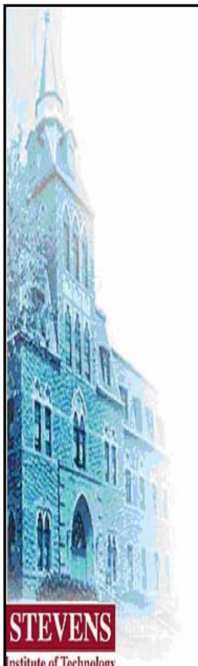

Opportunistic Encryption for Robust Wireless Security

R. Chandramouli ("Mouli")
mouli@stevens.edu

Multimedia System, Networking, and Communications (MSyNC) Laboratory,
Department of Electrical and Computer Engineering,
Stevens Institute of Technology

(joint work with **C. Nanjunda, M. Haleem, and K.P. Subbalakshmi**)

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Wireless Link Properties

- Wireless link states randomly vary with time and space.
  - Bursty errors (e.g., fading channels).
  - Random errors.
- Effect of link errors.
  - Bit flips.
  - Bit deletion and bit insertion

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Overview of Encryption Schemes

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- Block cipher.
  - Fixed blocks of plaintext encrypted to same blocks of ciphertext using an encryption key.
- Stream cipher.
  - Block size equal to one bit.
- Symmetric key encryption.
  - Same key for encryption and decryption.
- Public key encryption.
  - Encryption and decryption keys are different.

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Avalanche Criterion

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- Block ciphers satisfy avalanche criterion.
  - One input bit change causes (on an average) one half of output bits to be in error.
  - Removes statistical correlation between input and output bits.
  - Cryptanalysis is made harder (security increases).
- One bit error in received ciphertext block due to wireless link state implies:
  - Multiple bit errors in decrypted plaintext block (throughput decreases).

Trade-off in security vs. wireless throughput

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Popular Symmetric Block Cipher Modes

- Electronic codebook mode (ECB).
  - Every plaintext block is encrypted independently: $c_i = E(K, p_i)$
  - One bit error in ciphertext block causes error propagation in decrypted plaintext block.
  - No loss of synchronization if integer multiples of blocks are lost.
    - Explicit re-synchronization is needed otherwise.
  - Identical plaintext is mapped to identical ciphertext

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- Cipher block chaining (CBC).
  - Before encryption plaintext block is XORed with previous ciphertext block:

$$c_i = E(K, p_i \oplus c_{i-1})$$

$$p_i^{'} = c_{i-1} \oplus D(K, c_i);\ c_0 :\ \text{intial value (IV)}$$

  - An erroneous ciphertext block results in two plaintext blocks in error.
  - If an integer number of blocks are in error then one additional plaintext block is in error before re-synchronization.
    - Explicit re-sync is needed otherwise.
- Identical plaintext is encrypted to non-identical ciphertext.

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- Cipher feedback mode (CFB).
  - Operates on blocks of size j<b (plaintext block size).
  - Plaintext is XORed with output of an encryption algorithm.
  - Feedback to encryption algo. are previous ciphertexts.
  - An erroneous ciphertext block distorts corresponding decrypted plaintext block and following ceil{b/j} blocks.
  - If number of lost bits is an integer multiple of j then ceil{b/j} additional plaintext block are distorted before re-synchronization.
    - Explicit re-sync is needed otherwise.
- Encryption is performed more often.
  - Hardware throughput is low.
  - Higher power consumption—not desirable for low power mobile devices.

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- Output feedback mode (OFB).
  - Operates on blocks of size j<b (plaintext block size).
  - Plaintext is XORed with output of an encryption algorithm.
  - Feedback to encryption algo. are previous outputs.
  - One bit error in ciphertext causes single bit error in decrypted plaintext; no error propagation.
  - If some bits are lost explicit re-synchronization needed.
- Encryption is performed more often.
  - Hardware throughput is low.
  - Higher power consumption—not desirable for low power mobile devices.

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Trade-offs…

- High (hardware) throughput/low power consumption modes (ECB,CBC)
  - Bit error propagation after decryption.
  - Reduce network throughput.
- Low (hardware) throughput/high power consumption modes (1-CFB,OFB)
  - No bit error propagation.
  - Higher network throughput.

No single encryption mode is the clear winner.

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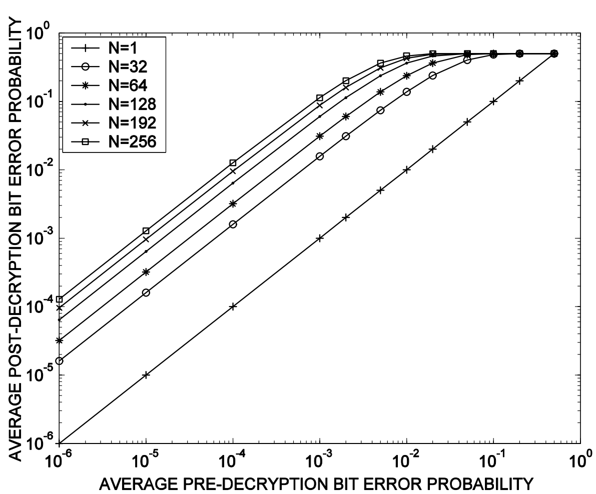
Error Propagation vs. Encryption Block Length

