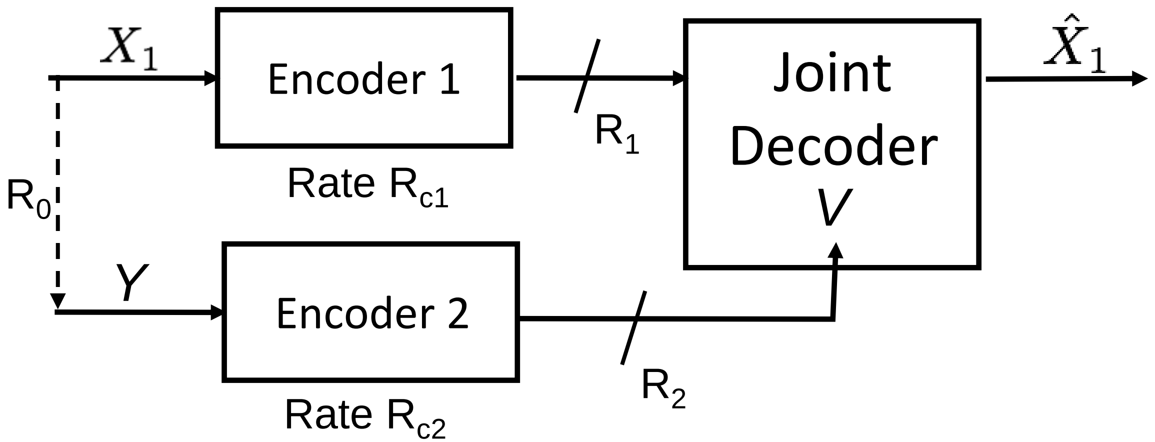


First Time Slot

Second Time Slot

Orthogonal Transmission

Joint decoding exploiting the *source- relay correlation*

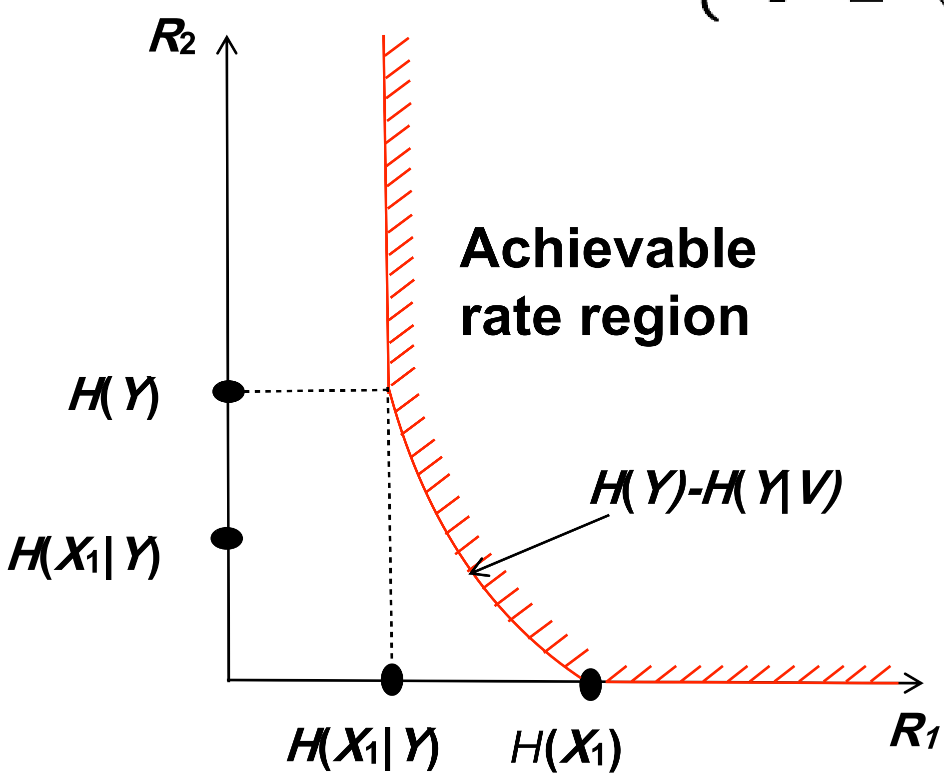


We do not care about the decoding result (=V) of b_R, but we can use b_R as a ***helper****! → Slepian –Wolf Lossless Multi-terminal Source Coding Theorem with a helper.*

LF Rate Region Analysis: ***Slepian –Wolf Lossless Multi-terminal Source Coding with a helper.***

With LF, the S-R link is lossy, the achievable rate region is given by:

$$\begin{cases} R_1 & \geq H(X_1 | V) \\ R_2 & \geq I(Y; V) = H(Y) - H(Y | V) \end{cases}$$



Open Problem:
The exact achievable rate region for distributed lossless and lossy source coding with **more than one helpers** is unknown, except for some special cases, even in the case of single source.

LF Rate Region Analysis

- How can we combine Shannon's Separation Theorem and the Rate Region?

By using the lossy Separation theorem $R_{c,1} \cdot R(\mathscr{D}) \leq C(\gamma_0)$

and with Inverse $C^{-1}(\gamma_0)$ of the Capacity Function $C(\gamma_0)$, we calculate the binary distortion ($\mathscr{D}$=BER) of the S-R link after decoding, as

$$p_e = \begin{cases} H_b^{-1}[1 - \Phi_1(\gamma_0)], & \text{for } \Phi^{-1}(0) \leq \gamma_0 \leq \Phi_1^{-1}(1) \\ 0, & \text{for } \gamma_0 \geq \Phi_1^{-1}(1), \end{cases}$$

and $\Phi_1(\gamma_0) = \frac{C(\gamma_0)}{R_{c,1}}$

with $H_b^{-1}(\cdot)$ denotes the inverse function of the binary entropy function $H_b(x) = -x \log_2 x - (1-x)\log_2(1-x)$, and $\Phi_1^{-1}(\cdot)$ is the inverse function of $\Phi_1(\cdot)$.

This means that given the *instantaneous SNR* γ_0 and $R_{c,1}$, we can calculate the binary distortion (=BER) of S-R link after decoding!

