PIMRC 2016: Practical Examples of Physical Layer Security

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How it looks from outside

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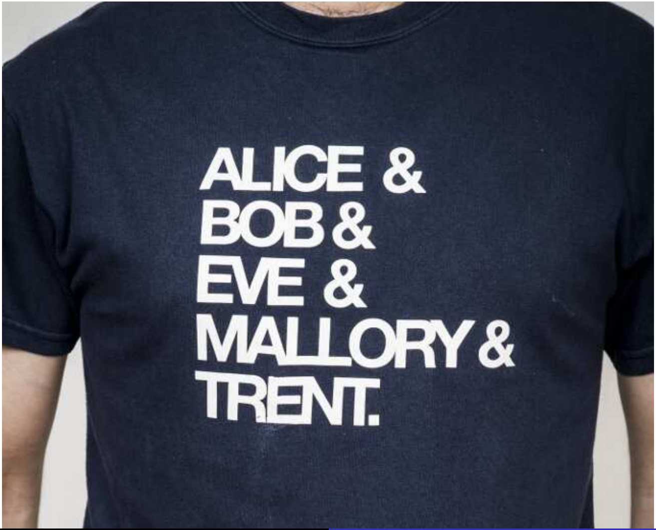
"All you need to do information theory is a log and a lim"

Serio Verdú

The usual suspects



The usual suspects

Openness of wireless channel: security more challenging

- Eavesdropping
- Denial of service attacks (jamming)

Two flavors of PLS

1. Generate keys from correlated sources through public discussion

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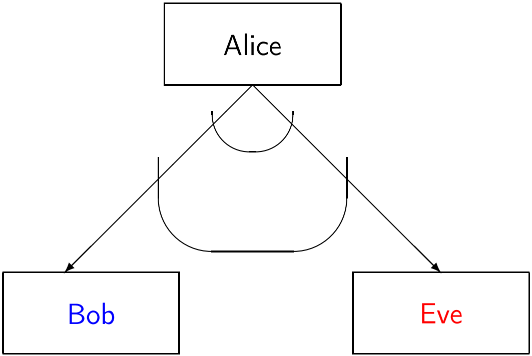
2. Build encoders for degraded adversarial links: "hide" part of the message in noise

What are the hurdles for PLS to gain trust?

1. The adversaries are not powerful enough (passive)



What real systems look like!

Sport US election Daily Edition

Lifestyle › Tech › News

There are officially more mobile devices than people in the world

The world is home to 7.2 billion gadgets, and they're multiplying five times faster than we are

Zachary Davies Boren | @zdboren | Tuesday 7 October 2014 | 0 comments

1K shares

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What about colluding eavesdroppers?

3. Practical issues: Gaussian signalling, long-length encoders

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What about the short codelength regime?
What about resource constrained devices?

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It is not! [2]

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- Massive multi-antenna systems (MIMO), BF and AN
- Small cells: natural PLS setting
- Full duplex: existence of structured interference
- Ad hoc networks, IoT, D2D: secret keys on the fly

Generating secret key from fading coefficients in the presence of active adversaries

Generating keys from correlated sequences

Wireless shared randomness techniques:

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1. Advantage distillation
2. Information reconcilliation
3. Privacy amplification

How good are the PLS keys?

NIST TEST	P-Value
Monobit Frequency	0.739918
Block Frequency	0.739918
Cumulative Sums	0.534146
Runs	0.739918
Longest Run	0.350485
Binary Matrix Rank	0.213309
FFT	0.911413
Non-overlapping Template	0.911413
Overlapping Template	0.534146
Maurer's Universal Test	0.122325
Approximate Entropy	0.739918
Serial	0.739918
Linear Complexity	0.122325

Physical layer authenticated encryption

Replace RSA by PLS key generation in ISO PKE protocol

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1. PLS key seed SeedGen : $\mathbb{R}^+ \rightarrow (0,1)^L \times (0,1)^l$ with (seed,coset) $=$ SeedGen($\mathbf{H}_0$)
2. Sem. sec. hash function G : $(0,1)^L \times (0,1)^l \rightarrow (0,1)^{\lfloor H(\text{seed}) \rfloor}$ with output key K=G(seed, coset), K={Ke, Ki}
3. Sem. sec. A.E.(encrypt-then-MAC): enc. alg. cipher=E(Ke, m), dec. alg. m=D(Ke, cipher), sign alg. t=Sign(Ki, c), ver. alg. v=Ver(Ki, c, t), v $\in \{$ c, $\perp\}$

