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Integrity Assurance in Resource-Bounded Systems through Stochastic Message Authentication

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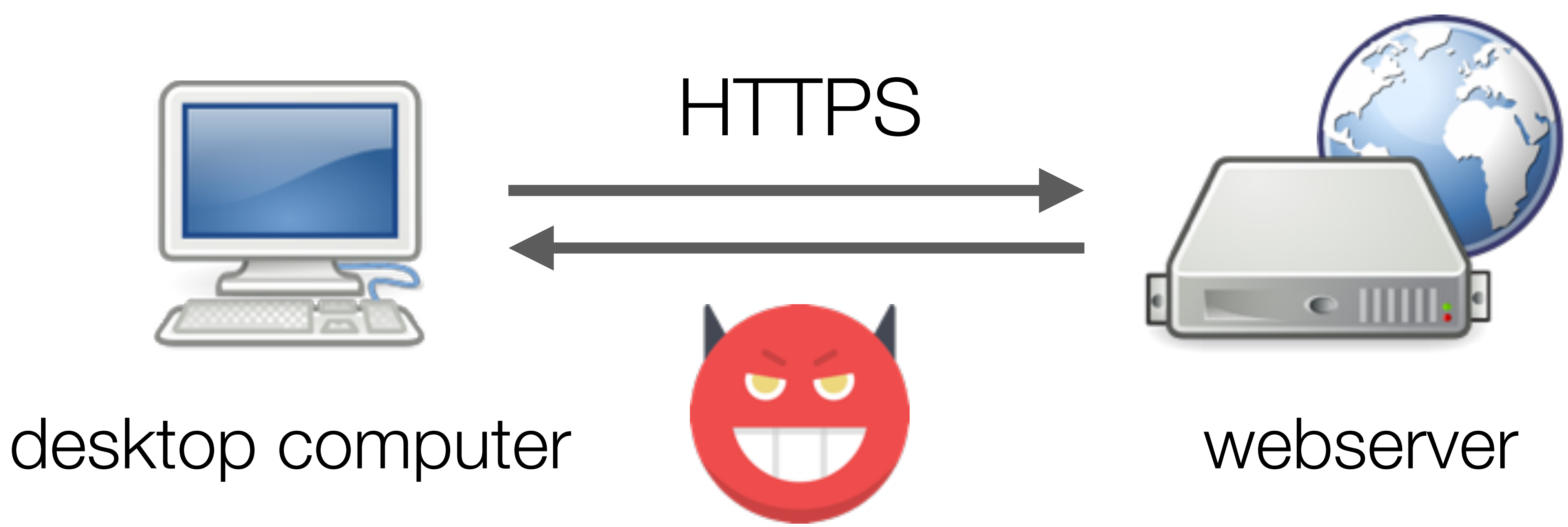
Data Integrity

- Data integrity:
  assuring that data cannot be modified in an unauthorized and undetected manner

- Classic, non-resource-bounded example:



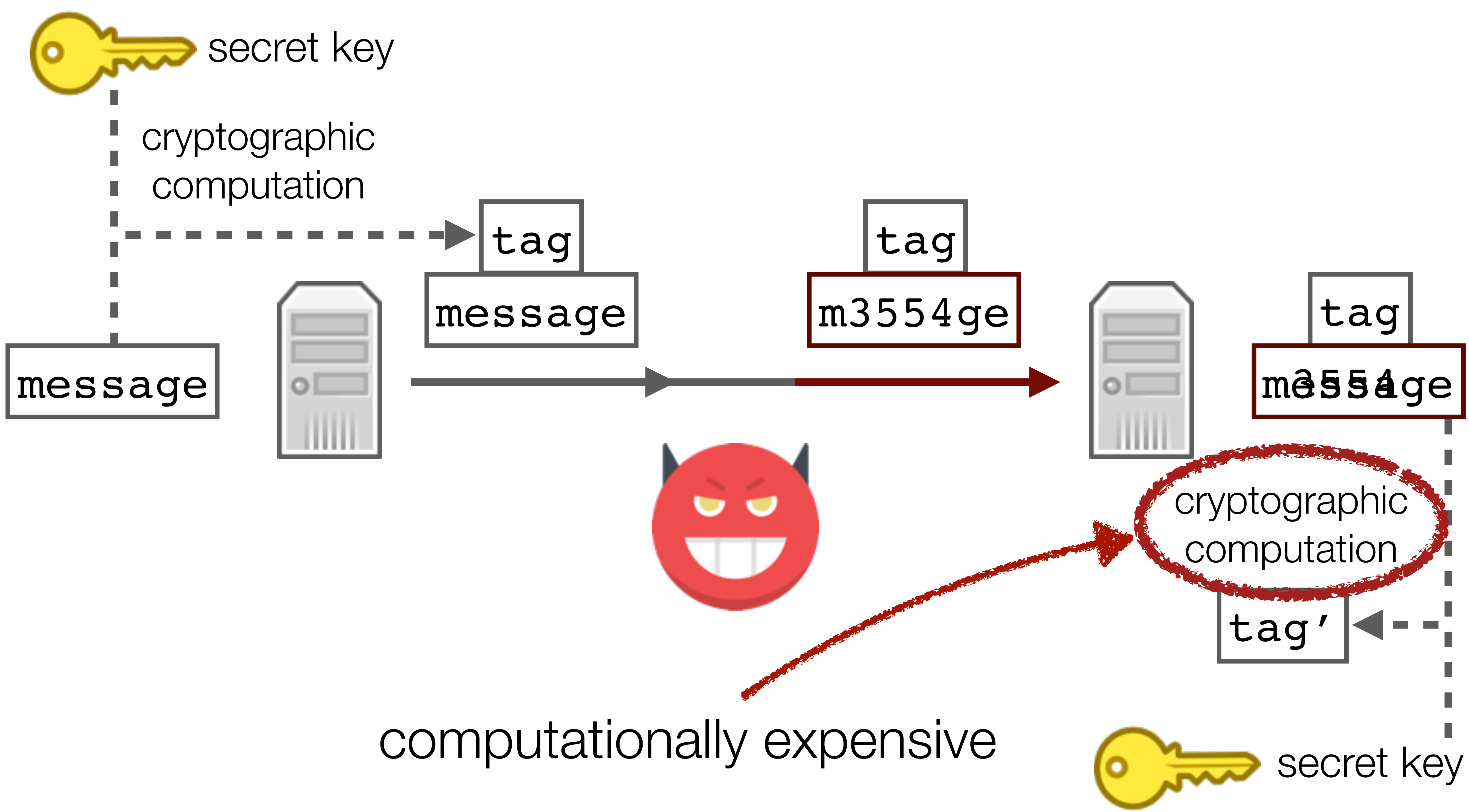
Not really an issue these days, right?