Binary Source

Consider a Binary source $x \in X$, $\quad Prob(x=1) = p \quad , \quad Prob(x=0) = 1-p$

Assume that p<1/2. The rate distortion function is given by:

$$R(D) = \begin{cases} H(p) - H(D) & , \quad 0 \le D \le \min(p, 1-p) \\ 0 & , \quad D > \min(p, 1-p) \end{cases}$$

where Hamming distortion measure is assumed.

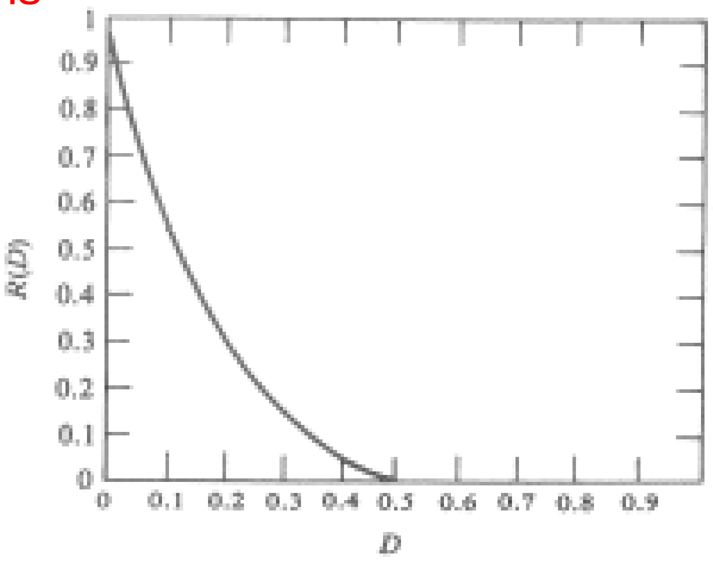
With p=1/2, $R(D)$=1-$H(D)$, of which test channel is BSC and $D=p_e$

↓

$H_b(p_e) = 1 - R(p_e)$

↓

$p_e = H_b^{-1}\left(1 - \frac{C(\gamma_0)}{R_{c,1}}\right)$



LF Rate Region Analysis

- We also do not need *lossless* R-D link. R-D link's error probability α after decoding can be calculated in the same way, as

$$\alpha = \begin{cases} H_b^{-1}[1 - \Phi_1(\gamma_2)], & \text{for } \Phi_1^{-1}(0) \leq \gamma_2 \leq \Phi_1^{-1}(1) \\ 0, & \text{for } \gamma_2 \geq \Phi_1^{-1}(1), \end{cases}$$

with $\Phi_1(\gamma_2) = \frac{C(\gamma_2)}{R_{c,1}}$

By combining all, we have

$$\begin{cases} R_1 \geq H(X_1 | V) = H_b(\alpha * p) \\ R_2 \geq I(Y; V) = H(Y) - H(Y|V) = 1 - H_b(\alpha) \end{cases}$$

, because V->Y->X_1 forms Markov Chain.

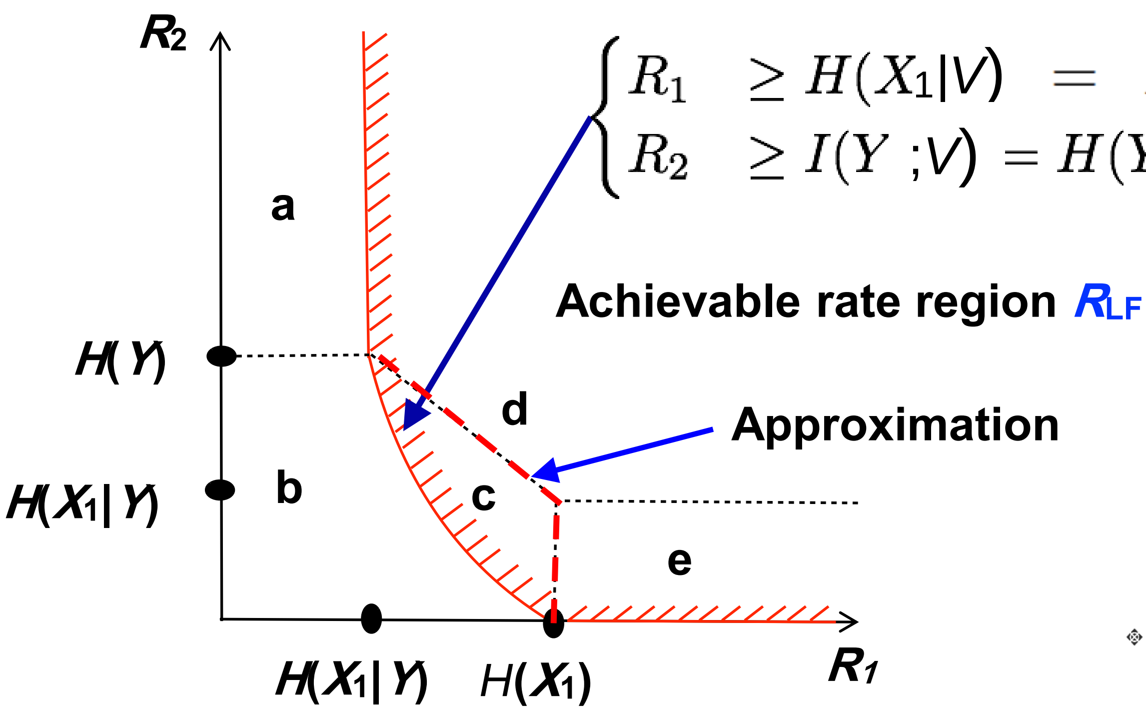
with $\alpha * p = (1-\alpha)p + \alpha(1-p)$

We do not know γ_0, γ_1, γ_2 but we know their distributions.

To Calculate the Outage, we need threefold Integral!

- IMPORTANT:

$$\begin{cases} R_1 \geq H(X_1|V) = H_b(\alpha * p) \\ R_2 \geq I(Y;V) = H(Y) - H(Y|V) = 1 - H_b(\alpha) \end{cases}$$



- This region is a function of γ_0, γ_1, and γ_2!
- (SNR of S-R, S-D and R-D links)

→ We need threefold integral with respect to the pdf's of γ_0, γ_1, and γ_2!

