Integrity (I) Codes: Message Integrity Protection and Authentication Over Insecure Channels

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May 23, 2006

Motivation

- Common wisdom
  - Any security system is only as secure as its weakest link
  - Weakest link commonly the user, given that the considered system is not user-friendly
- Folk theorem:

User-unfriendliness $\Rightarrow$ security systems highly insecure

Problem Statement

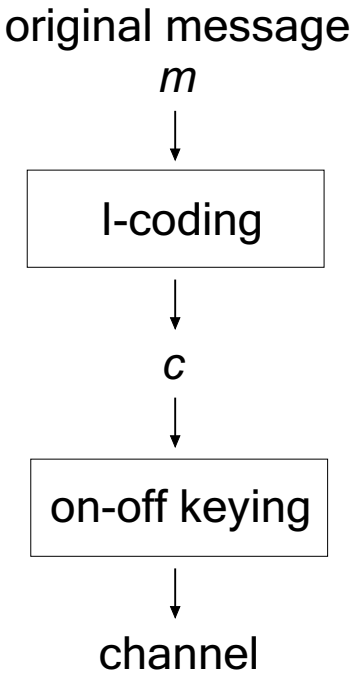
$$\text{Alice} \xrightarrow{\text{message}} \text{Bob}$$

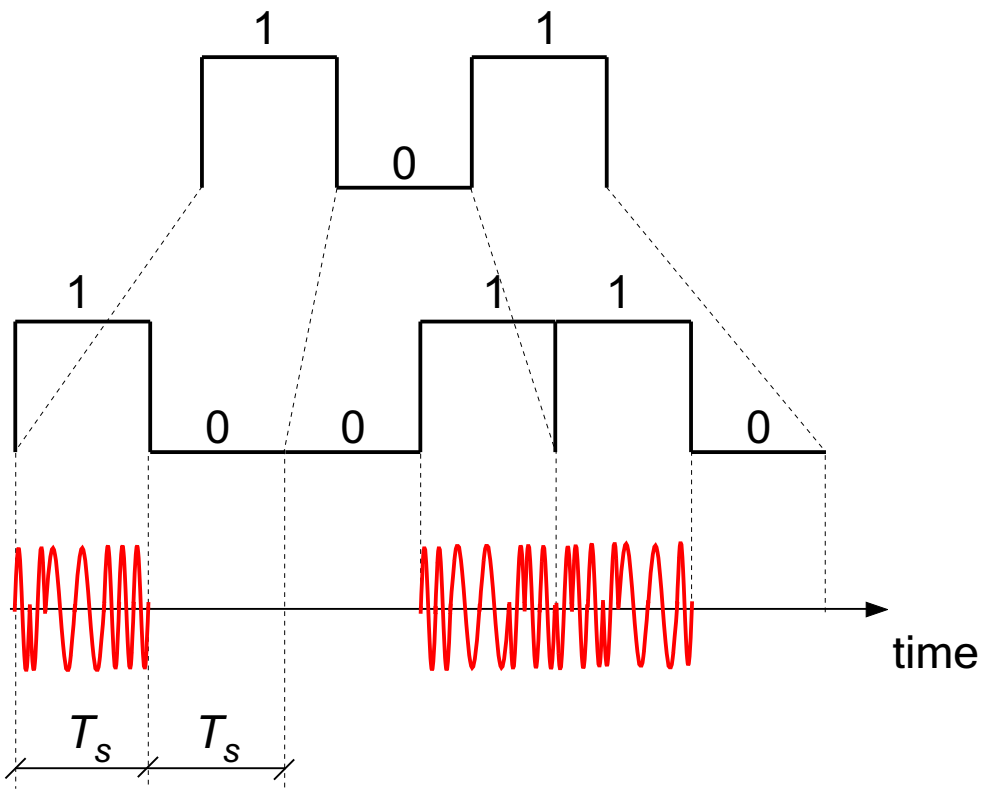
- "$\longrightarrow$" public (insecure) radio channel
- Alice and Bob within each others' transmission range
- Alice and Bob share neither secrets nor certified public keys
- How to preserve the integrity of the "message", while minimizing the users' involvement?