Example of Data-Tampering

Traffic monitoring: Sensys Networks VDS240

- wireless vehicle detection system based on magnetic sensors embedded in roadways
- insecure communication protocol lacks integrity protection
- attacker may cause disastrous traffic congestions

Message Authentication



Insufficient resources

messages are **not** verified

zero security

Limited amount of resources

some messages are verified

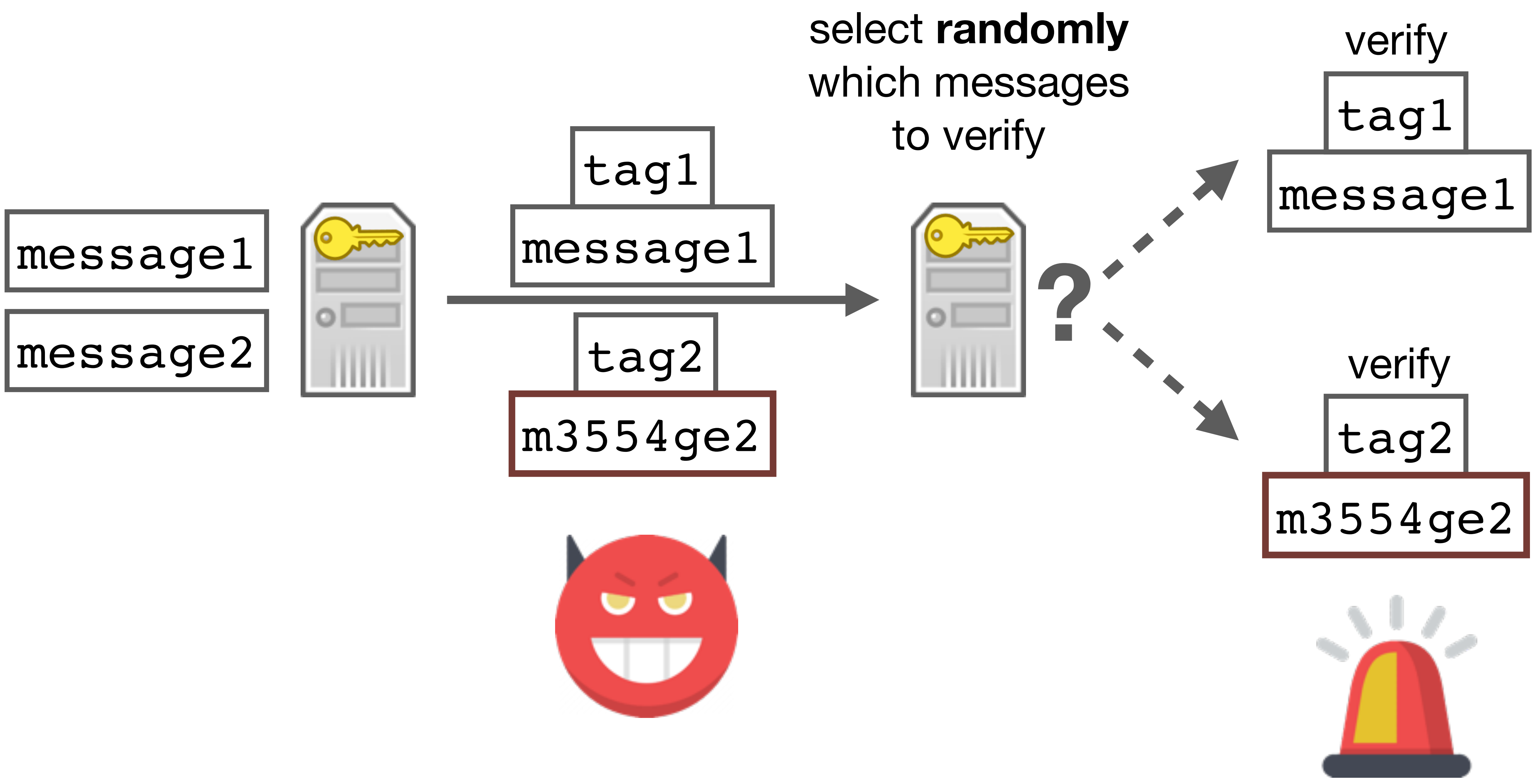
maximal achievable security

Sufficient resources

messages are verified

maximum security

Stochastic Verification



Applications

- In many scenarios, suboptimal data acquisition and control is **costly** but **not disastrous**
  - inefficient traffic control
  - incorrect smart-metering
  - …
- Resource-bounded devices
  - battery-powered devices
  - legacy devices
  - low-performance devices
  - …
- Comparison to lightweight cryptography
  - we build on well-known and widely deployed cryptographic primitives
  - our system adapts to arbitrary resource bounds

Game-Theoretic Model

"Which messages to verify?"