- To ease the calculation, we decompose the region into 5 sub-regions!
  - R_a, R_b, R_c, R_d and R_e
  - $R_{LF} = R_c \cup R_d \cup R_e$

To Calculate the Outage, we need threefold Integrals!

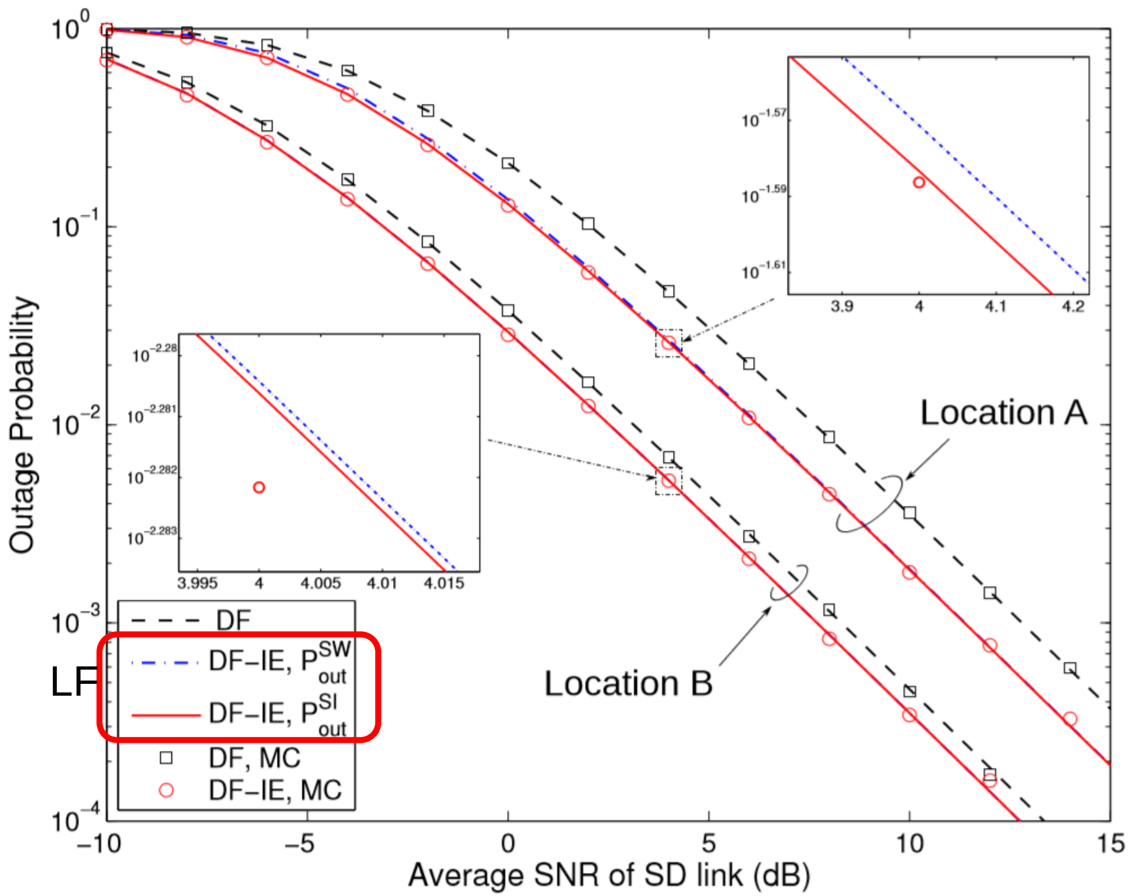
$$
\begin{aligned}
P_{1,a} &= \Pr\{p=0, R_2 \geq 1, 0 \leq R_1 \leq H_b(p)\} \\
&= \Pr\{\gamma_0 \geq \Phi_1^{-1}(1), \gamma_2 \geq \Phi_2^{-1}(1), \\
&\qquad \Phi_1^{-1}(0) \leq \gamma_1 \leq \Phi_1^{-1}(0)\} \\
&= \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}(1)} d\gamma_0 \int_{\Phi_2^{-1}(0)}^{\Phi_2^{-1}(1)} d\gamma_2 \\
&\quad \cdot \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}(0)} p(\gamma_0)\cdot p(\gamma_1)\cdot p(\gamma_2) d\gamma_1 \\
&= 0,
\end{aligned}
$$

$$
\begin{aligned}
P_{1,b} &= \Pr\{p=0, 0 \leq R_2 \leq 1, 0 \leq R_1 \leq H_b(\alpha * p)\} \\
&= \Pr\{\gamma_0 \geq \Phi_1^{-1}(1), \Phi_2^{-1}(0) \leq \gamma_2 \leq \Phi_2^{-1}(1), \\
&\qquad \Phi_1^{-1}(0) \leq \gamma_1 \leq \Phi_1^{-1}[1-\Phi_2(\gamma_2)]\} \\
&= \int_{\Phi_1^{-1}(1)}^{\Phi_1^{-1}(\infty)} d\gamma_0 \int_{\Phi_2^{-1}(0)}^{\Phi_2^{-1}(1)} d\gamma_2 \\
&\quad \cdot \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}[1-\Phi_2(\gamma_2)]} p(\gamma_0)\cdot p(\gamma_1)\cdot p(\gamma_2) d\gamma_1 \\
&= \frac{1}{\Gamma_2} \exp\left[-\frac{\Phi_1^{-1}(1)}{\Gamma_0}\right] \int_{\Phi_2^{-1}(0)}^{\Phi_2^{-1}(1)} \exp(-\frac{\gamma_2}{\Gamma_2}) \\
&\quad \cdot \left[1-\exp(-\frac{\Phi_1^{-1}[1-\Phi_2(\gamma_2)]}{\Gamma_1})\right] d\gamma_2,
\end{aligned}
$$