Existing Approaches

- Users share prior context
  - Certified public keys
  - Passwords (Bellovin and Merritt - PAKE)
- No prior context
  - Physical contact (Stajano and Anderson)
  - Location limited infrared channel (Balfanz et al.)
  - Hash visualization (Perrig and Song)
  - Hash functions to readable words (Dohrmann and Ellison)
  - Seeing is believing (McCune, Perrig and Reiter)
  - Short string comparison (Čagalj, Čapkun and Hubaux)

Integrity Coding and a Radio Channel





- The presence or absence of energy in a given time slot of duration T_s conveys information

Integrity (I) Codes

Definition

An integrity code is a triple $(\mathcal{S}, \mathcal{C}, e)$, where the following conditions are satisfied:

1. $\mathcal{S}$ is a finite set of possible source states (plaintext)
2. $\mathcal{C}$ is a finite set of codewords
3. e is a source encoding rule $e : \mathcal{S} \rightarrow \mathcal{C}$, satisfying the following:
   - e is an injective function
   - it is not possible to convert codeword $c \in \mathcal{C}$ to another codeword $c' \in \mathcal{C}$, such that $c' \neq c$, without changing at least one bit 1 of c to bit 0.

I-code Example: Complementary Encoding

- Complementary encoding rule (Manchester) e:

$$\begin{array}{ccc} 1 & \longrightarrow & 10 \\ 0 & \longrightarrow & 01 \end{array}$$

- $\mathcal{S} = \{00, 01, 10, 11\} \xrightarrow{e} \mathcal{C} = \{0101, 0110, 1001, 1010\}$

$$\begin{array}{ccc} 0101 & \longrightarrow & 0111 \\ 0101 & \longrightarrow & 1101 \\ 0101 & \longrightarrow & 1111 \end{array} \qquad \begin{array}{ccc} 0110 & \longrightarrow & 0111 \\ 0110 & \longrightarrow & 1111 \\ 0110 & \longrightarrow & 1110 \end{array}$$

I-codes Security

- Assumptions
  1. Sender and receiver are in synch wrt. the beginning and the end of c
  2. Adversary cannot block (annihilate) signal 1 (except with ε)

Theorem

The adversary cannot trick the receiver into accepting the message $\widehat{m}$ when $m \neq \widehat{m}$ is sent, except with ε probability.

- Proof:
  - $\widehat{m} \neq m \Rightarrow \widehat{c} \neq c$ (I-code)
  - $c \rightarrow \widehat{c}$ implies at least one bit 1 of c to bit 0 (I-code)
  - Adversary has to annihilate some of the emitted signals (with ε prob.)

q.e.d.

Synchronization via Incongruous (i) Delimiters

Definition (informal)

Given $\mathcal{C}$, i-delimiter is a *minimum-length* bit string such that any valid codeword $c \in \mathcal{C}$ received between two consecutive i-delimiters is authentic.

- Example (complementary encoding)

$$\mathcal{S} = \{0, 1, 00, 01, \ldots, \underbrace{11\ldots1}_{k}\},\ \mathcal{C} = \{01, 10, 0101, 0110, \ldots, \underbrace{1010\ldots10}_{2k}\}$$

$$\ldots\ \underbrace{111000}_{i\text{-delimiter}}\overbrace{1010011001}^{c}\underbrace{111000}_{i\text{-delimiter}}\overbrace{1010011001}^{c}\underbrace{111000}_{i\text{-delimiter}}\ \ldots$$

- Receiver does not have to know the length of the c in advance
- "Correct" c, received between two subsequent i-delimiters is authentic