- Stackelberg security game with a defender and an attacker

Messages

- divided into classes
- messages of class i may cause L_i damage

1. Defender

- chooses verification probabilities p_i
- subject to computational budget constraint

$$\sum p_i T_i \leq B$$

where T_i is the cost of verifying all messages of class i

Game-Theoretic Model (contd.)

1. Defender

2. Attacker

- selects the number a_i of modified/forged messages for each class i
- knows the defender's strategy (i.e., p_i for every i)

3. Payoffs

outcome:

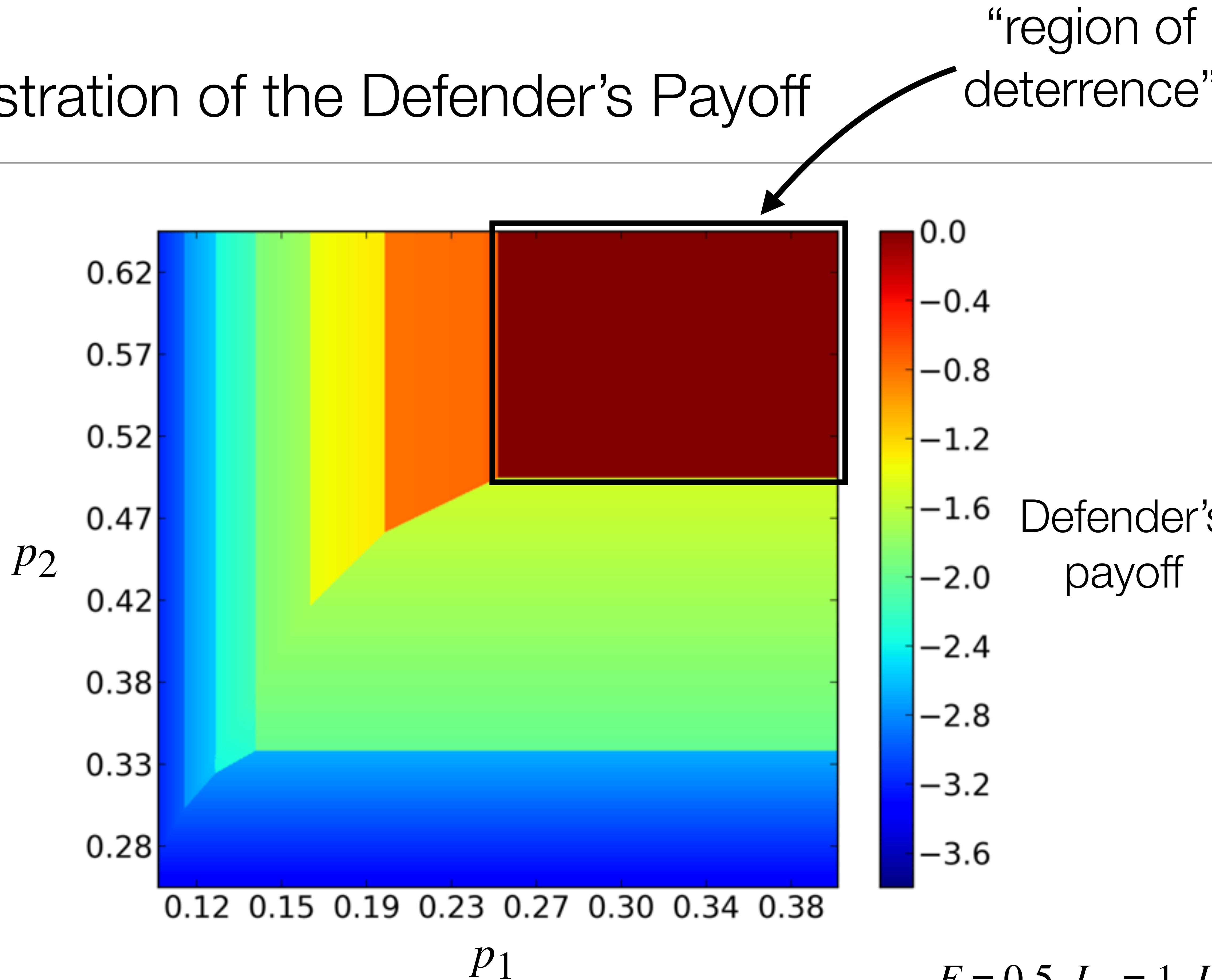
$1 - \prod(1 - p_i)^{a_i}$

attack detected:
attacker receives
punishment F

$\prod(1 - p_i)^{a_i}$

attack not detected:
defender loses /