$$
\begin{aligned}
P_{2,a} &= \Pr\{0 < p \leq 0.5, R_2 \geq 1, 0 \leq R_1 \leq H_b(p)\} \\
&= \Pr\{\Phi_1^{-1}(0) \leq \gamma_0 \leq \Phi_1^{-1}(1), \gamma_2 \geq \Phi_2^{-1}(1), \\
&\qquad \Phi_1^{-1}(0) \leq \gamma_1 \leq \Phi_1^{-1}[1-\Phi_1(\gamma_0)]\} \\
&= \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}(1)} d\gamma_0 \int_{\Phi_2^{-1}(1)}^{\Phi_2^{-1}(\infty)} d\gamma_2 \\
&\quad \cdot \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}[1-\Phi_1(\gamma_0)]} p(\gamma_0)\cdot p(\gamma_1)\cdot p(\gamma_2) d\gamma_1 \\
&= \frac{1}{\Gamma_0} \exp\left[-\frac{\Phi_2^{-1}(1)}{\Gamma_2}\right] \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}(1)} \exp(-\frac{\gamma_0}{\Gamma_0}) \\
&\quad \cdot \left[1-\exp(-\frac{\Phi_1^{-1}[1-\Phi_1(\gamma_0)]}{\Gamma_1})\right] d\gamma_0,
\end{aligned}
$$

$$
\begin{aligned}
P_{2,b} &= \Pr\{0 < p \leq 0.5, 0 \leq R_2 \leq 1, 0 \leq R_1 \leq H_b(\alpha * p)\} \\
&= \Pr\{\Phi_1^{-1}(0) \leq \gamma_0 \leq \Phi_1^{-1}(1), \Phi_2^{-1}(0) \leq \gamma_2 \leq \Phi_2^{-1}(1), \\
&\qquad \Phi_1^{-1}(0) \leq \gamma_1 \leq \Phi_1^{-1}[\Psi(\gamma_0, \gamma_2)]\} \\
&= \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}(1)} d\gamma_0 \int_{\Phi_2^{-1}(0)}^{\Phi_2^{-1}(1)} d\gamma_2 \\
&\quad \cdot \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}[\Psi(\gamma_0,\gamma_2)]} p(\gamma_0)\cdot p(\gamma_1)\cdot p(\gamma_2) d\gamma_1 \\
&= \frac{1}{\Gamma_0\Gamma_2} \int_{\Phi_1^{-1}(0)}^{\Phi_1^{-1}(1)} \int_{\Phi_2^{-1}(0)}^{\Phi_2^{-1}(1)} \exp(-\frac{\gamma_0}{\Gamma_0} - \frac{\gamma_2}{\Gamma_2}) \\
&\quad \cdot \left\{1-\exp\left[-\frac{\Phi_1^{-1}[\Psi(\gamma_0,\gamma_2)]}{\Gamma_1}\right]\right\} d\gamma_0 d\gamma_2
\end{aligned} \tag{16}
$$

Comparison of exact and approximated SW region with a helper (Orthogonal Case)



Location A, d0=d1=d2

Location B, d0=(1/4)d1, d2=(3/4)d1

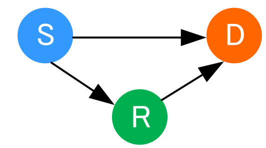
[1] X. Zhou, M. Cheng, X. He and T. Matsumoto, "Exact and Approximated Outage Probability Analyses for Decode-and- Forward Relaying System Allowing Intra-Link Errors," in IEEE Transactions on Wireless Communications, vol. 13, no. 12, pp. 7062-7071, Dec. 2014.

Toy Scenarios

2014 **Xiaobo Zhou *et al.***

"Exact and approximated outage probability analyses for decode-and-forward relaying system allowing intra-link errors"

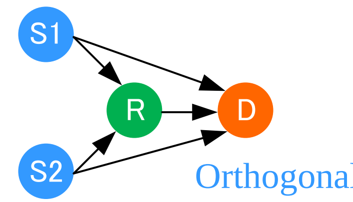
E2E Lossless
One source
One helper



2015 **Pen-Shun Lu *et al.***

"Outage probabilities of orthogonal multiple-access relaying techniques with imperfect source-relay links"

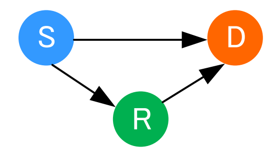
E2E Lossless
Two sources
One helper



2017 **Qian Shen *et al.***

"Impact analysis of fading distributions: Rayleigh, Rician, Nakagami-m, etc"

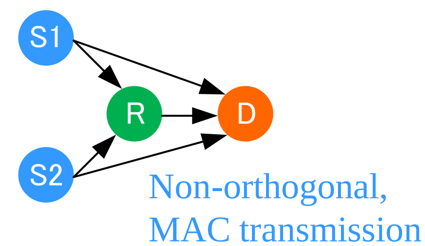
E2E Lossless
One source
One helper



2018 **Jiguang He *et al.***

"Performance analysis of lossy decode-and-forward for non-orthogonal MARCs"

E2E Lossless
Two sources
One helper



S Source R Relay D Destination

Since then, we intensively researched Lossy Forward …. Finally

IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. X, NO. Y, MONTH 2018

Impact Factor=29.83

A Tutorial on Lossy Forwarding Cooperative Relaying

Jiguang He, *Student Member, IEEE,* Valtteri Tervo, Xiaobo Zhou, *Member, IEEE,* Xin He, *Member, IEEE,* Shen Qian, *Student Member, IEEE,* Meng Cheng, Markku Juntti, *Senior Member, IEEE,* and Tad Matsumoto, *Fellow, IEEE*

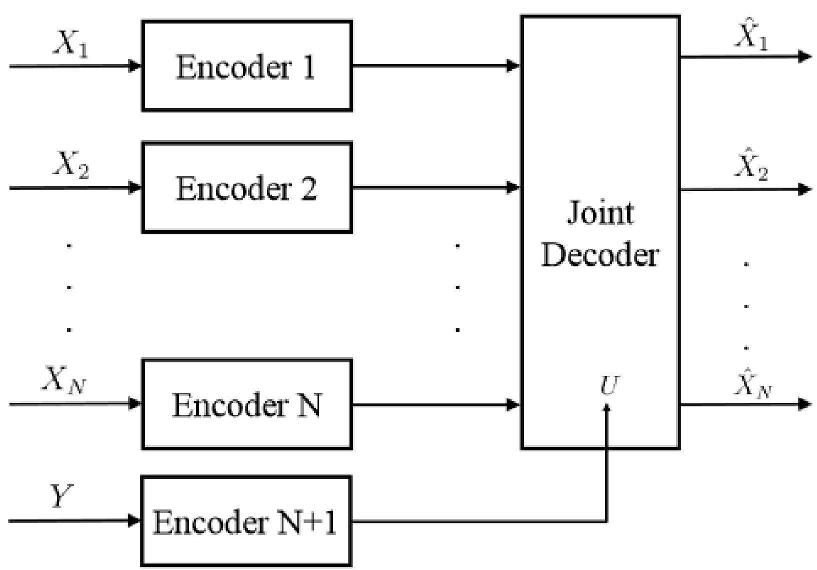


Fig. 2: Distributed lossless source coding of an arbitrary number of sources with a helper.