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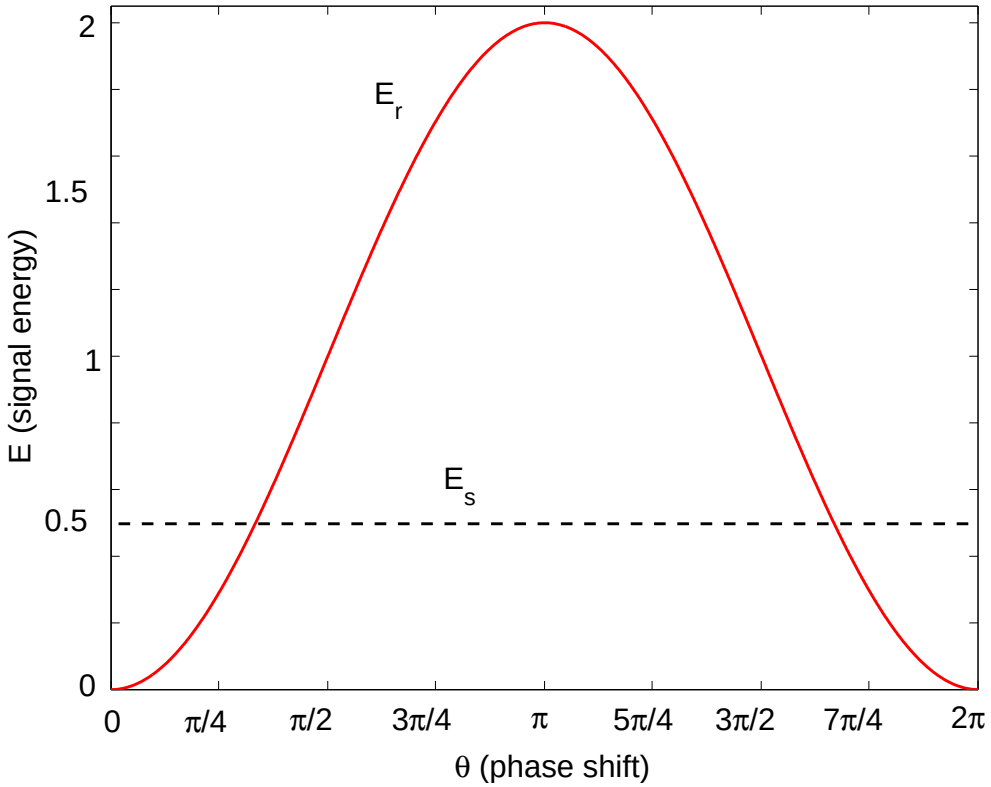
Anti-blocking Property of a Radio Channel ($1 \nrightarrow 0$)

$$\underbrace{r(t)}_{\text{receiver}} = \underbrace{\cos(\omega_0 t)}_{\text{sender}} - \underbrace{\cos(\omega_0 t - \theta)}_{\text{adversary}}, \text{ where } \theta \in [0, 2\pi)$$

$$E_r = \int_0^{T_s} r^2(t)dt$$
$$\approx 2T_s \sin^2\left(\frac{\theta}{2}\right)$$



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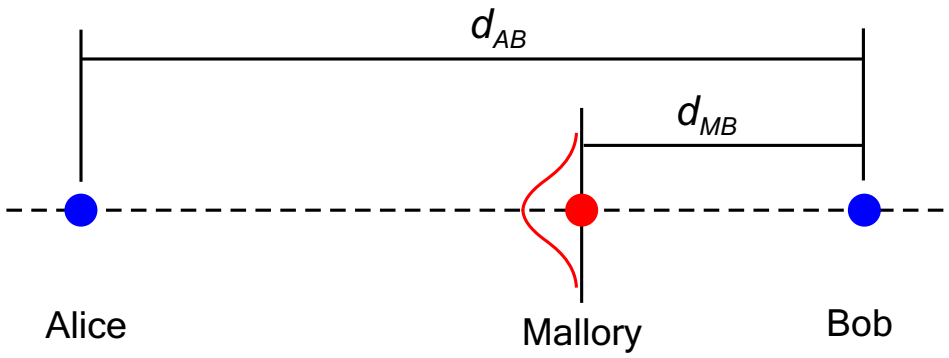
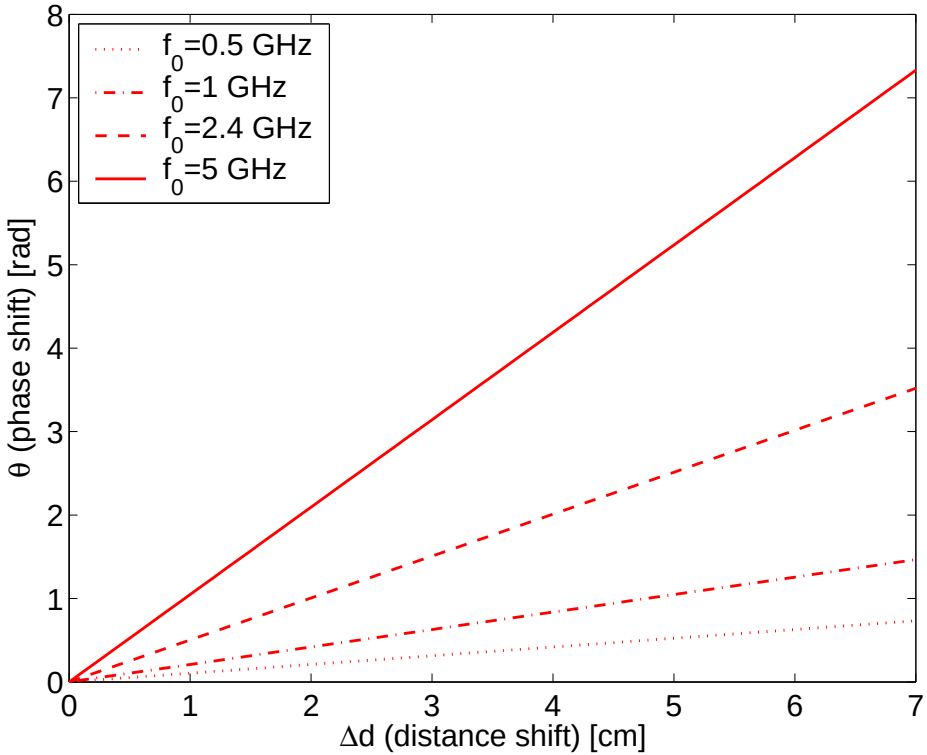