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Alice transmits extended ciphertext C $=$ [coset||cipher||t]

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Anti-jamming zero-sum game over N parallel subchannels

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Anti-jamming zero-sum game over N parallel subchannels

$$\begin{aligned}
Y_{A,i} &= \sqrt{p_i}H_i + \sqrt{\gamma_i}G_{A,i} + Z_{A,i}, i = 1, \ldots, N \\
Y_{B,i} &= \sqrt{p_i}H_i + \sqrt{\gamma_i}G_{B,i} + Z_{B,i}, i = 1, \ldots, N, \;\; i = 1, \ldots, N
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$$C(p_i, \gamma_i) = I(Y_{A,i}; Y_{B,i}) = \frac{1}{2} \log_2 \left(1 + \frac{\sigma_H^2 p_i}{N_{A,i} + N_{B,i} + \frac{N_{A,i} N_{B,i}}{\sigma_H^2 p_i}} \right),$$

with $\quad N_{A,i} = 1 + \sigma_A^2 \gamma_i, \quad N_{B,i} = 1 + \sigma_B^2 \gamma_i$

Probabilities $\alpha_i, \beta_i, i \leq N$ for legitimate users and jammer respectively to hop on channel i for
Probabilities $\alpha_{N+1}, \beta_{N+1}$ to spread

$$u(\alpha, \beta) = \sum_{i=1}^{N} \{\alpha_i(1 - \beta_i - \beta_{N+1})C(NP, 0) + \alpha_i\beta_i C(NP, N\Gamma)$$
$$+\alpha_i\beta_{N+1}C(NP, \Gamma) + \alpha_{N+1}(1 - \beta_i - \beta_{N+1})C(P, 0)$$
$$+ \alpha_{N+1}\beta_i C(P, N\Gamma) + \alpha_{N+1}\beta_{N+1}C(P, \Gamma)\} .$$

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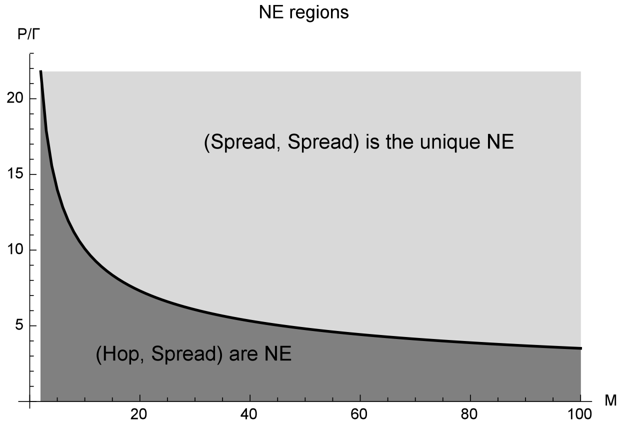

MQAM encoders for the $x + y$ channel

$x + y$ channels

- Wireless network coding systems
- Full duplex

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Creating channel advantage

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Creating channel advantage
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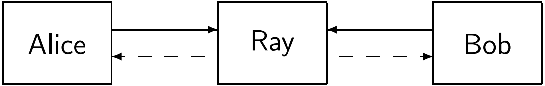
Gaussian signalling does not offer this opportunity

Wireless network coding

In standard relay channels we need 4 cycles to exchange x, y.



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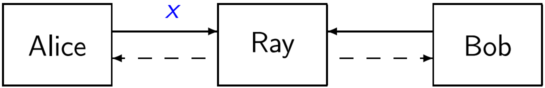

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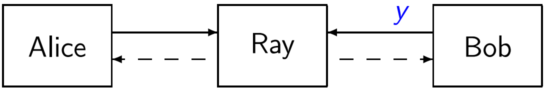

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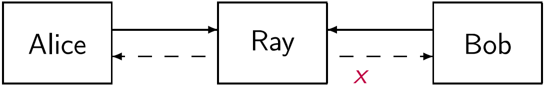