attacker gains $\sum a_i L_i$

Illustration of the Defender's Payoff



$F = 0.5, L_1 = 1, L_2 = 3$

Deterrence Strategies

- Deterrence strategy:
  attacker's best response is not to modify any messages

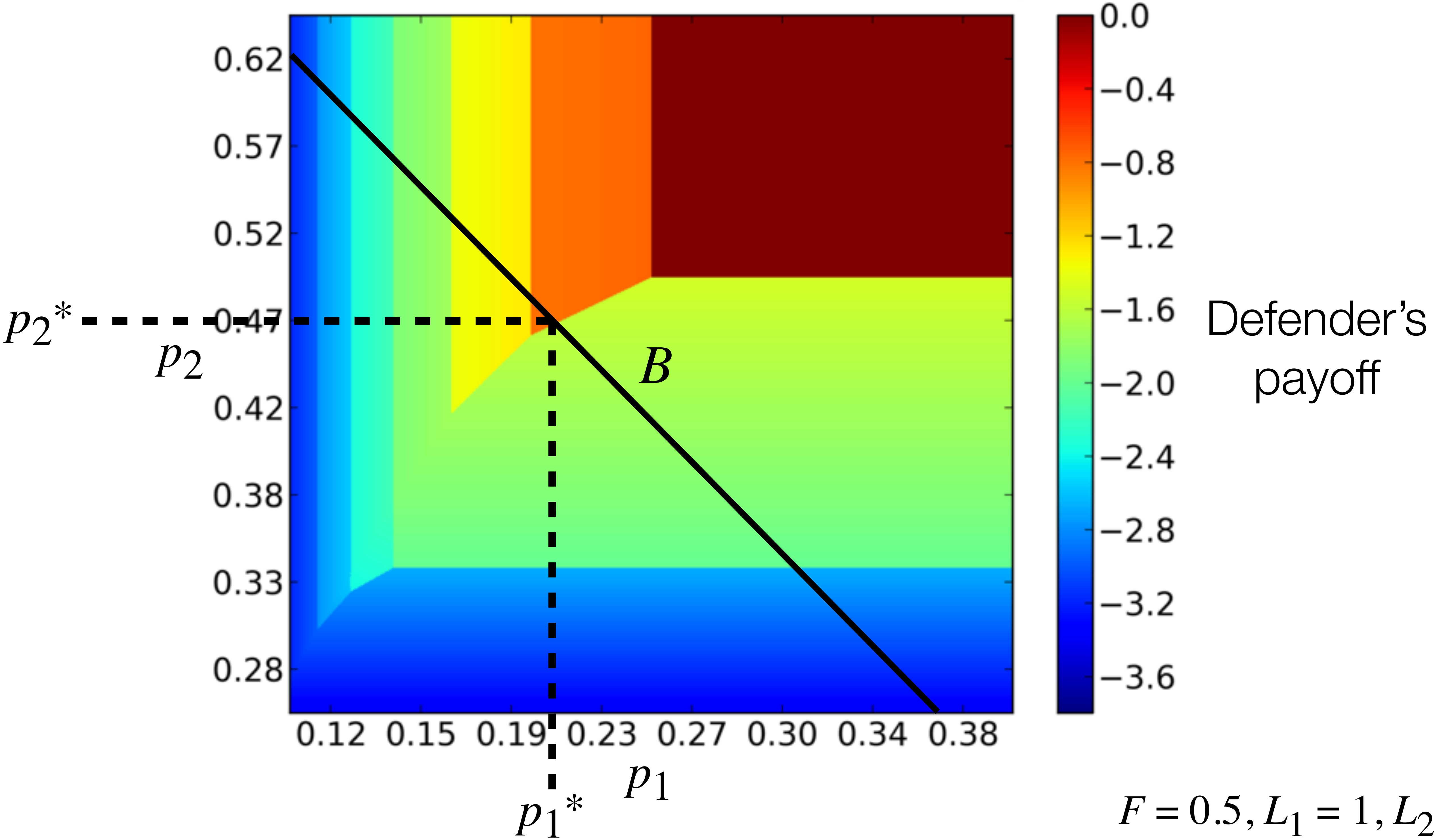
Theorem: The defender has a deterrence strategy if and only if

$$B \geq \sum_i \frac{L_i}{L_i + F} T_i$$

and the minimal deterrence strategy is

$$p_i = \frac{L_i}{L_i + F}$$

Non-Deterrence Strategies



$F = 0.5, L_1 = 1, L_2 = 3$

Continuous Relaxation

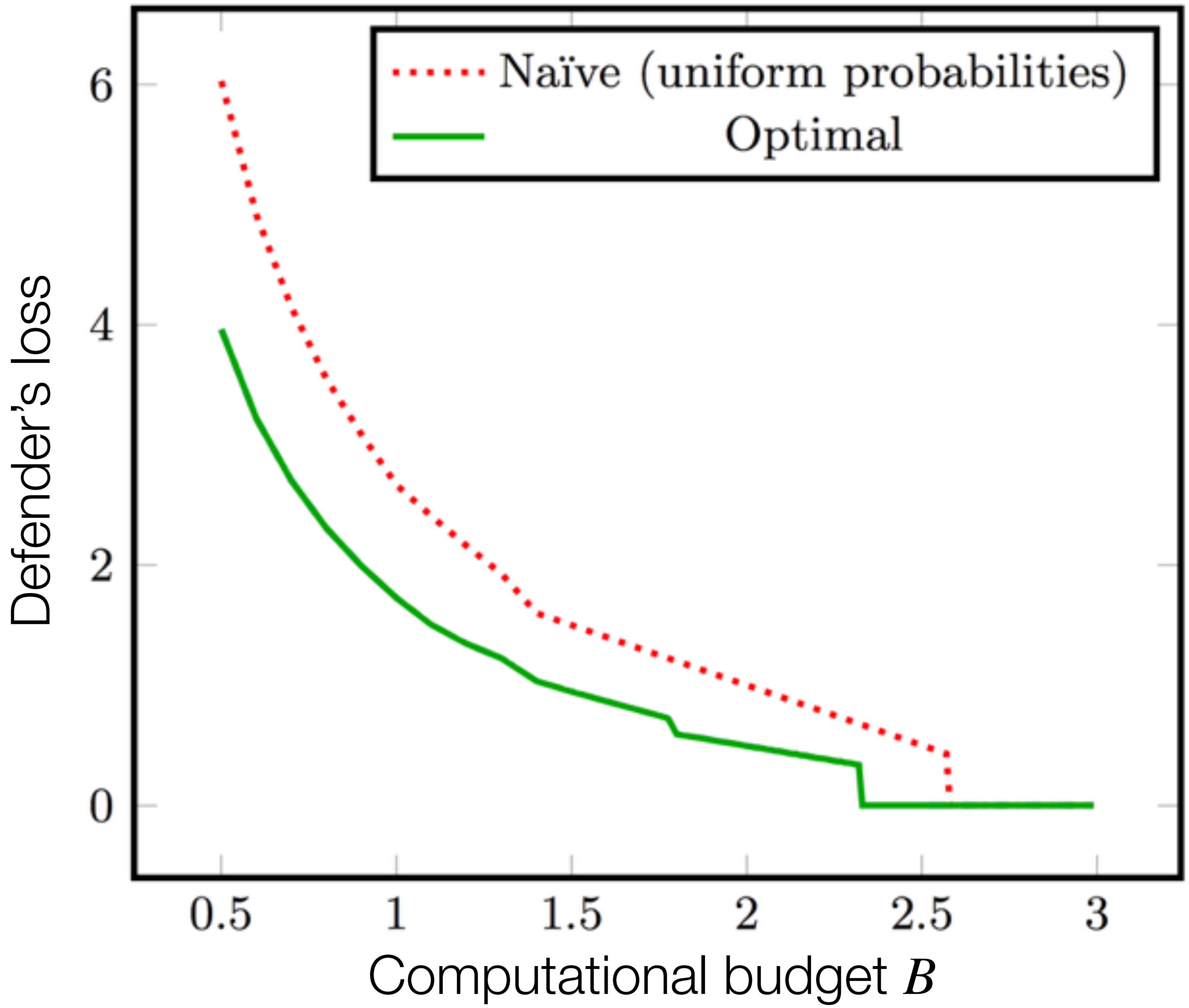
- No closed-form solution for the original model
- Continuous relaxation of the model
  - a_i is continuous (i.e., $a_i = 1.5$ means that the attacker modifies one and a half messages)