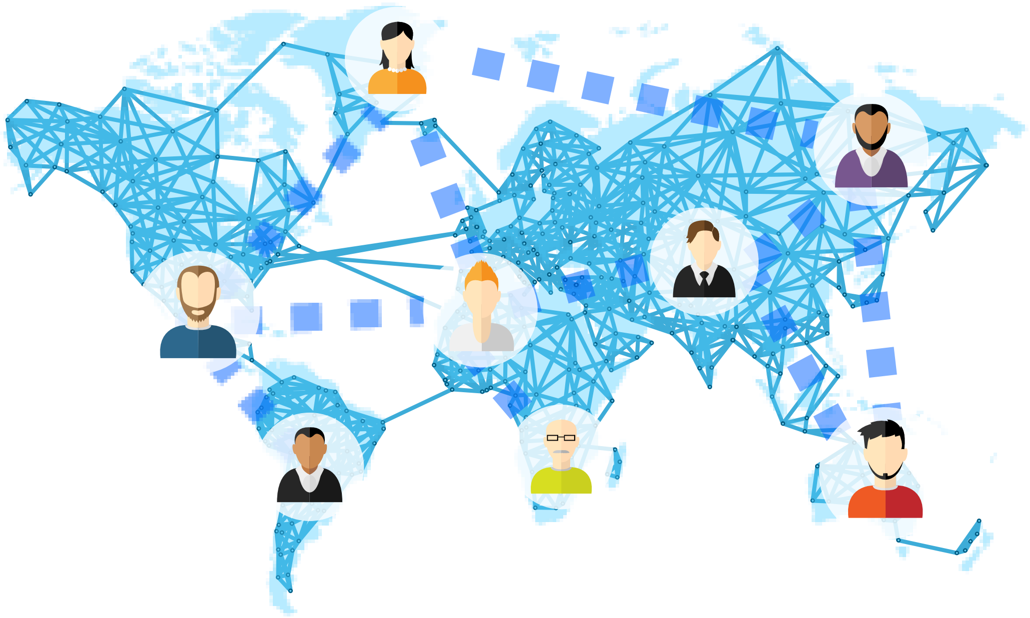
3. E2E Lossy

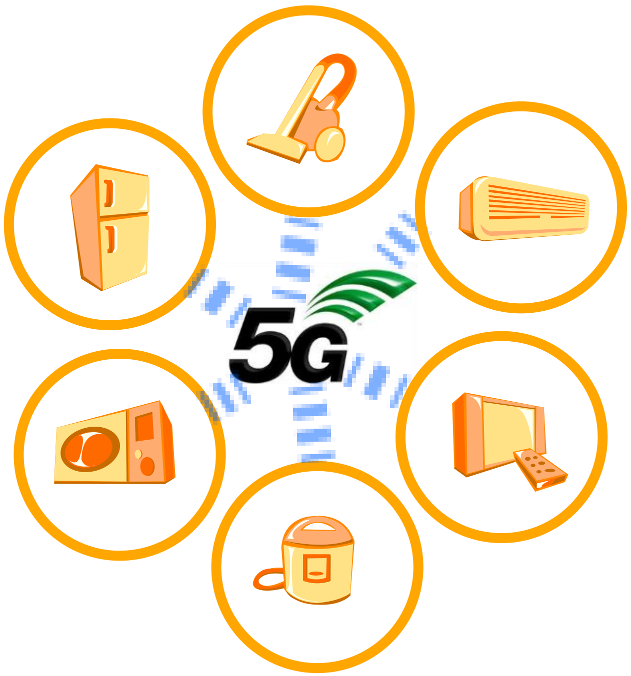
- Traditional Internet

  Connect people

- Internet of Things (IoT)