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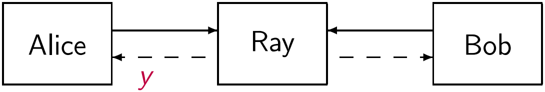
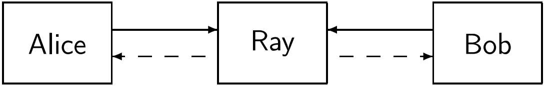


Physical layer network coding ctd'

In PNC we need 2 cycles



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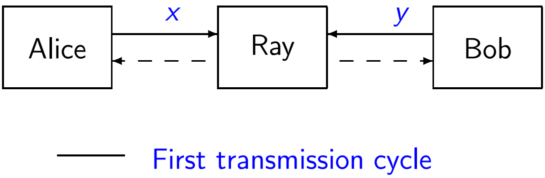

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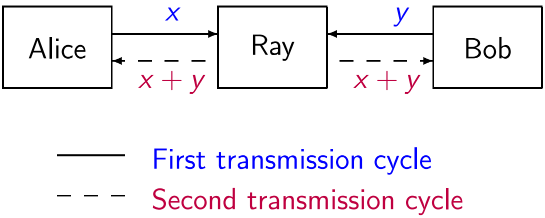
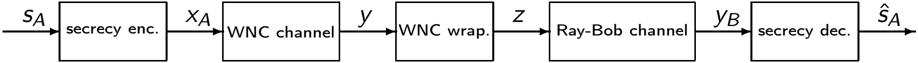


Untrusted (but honest) relay



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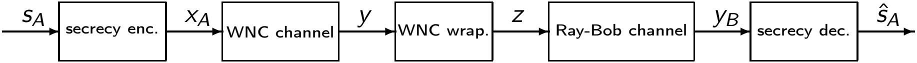

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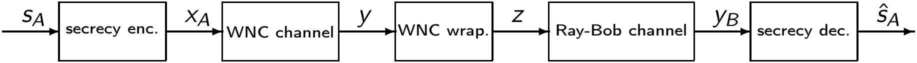

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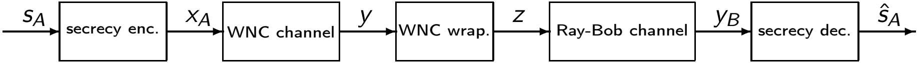

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- Labeling functions $b_A : \mathcal{X}_A \to \mathcal{S}_A \cup \{\varepsilon\}$, $b_B : \mathcal{X}_B \to \mathcal{S}_B \cup \{\varepsilon\}$ where ε represents the empty string
- $\forall s_A \in \mathcal{S}_A \cup \{\varepsilon\}$ we set $b_A^{-1}(s_A) = \{x_A \mid b_A(x_A) = s_A\}$ and $\forall s_B \in \mathcal{S}_B \cup \{\varepsilon\}$ we set $b_B^{-1}(s_B) = \{x_B \mid b_B(x_B) = s_B\}$

Transmission cycles

1. First Transmission Cycle

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   - Stochastic encoders $\varphi_A(s_A), \varphi_B(s_B)$ uniformly distributed over $b_A^{-1}(s_A)$ and $b_B^{-1}(s_A)$

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   - Stochastic encoders $\varphi_A(s_A), \varphi_B(s_B)$ uniformly distributed over $b_A^{-1}(s_A)$ and $b_B^{-1}(s_A)$
   - Ray observes
$$Y = X_A + X_B + W$$

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2. Second Transmission Cycle
   - Ray transmits Z, Alice and Bob observe

$$Y_A = Z + W_A,$$
$$Y_B = Z + W_B,$$

W, W_A, W_B AWGN noise

Upper Bounds on Secrecy Rates

Perfect Secrecy w.r.t. Ray if

- $I(Y; S_A) = 0$, perfect secrecy condition for Alice
- $I(Y; S_B) = 0$, perfect secrecy condition for Bob