Theorem: Optimal strategy in the continuous relaxation is

$$\frac{L_1}{\ln(1-p_1)} = \frac{L_2}{\ln(1-p_2)} = \ldots = \frac{L_C}{\ln(1-p_C)}$$

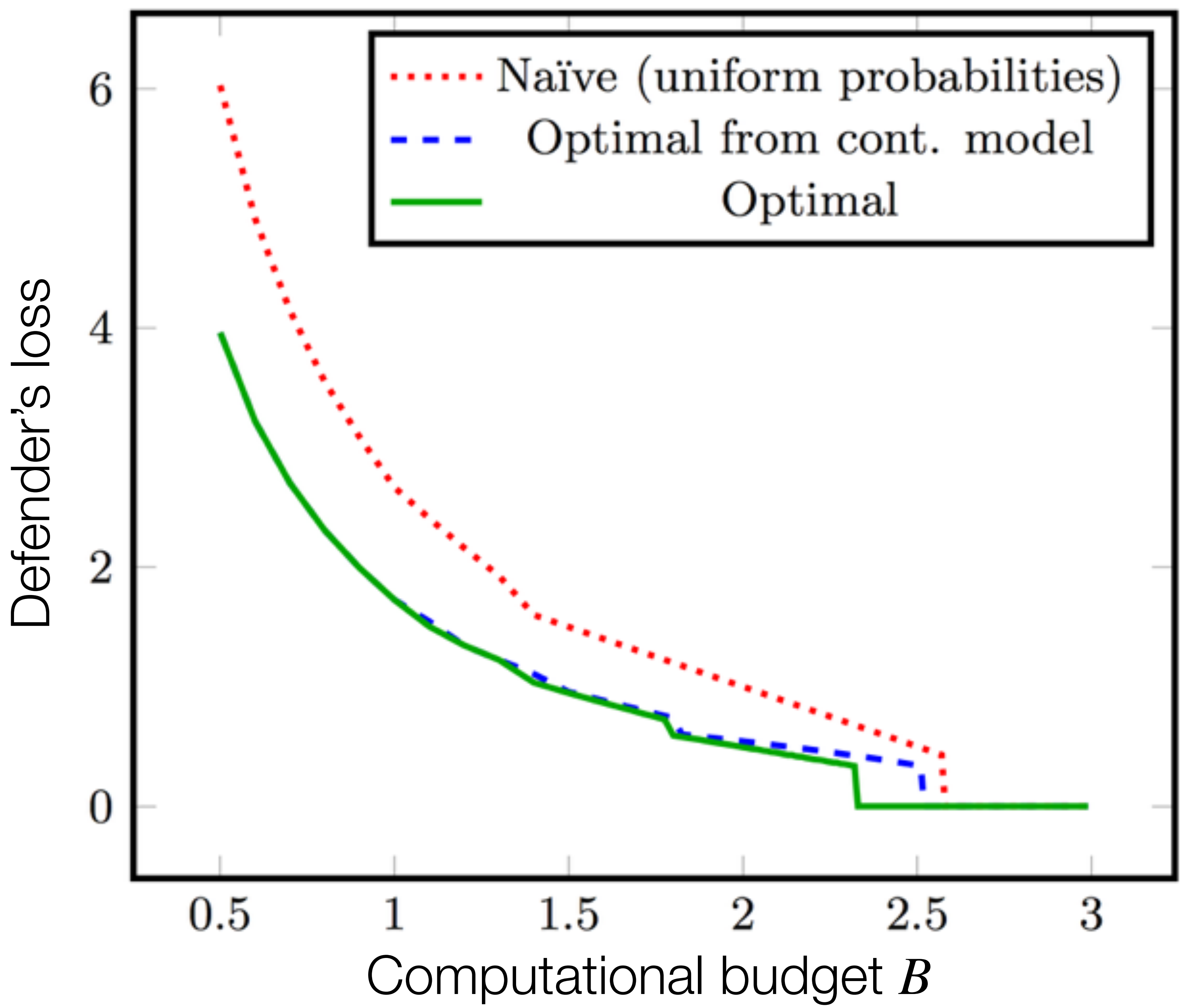
$$\sum p_i T_i = B$$

Numerical Example Comparing Strategies