Anti-blocking Property of a Radio Channel ($1 \nrightarrow 0$)

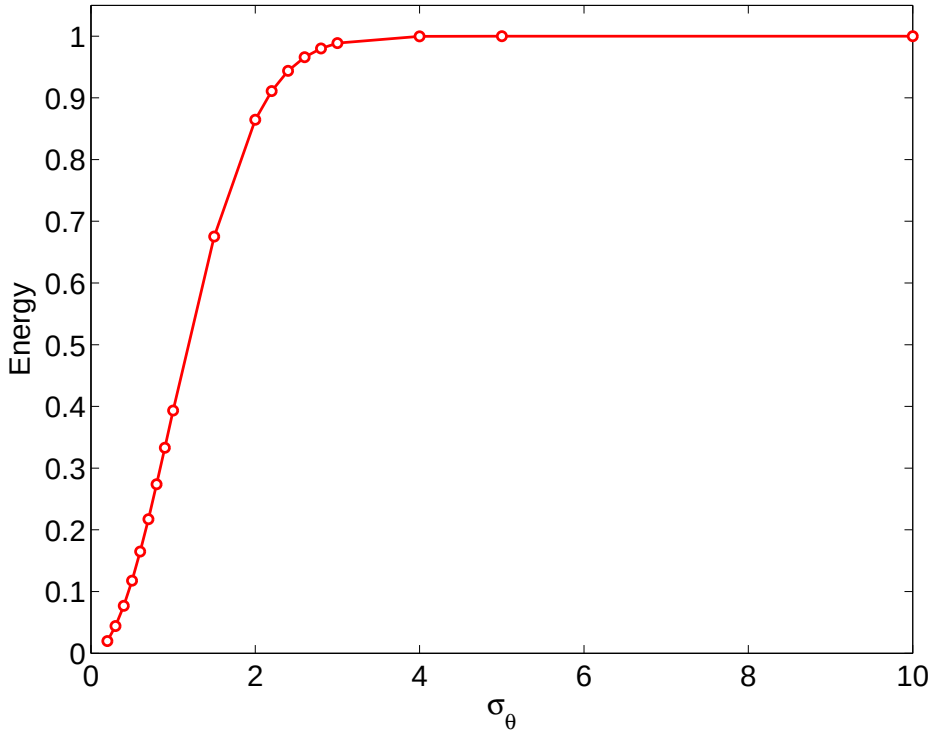
$$\underbrace{R(t)}_{\text{receiver}} = \underbrace{\cos(\omega_0 t + \Phi)}_{\text{sender}} - \underbrace{\cos(\omega_0 t - \Theta)}_{\text{adversary}}, \quad \Phi \in_U [0, 2\pi)$$

- Θ a random variable (example, $\Phi = 0$)
  - Energy content $\mathcal{E}_R = \mathbb{E}\left[\int_0^T R^2(t)dt\right] \approx T$, for uniform Θ
  - Gaussian Distribution of Θ with zero mean and variance σ_θ^2