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Proposition 1

The perfect secrecy rates are bounded by $R_A^s \leq \widehat{R}_A^s$ and $R_B^s \leq \widehat{R}_B^s$,

$$\widehat{R}_A^s = I(X_A; Y_B|X_B) - I(X_A; Y) + \delta_A$$
$$\widehat{R}_B^s = I(X_B; Y_A|X_A) - I(X_B; Y) + \delta_B$$

with $\delta_A = H(X_A|Y_B, X_B)$ and $\delta_B = H(X_B|Y_A, X_A)$

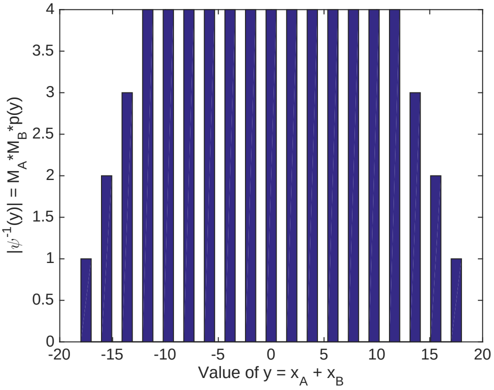

Figure: Pmf of Ray's observation $y = x_A + x_B$ in the noiseless scenario for a 4-PAM modulator and a 16-PAM modulator.

Upper bound in M-PAM systems

Theorem 1

In the noiseless setting with unit channel gains when Alice and Bob employ M_A-PAM and M_B-PAM modulators with $M_B \geq M_A$, we have

$$\widehat{R}^s = m_A \frac{M_B - M_A + 1}{M_B} + \frac{2}{M_A M_B} \sum_{a=1}^{M_A - 1} a \log_2(a).$$

In particular, for fixed M_A we have $\lim_{M_B \to \infty} \widehat{R}^s = m_A$.

Encoder Construction at Bob

Bob's Secret Subset

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Encoder Construction at Bob cnt'd

Bit Labeling

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Bit Labeling

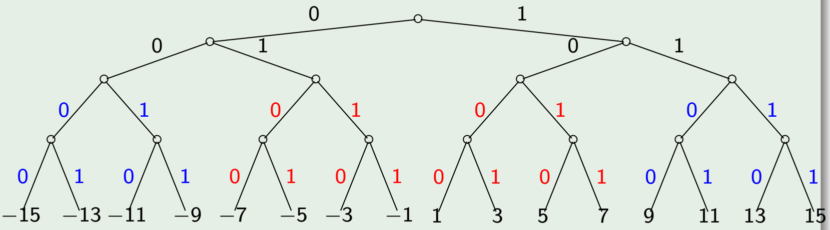
- Bit labeling for $\mathcal{X}_B$: perfect binary tree with edges alternately labeled
- x_B given bit labeling $l(x_B)$ tracing the tree downwards
- Bob's labeling function $b_B : \mathcal{X}_B \to \mathcal{S}_B \cup \{\varepsilon\}$ defined by

$$b_B(x_B) = \begin{cases} \text{the last } m_A \text{ bits of } l(x_B) & x_B \in \mathcal{X}_B^s \\ \varepsilon & x_B \notin \mathcal{X}_B^s \end{cases}$$

Bob's Encoder Example

Example: $M_A = 4$, $M_B = 16$, $\mathcal{X}_B^s = \{-7, \ldots, +7\}$, $\mathcal{X}_B = \{-15, \ldots, +15\}$

Bob transmits $m_A = 2$ bits on $\mathcal{X}_B^s$ with rate $R_B^s = m_A \frac{M_B - 2M_A}{M_B}$



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$M_A = 4$ and $M_B = 16$

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2. $\in \mathcal{X}_B^s \Rightarrow 11$ from $\mathcal{Q}_B^s \Rightarrow x_B = +7$ transmitted
3. and so on...

$$\begin{aligned} &\text{time } t = 1 \quad 1011 \rightarrow +7 = x_B(1) \\ &\text{time } t = 2 \quad 1101 \rightarrow +11 = x_B(2) \\ &\text{time } t = 3 \quad 0111 \rightarrow -1 = x_B(3) \end{aligned}$$

Alice's Bit Labeling

With side info, Alice's bit labeling function

$$b_A : \mathcal{X}_A \times \mathcal{X}_B \to \mathcal{S}_A \cup \{\varepsilon\}$$

where $\mathcal{X}_A$ and $\mathcal{X}_B$ M_A-PAM, M_B-PAM and

$$b_A(x_A, x_B) = \begin{cases} l(x_A) & \text{if } |\psi^{-1}(x_A + x_B)| = M_A \\ \varepsilon & \text{otherwise} \end{cases}$$

Theorem 3

Suppose that $M_B \geq M_A$. For the above encoder, $I(S_A; Y) = 0$, $R_A^s = m_A \frac{M_B - M_A + 1}{M_B}$ and for fixed M_A, $\lim_{M_B \to \infty} R_A^s = m_A$.