$F = 0.5, L_1 = 1, L_2 = 2, L_3 = 3, T_1 = T_2 = T_3 = 1$

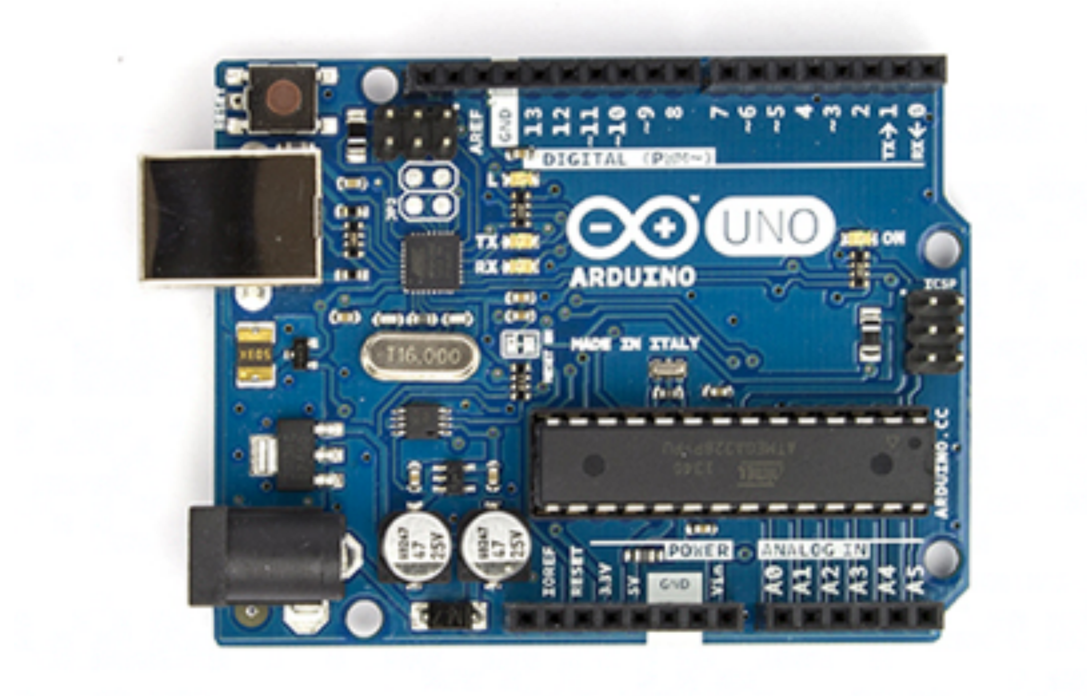
Numerical Example Comparing Strategies



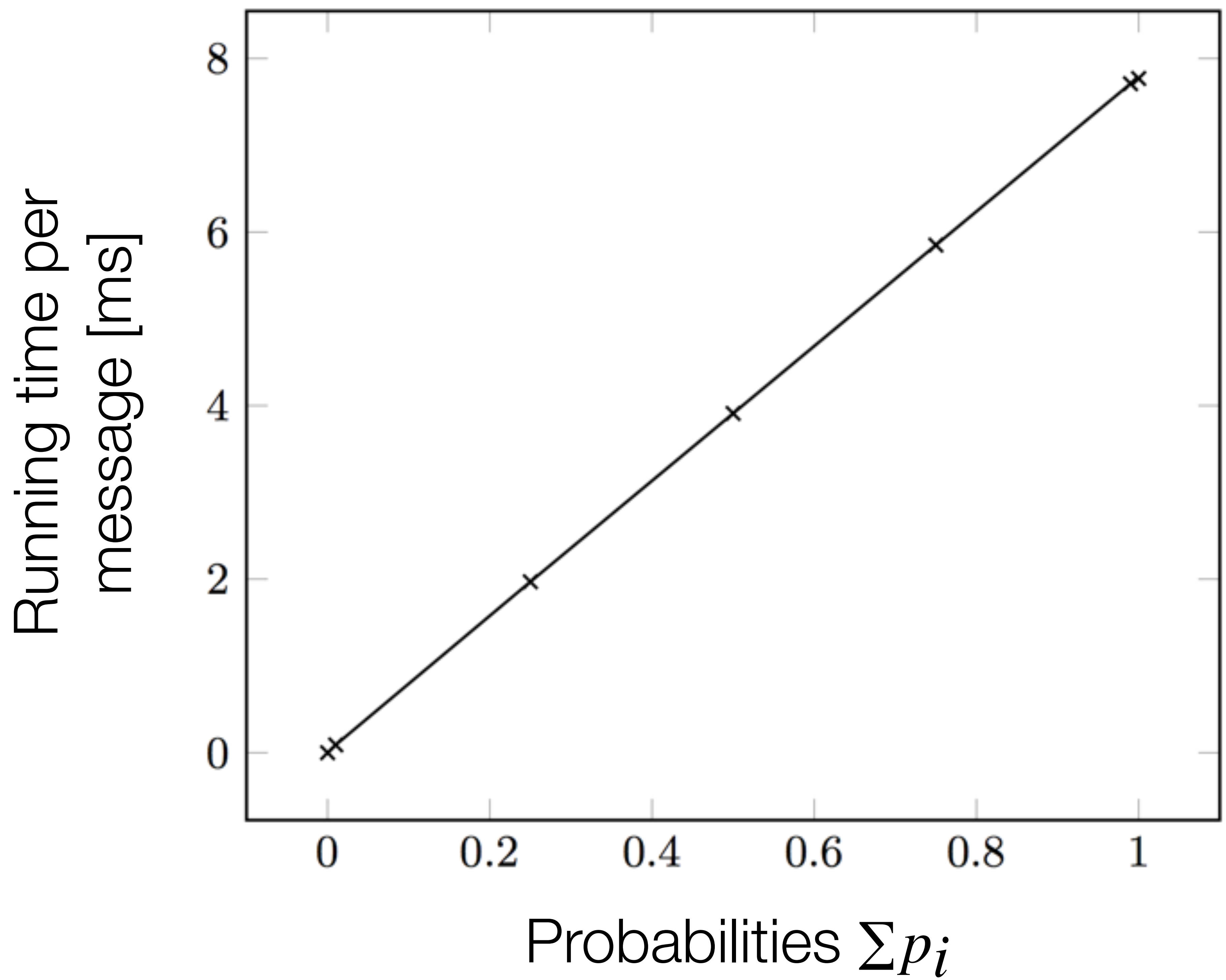
$F = 0.5, L_1 = 1, L_2 = 2, L_3 = 3, T_1 = T_2 = T_3 = 1$