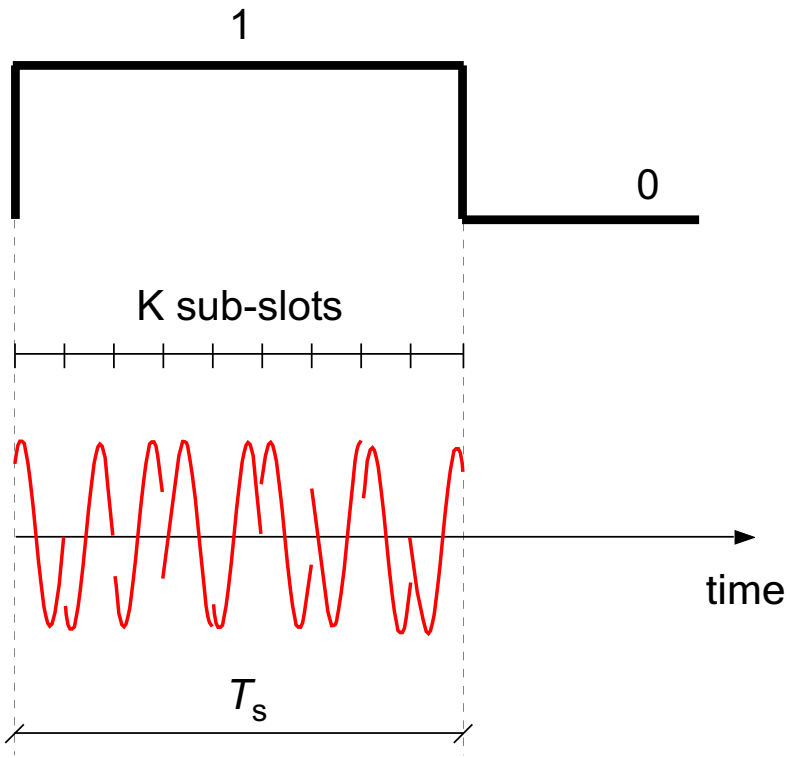
$$\sigma_\theta^2 = (2\pi f_0/c)^2 \sigma_d^2$$