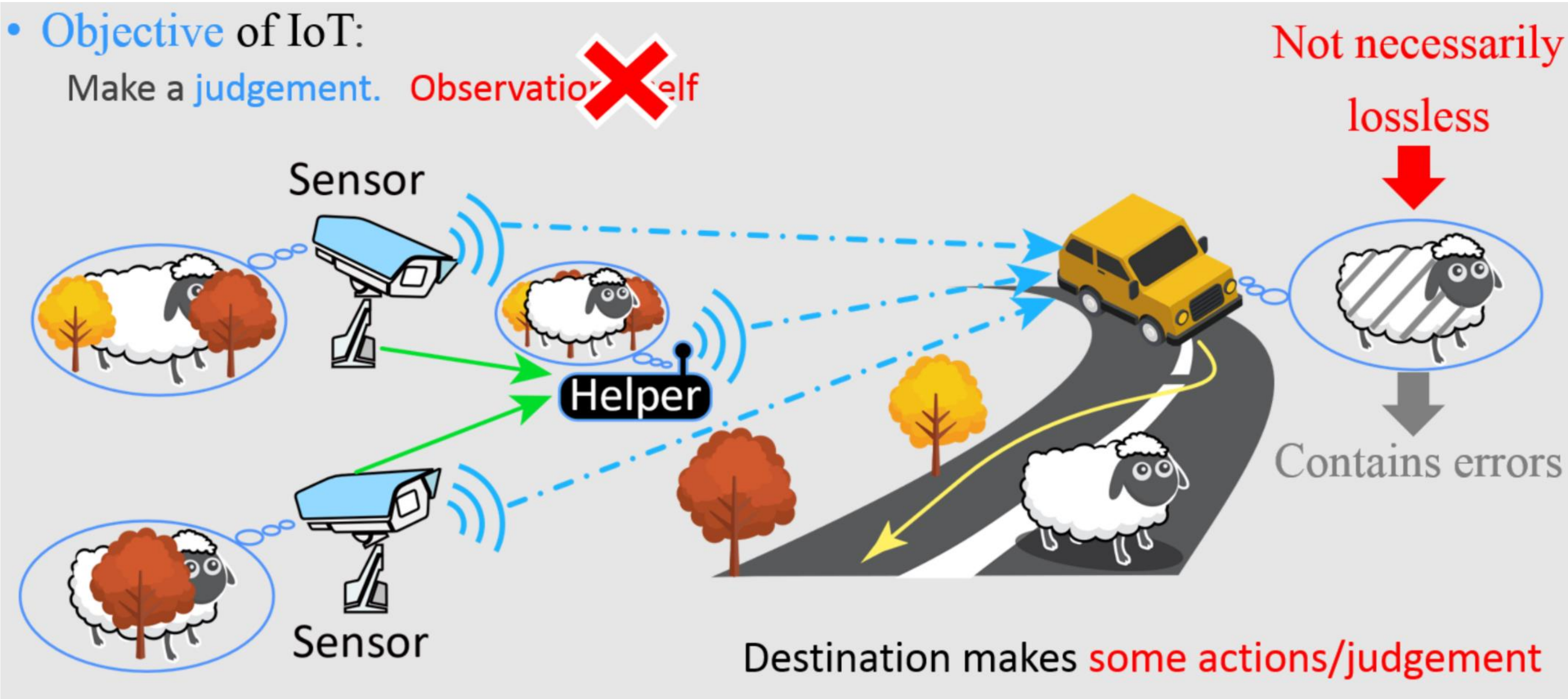
  Connect objects





IoT for Autonomous Driving

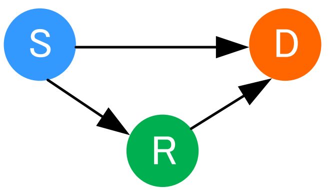
End-to-End (E2E) Lossless → E2E Lossy



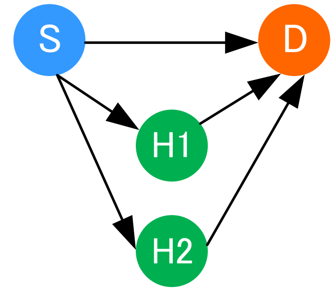
Toy Scenarios

- What are the challenges for the next stage?

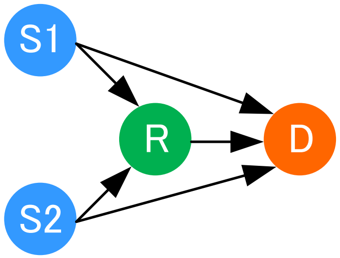
  (1) There are many open problems: end-to-end lossy cases.