Experiments

- Implementation and testing on an `ATmega328P` microcontroller
- Message authentication tag generation and verification:
  - HMAC (keyed-hash message authentication code)
  - using the SHA-1 hash function
- Random number generation:
  - linear-feedback shift register



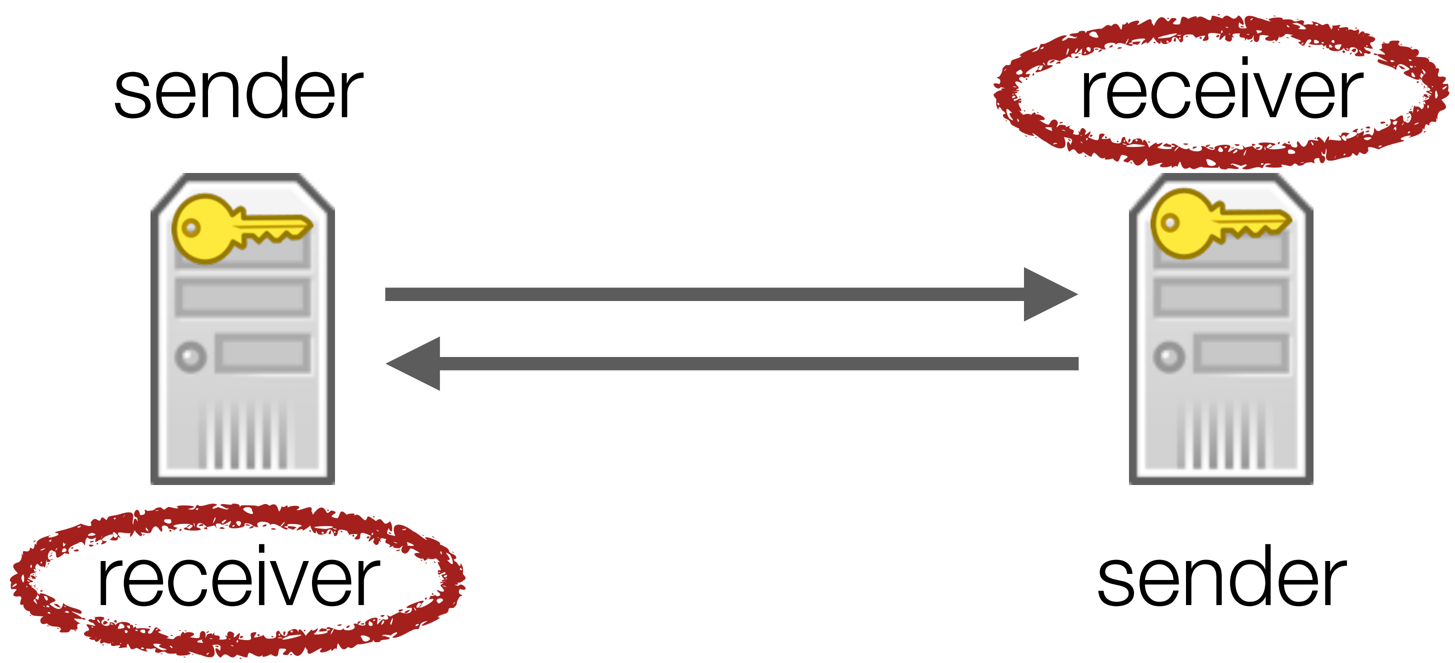
Experimental Results



Resource-Bounded Senders

- So far, we have saved computation **only at the receiver**

- Two-way communication



up to 100% saving when receiving
+ 0% saving when sending

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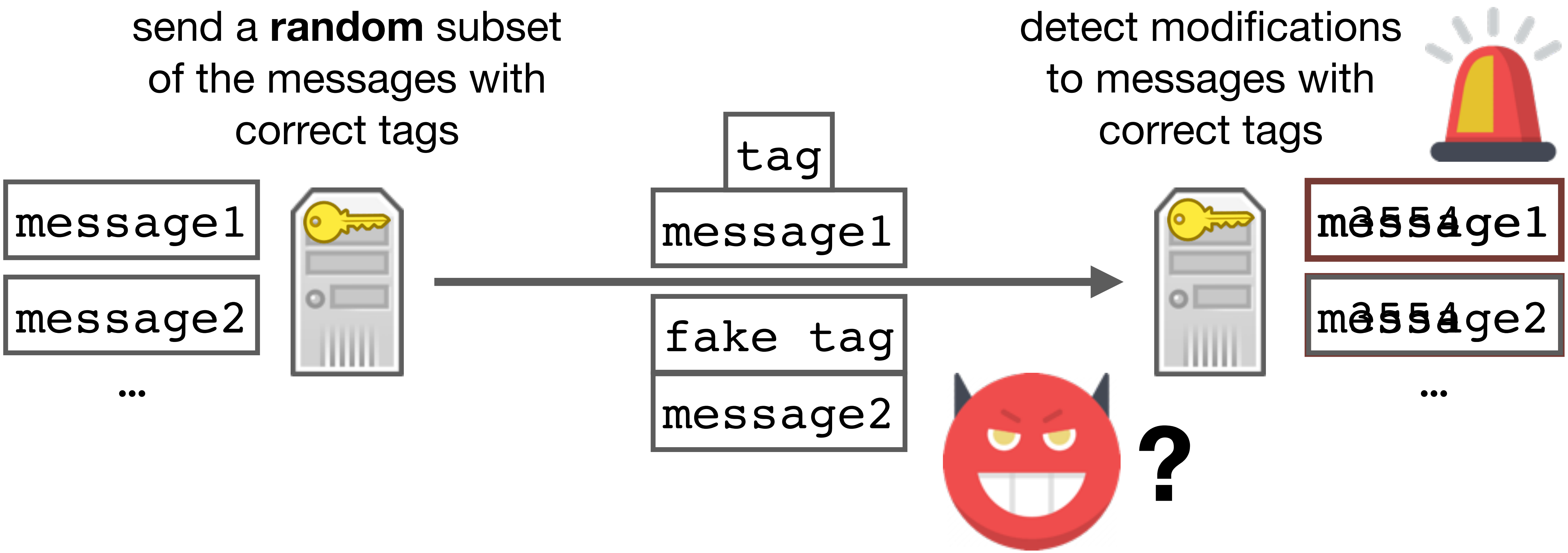
up to 50% saving overall

“Could we also save computation when generating tags?”

- **next: stochastic authentication tag generation**

Stochastic Message Authentication



- Fake tags
  - indistinguishable from correct tags for the attacker
  - distinguishable from incorrect tags for the receiver
  - computationally inexpensive to generate and verify

Generating and Verifying Fake Tags

- Proof-of-concept algorithms based on the HMAC construction with a Merkle-Damgard hash function

Algorithm 1 MAC tag generation in partial HMAC

function GENERATETAG(K, $\boldsymbol{m}$)
    $rnd \leftarrow \mathcal{U}(0,1)$
    if $rnd \leq p_{\text{class}(\boldsymbol{m})}$ **then**