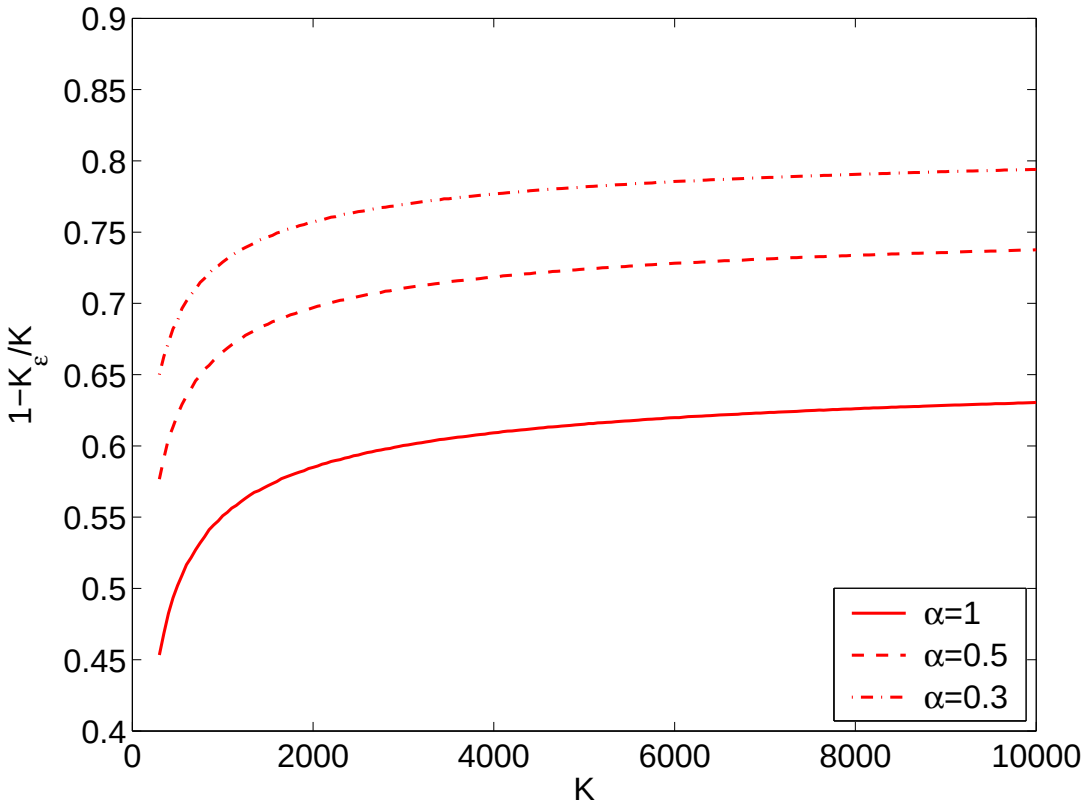
$$f_0 = 5GHz,$$

$$\sigma_\theta = 1.189 \text{ rad} \Leftrightarrow \sigma_d = 1.14 \text{ cm}$$



Randomization at the Sender

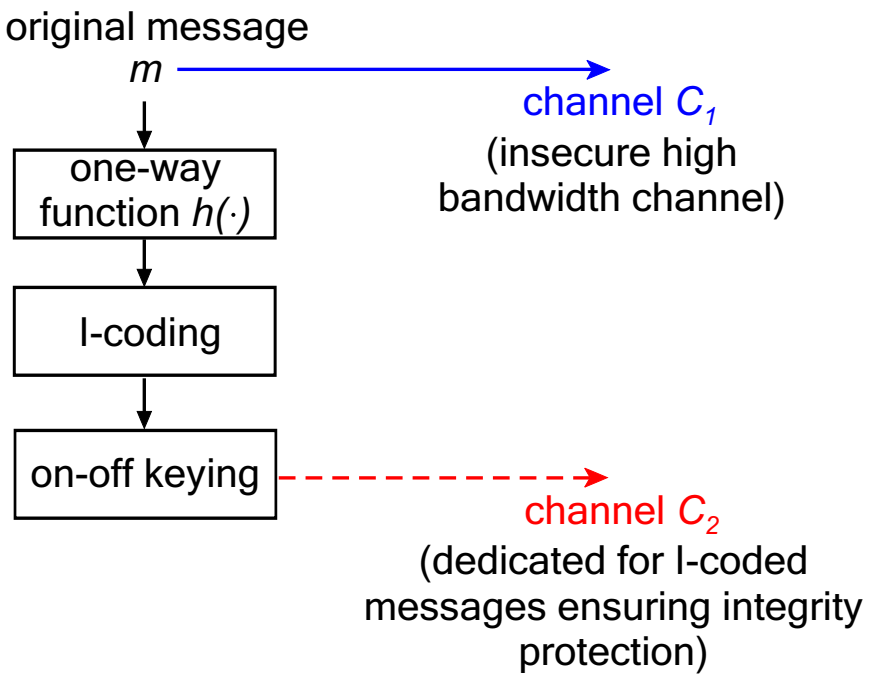




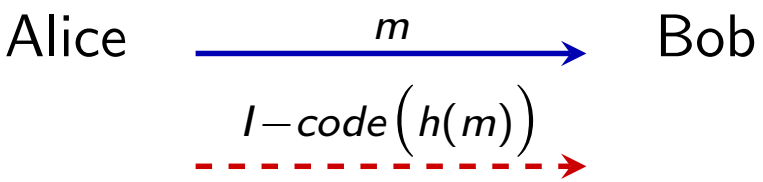
$$\mathbb{P}[K_{\text{attenuated}} \leq K_\varepsilon] \geq 1-\varepsilon,\ \varepsilon = 10^{-14}$$