Example of Alice's Encoder Construction

$$M_A = 4,\ M_B = 8\ \mathcal{Q}_A^s = 1011,\ x_B(1) = 7,\ x_B(2) = -5,\ x_B(3) = +5$$

x_B

x_A		-7	-5	-3	-1	$+1$	$+3$	$+5$	$+7$
	$+3$	00	00	00	00	00	ε	ε	ε
	$+1$	ε	01	01	01	01	01	ε	ε
	-1	ε	ε	11	11	11	11	11	ε
	-3	ε	ε	ε	10	10	10	10	10

Alice's encoder

time $t = 1$ $\quad x_B(1) = +7, \Rightarrow x_A(1) = -3$

time $t = 2$ $\quad x_B(2) = -5, \Rightarrow x_A(2) = \varepsilon$

time $t = 3$ $\quad x_B(3) = +5, \Rightarrow x_A(3) = -1$

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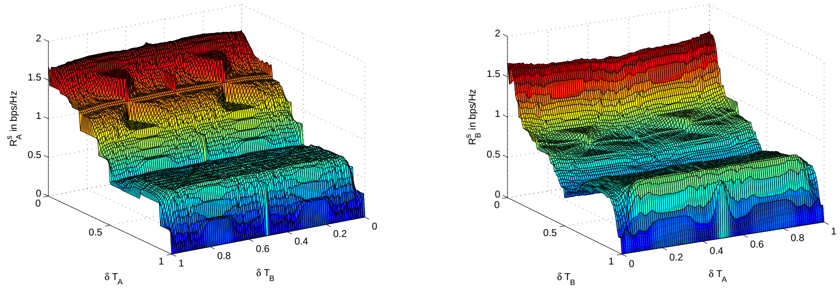

Advantage in population size

Cooperative multiuser setting

- Network with M parallel Rayleigh subchannels, K legitimate users and E eavesdroppers

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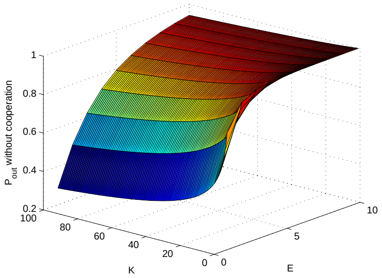
- Fully cooperative scenario (virtual MIMO)

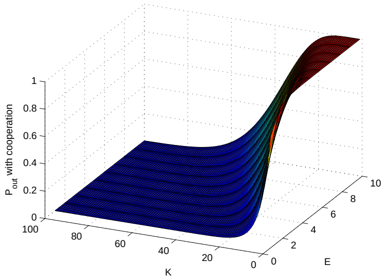
$$P_{out}^{(co)}(K, E, \tau) 1 - \frac{\sum_{n=0}^{K-1} \binom{K+E-1}{n} 2^{n\tau}}{(1+2^{\tau})^{K+E-1}}$$

$\tau = 1$ bit/sec/Hz

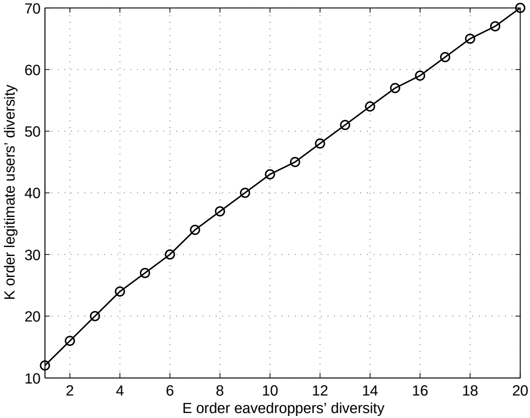
Non-cooperative case $P_{out}^{(nc)}$



Cooperative case $P_{out}^{(co)}$



Required minimum number of K versus E to upper-bound the $P_{out}^{(co)} \leq 1\%$ for $\tau = 1$ bit/sec/Hz



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- **Synergy between information theoretic security and crypto necessary**
- **Nested structures?**
- **New opportunities: user centric adaptive security**

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gracias!

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