        return HMAC($\boldsymbol{m}$)
    else
        return $f(f(IV,\ K \oplus ipad),\ m_1)$
    end if
end function

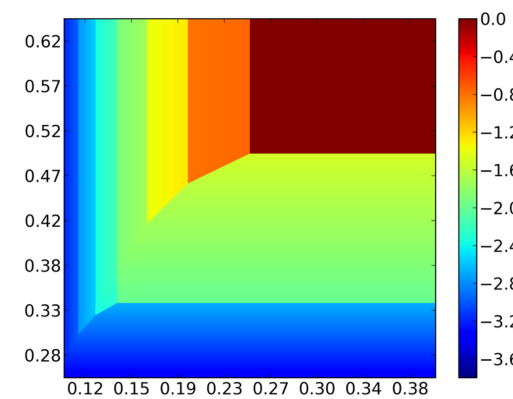
Algorithm 2 MAC tag verification in partial HMAC

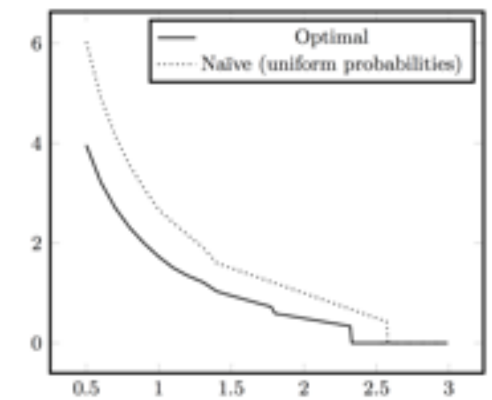
function VERIFYTAG(K, $\boldsymbol{m}$, t)
    $t_f \leftarrow f(f(IV,\ K \oplus ipad),\ m_1)$
    if $t = t_f$ **then**
        return *fake*
    else
        $t_c \leftarrow H\big((K \oplus opad) \mid \underbrace{f(f(\ldots f(t_f, m_2), \ldots, m_n), \text{length padding})}_{=H(K \oplus ipad \mid \boldsymbol{m})}\big)$
        if $t = t_c$ **then**
            return *correct*
        else
            return *incorrect*
        end if
    end if
end function

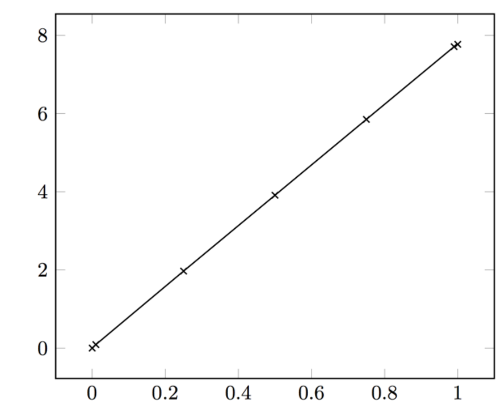
- Implementation and testing show substantial savings for both the receiver and sender on an `ATmega328P` microcontroller

Conclusion

- Stochastic message verification
  - message authentication for resource-bounded devices
  - game-theoretic model for defending against worst-case attackers
  - experimental results confirm computational cost model







- Next: stochastic message authentication tag generation
  - allows saving computation for both sender and receiver

Thank you for your attention!

Questions?