Applications of I-codes

- **Authentication through presence (radio channel)**

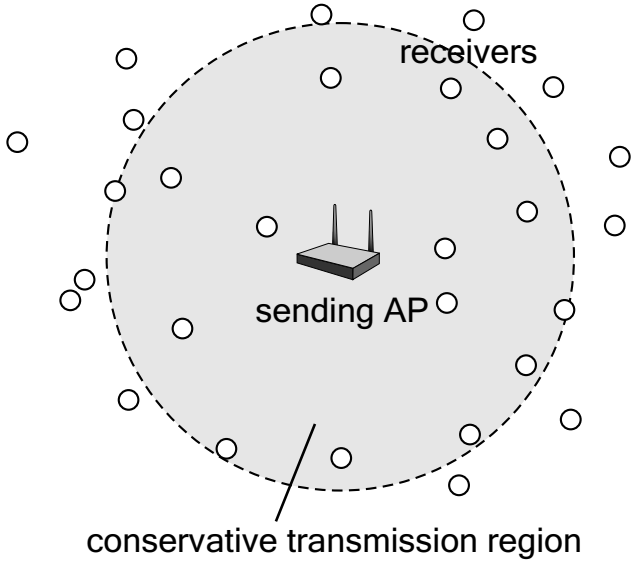


- Solving our initial problem



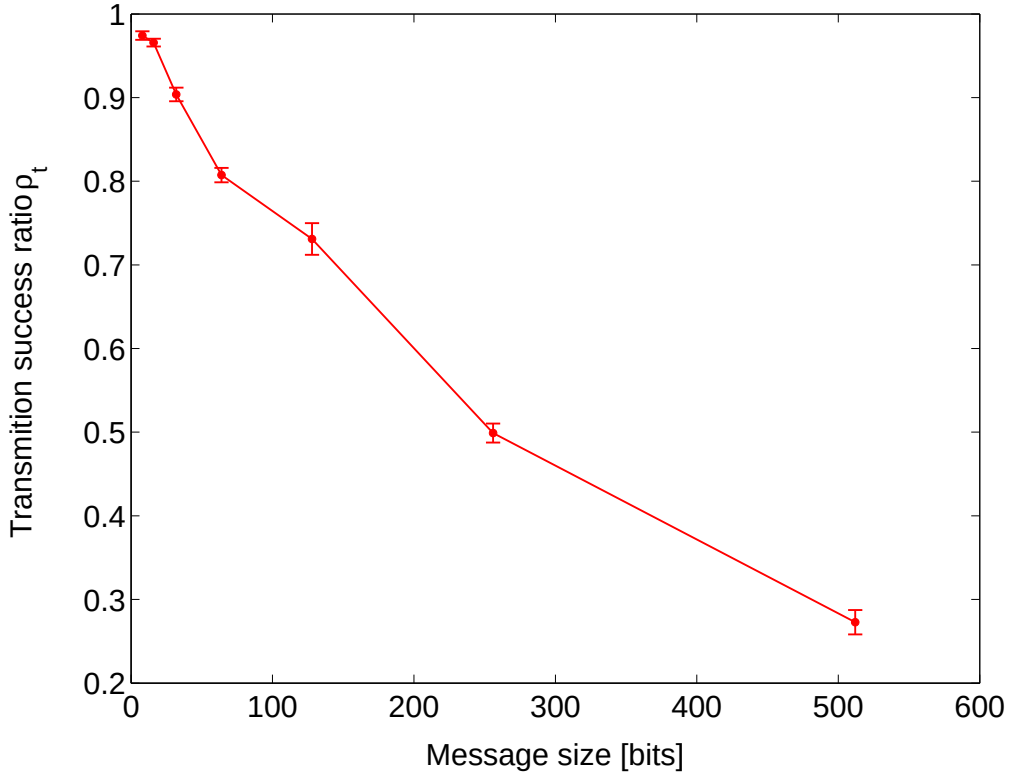
Other Applications

- Broadcast Authentication
  - Access Point Authentication

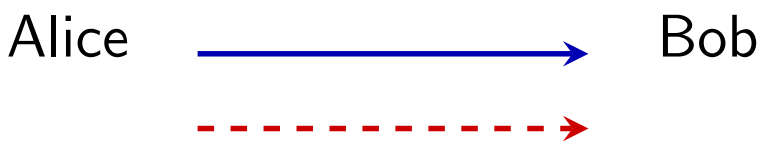


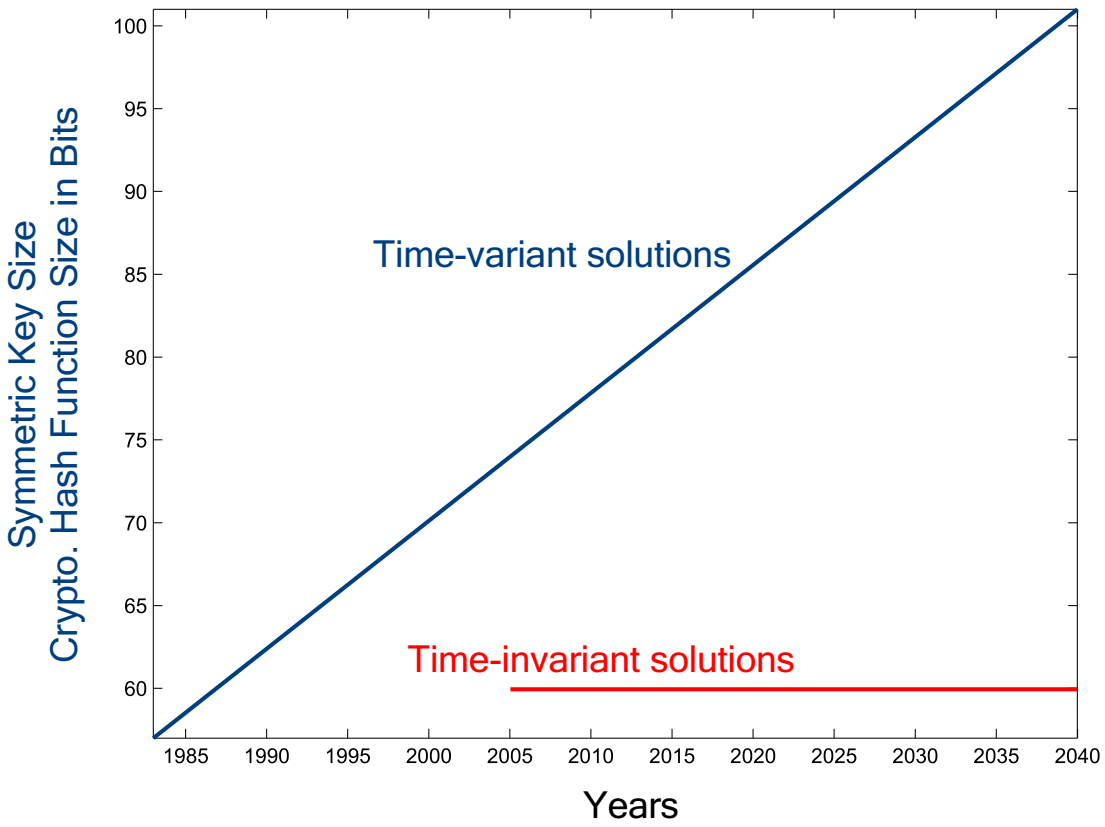
Implementation of I-codes

- Mica2 sensor networking platform (UCLA SOS operating system)
  - Frequency Shift Keying, output power −20 to 10 dBm
- Complementary encoding
  - Every bit 1 transmitted as an 48-bit packet ($T_s = 10$ ms)
  - Every bit 0 transmitted as an absence of signal ($T_s = 10$ ms)



Time-invariance





Optimal Message Transfer (MT) Authenticator[1]

Alice		Bob
Given m		
Pick $N_A \in_U \{0,1\}^k$		Pick $N_B \in_U \{0,1\}^k$
$(c, d) \leftarrow \mathrm{commit}(m \| N_A)$		
	$\xrightarrow{c}$	
	$\xleftarrow{N_B}$	
$s_A \leftarrow N_A \oplus \widehat{N}_B$	$\xrightarrow{d}$	$\widehat{m} \| \widehat{N}_A \leftarrow \mathrm{open}(\widehat{c}, \widehat{d})$
	$\xrightarrow{s_A}$	$s_B \leftarrow N_B \oplus \widehat{N}_A$
		If $s_A = s_B$, "Accept" $\widehat{m}$

- Transmit s_A using I-codes
- Free choice of the size of s_A (e.g., 50 bits)
- **Time-invariant solution**

[1] Čagalj, Čapkun and Hubaux. "Key Agreement in Peer-to-Peer Wireless Networks". *Proceedings of the IEEE (Special Issue on Cryptography and Security)*, 2006.

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Summary and Future Work

- Integrity and authentication without shared keys/certificates (over insecure radio channels)
  - Anti-blocking property of a radio channel
  - Location awareness
- Applications
  - Walk-in scenarios (AP authentication)
  - Broadcast authentication with low-power devices (Mica2 sensor platform)
  - P2P and group key establishment
- Authentication through presence

Future work: Application of I-codes to a wired channel?