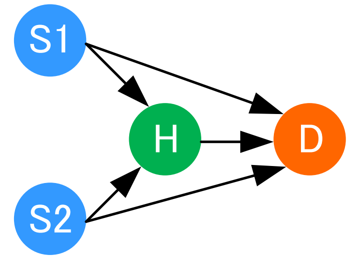
E2E Lossless
One source
One helper



E2E Lossy
Many helpers



E2E Lossless
Two sources
One helper



E2E Lossy
Two sources
One helper

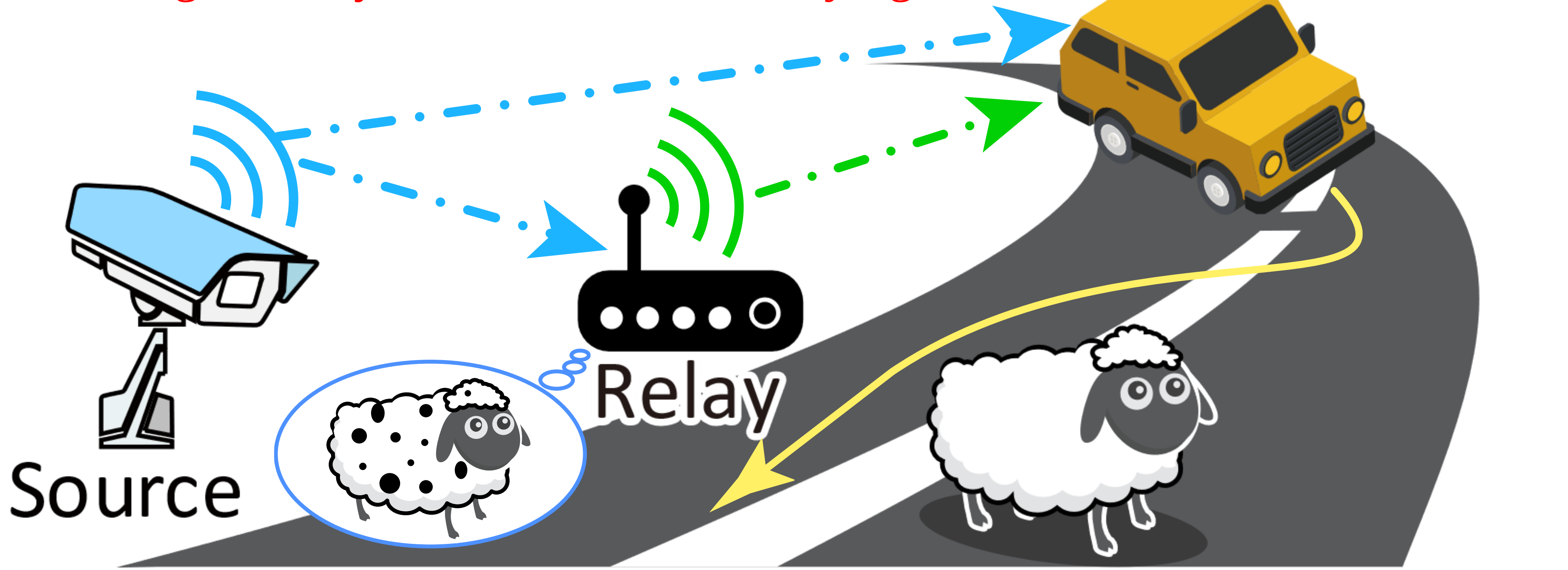
S Source R Relay D Destination A Agent

LF for Lossy Communications

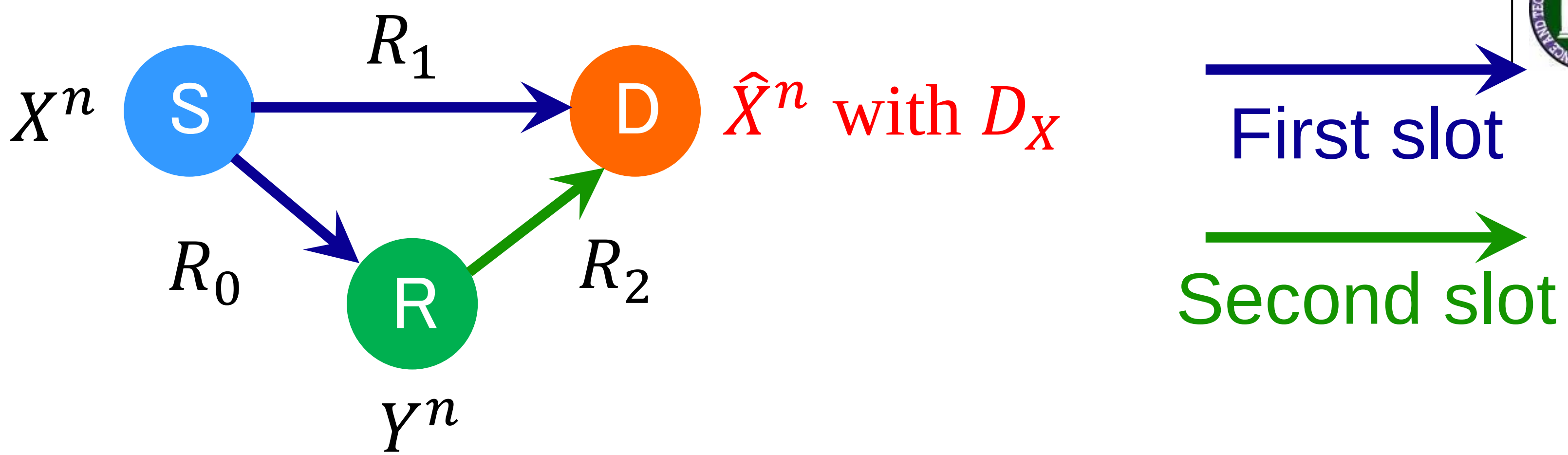
- Objective of IoT:
  - Make a judgement rather than recover information itself
  - The picture exemplifies LF for lossy communications:

NOT necessarily be End-to-End lossless

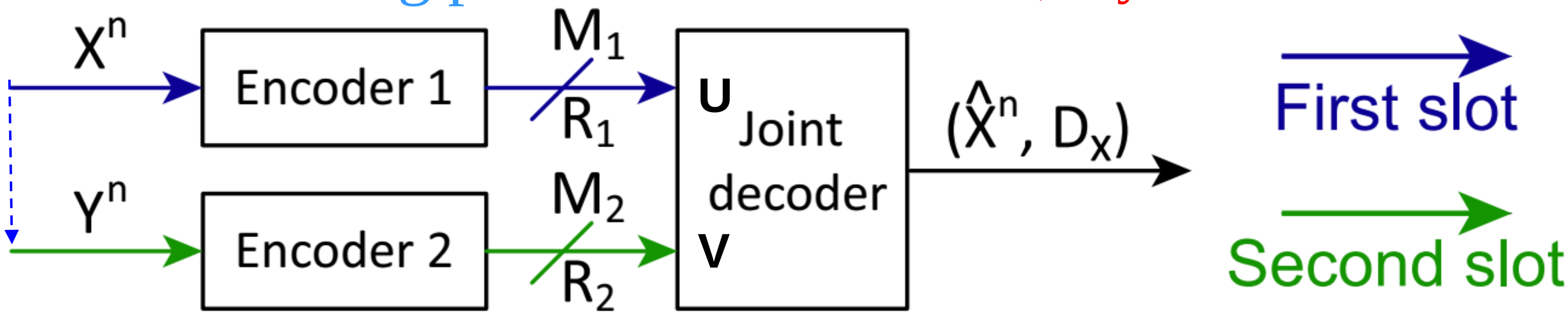
as long as the system can make correct judgement.



Lossy Distributed Multi-terminal Source Coding



- S-R link: point-to-point communication.
- S-D and R-D links: distributed lossy multi-terminal source coding problem. → As a whole, Wyner-Ziv Problem



Achievable Rate-Distortion Region

- Inner bound of WZ *R(D)* function for general sources

$$R_1 > I(X; U|V),$$
$$R_2 > I(Y; V).$$

- Inner bound for binary sources
  - S-R link

$$R_0 > 1 - H_b(\rho).$$

  - R-D link

$$R_2 > 1 - H_b(\rho').$$

  - S-D link

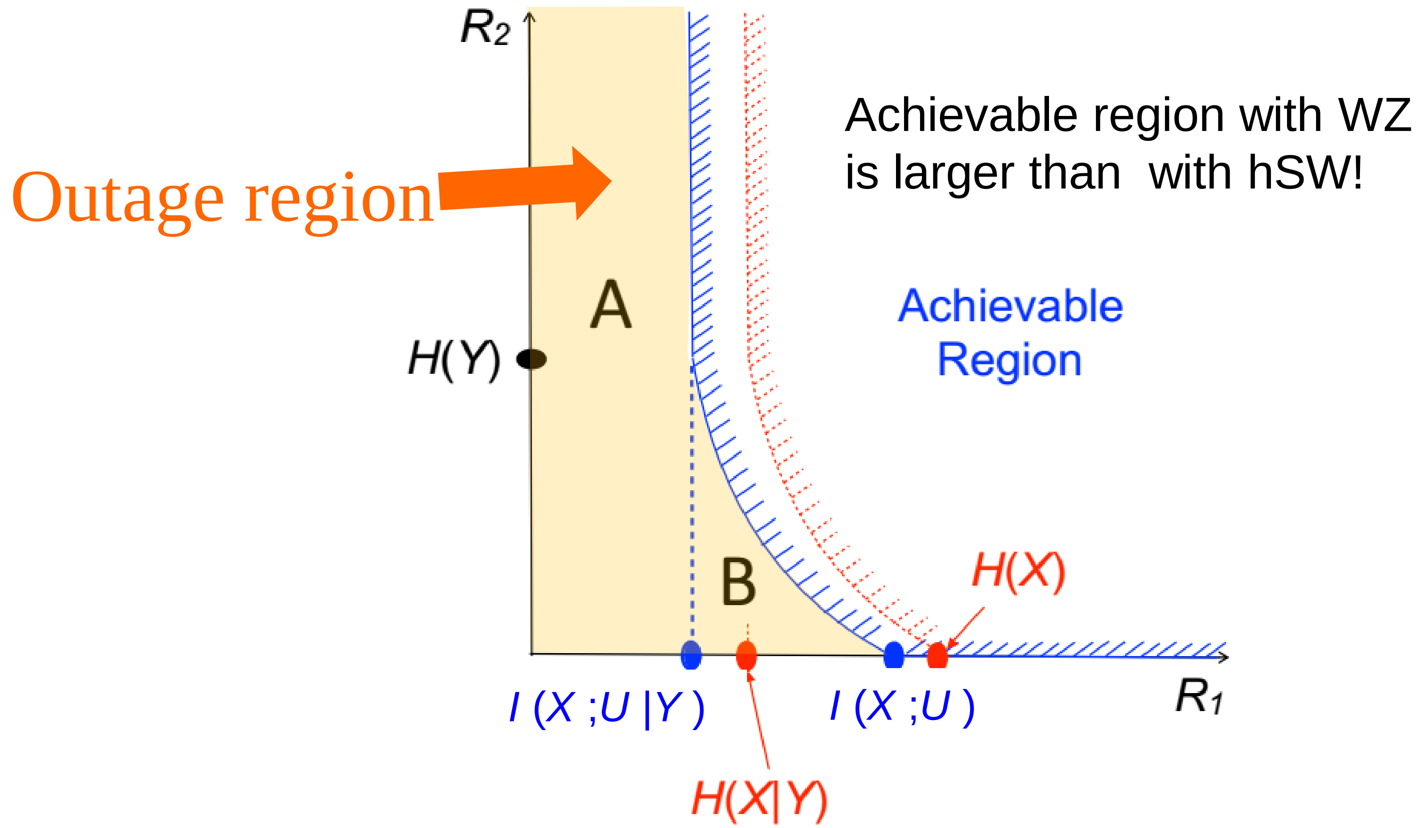
$$R_1 > H_b(\rho' * \rho * D_X) - H_b(D_X).$$

because V->Y->X->U forms Markov Chain.

ρ: crossover probability between X and Y

ρ': crossover probability between Y and V

Outage Event



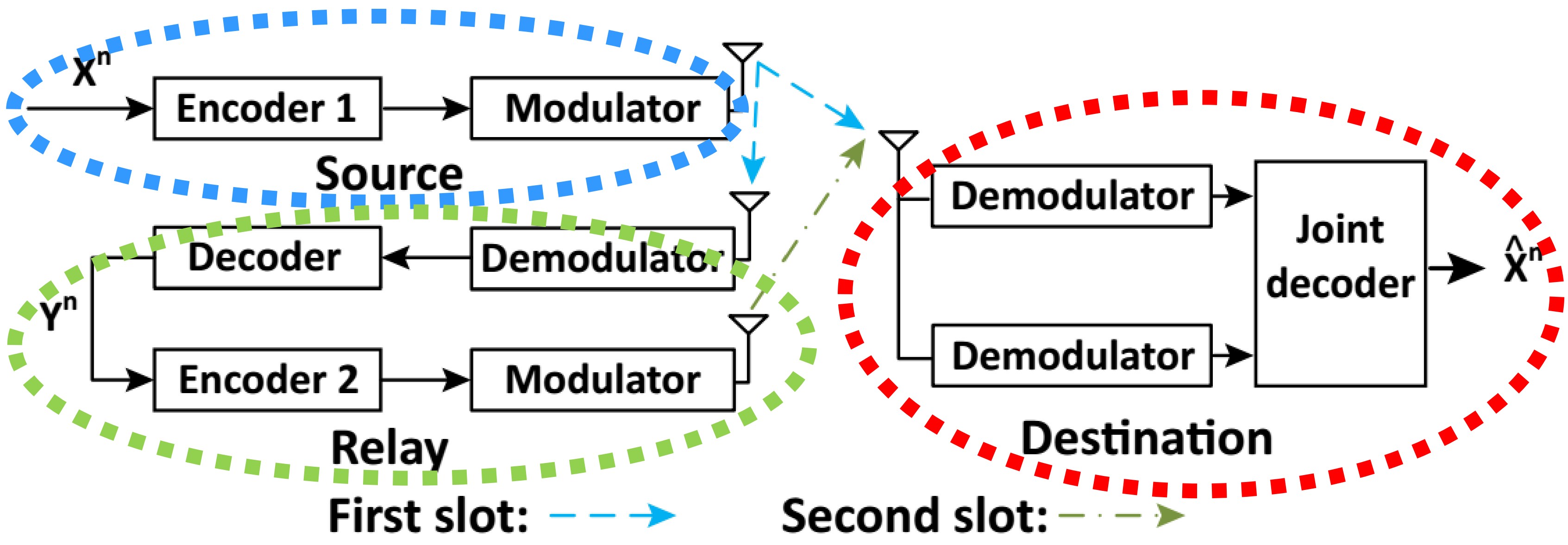
- The link rates (R_0, R_1, R_2) supported by channel capacities cannot satisfy the distortion requirement D_X, when they fall outside the achievable rate-distortion region.→ Outage

Again, we need threefold Integrals!

See the Paper!

Verification by Simulation

We evaluated the outage probability using a very simple signaling chain and the joint decoding shown in Introduction.



Simulation Results

1. The simulation result has the same tendency and the slope decay (=Diversity Order) as the theoretical bound.

2. The gap between the simulation and theoretical results becomes larger as D_X increases. →*We need more efficient rate-distortion code* !