- P_b : wireless link bit error rate
- $P_{b,post}$: post decryption bit error rate
- N : encryption block length



$$P_{b,post} \approx \frac{N}{2} P_b$$

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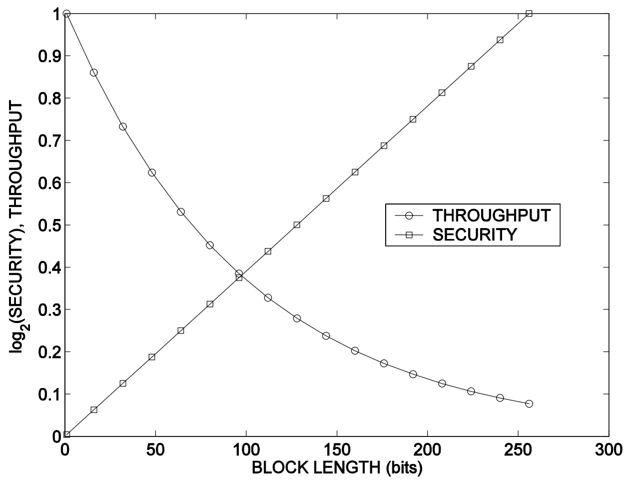
Throughput vs. Security Trade-off

- Throughput, $D=R(1-NP_b)$bits/sec;
- R: Transmission rate.
- Security level against brute force attack is ~ 2^N



$P_b=10^{-2}$,
BPSK modulation,
Rayleigh distributed,
flat fading channel.

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Approaches to Error Control

- Forward error control (FEC) code.
  - FEC may fail due to error propagation effect.
- Reduce diffusion in encryption.
  - Reduced error propagation.
  - Reduced security.
- Interleaving.
  - Causes delay depending on interleaving depth.
- ARQ protocols.
  - Overhead, high delay bandwidth product…
- **Opportunistic encryption.**
  - Optimize encryption block size based on security and wireless link state conditions.
  - Optimally trade-off security for throughput.

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Scenarios

- Case 1: Exact wireless channel signal to noise ratio (SNR) known.
- Case 2: Only current average SNR and probability distribution of randomly time-varying SNR also known.
- Case 3: A Markov channel model is known for channel/link states.

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Security and Adversary Models

- Q_N: Set of available encryption block lengths

$$S_i(N_i) = \frac{\log_2 N_i}{S_{\max}}, \quad S_{\max} = \log_2\left(\max_{N_i \in Q_N} N_i\right)$$

Average Security: $\bar{S} = \frac{1}{n}\sum_{i=1}^{n} S_i(N_i)$

$\Phi_i(N_i) = \Pr(\alpha \geq N_i)$ where α is the "attacker success prob."

Average vulnerability: $\Phi = \frac{1}{n}\sum_{i=1}^{n} \Pr(\alpha \geq N_i)$

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Case 1: Exact Channel SNR Known (I)

- Channel SNR at ith time slot: γ_i

Throughput (of *i*th time slot): $D_i(\gamma_i, N_i) = R_i(1 - N_i P_b(\gamma_i))$

Required Security: $S_{req} = \frac{1}{n}\sum_{i=1}^{n} S_i(N_i)$

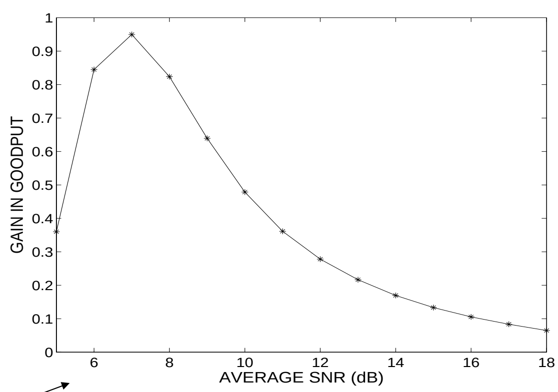
The Lagrangian of the problem:

$$C^{(n)} = \frac{1}{nR_{\max}}\sum_{i=1}^{n} D_i(\gamma_i, N_i) + \frac{\lambda}{n}\sum_{i=1}^{n} S_i(N_i)$$

Optimum encryption block length:

$$N_i = \frac{\left(\prod_{i=1}^{n}\left[R_i P_b(\gamma_i)\right]\right)^{\frac{1}{n}}}{R_i P_b(\gamma_i)} e^{(S_{\max} S_{req})\log_e 2}$$

Goodput Gain



Performance with fixed rate (BPSK)

Case 1: Exact Channel SNR Known (II)

$\Phi_i\left(N_i\right) = \Pr\left(\alpha \geq N_i\right)$ where α is the "attacker success prob."

Allowable vulnerability level of the message, $\Phi = \frac{1}{n}\sum_{i=1}^{n}\Pr\left(\alpha \geq N_i\right)$

$\Phi_{\max} > \Phi_i > \Phi_{\min}$, for all i

1. Exponential

$\Pr(\alpha \geq N_i) = e^{-kN_i}$

Optimum solution resembles "Water-filling" algorithm

2. Uniform

$\Pr(\alpha \geq N_i) = \frac{N_{\max} - N_i}{N_{\max} - N_{\min}}$

Optimum solution is found Using *fractional knapsack* algorithm

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Exponential distribution: $\Pr(\alpha \geq N_i) = e^{-kN_i}$

Throughput (of *i*th time slot): $D_i\left(\gamma_i, N_i\right) = R\left(1 - N_i P_b\left(\gamma_i\right)\right)$

The Lagrangian of the problem:

$$C = \frac{R}{n}\sum_{i=1}^{n}\left(1 + \frac{1}{k}\ln \Phi_i P_i\right) + \nu\left(\frac{1}{n}\sum_{i=1}^{n}\Pr\left(\alpha \geq N_i\right) - \Phi\right) + \sum_{i=1}^{n}\lambda_i\left(\Phi_i - \Phi_{\min}\right) + \sum_{i=1}^{n}\mu_i\left(\Phi_{\max} - \Phi_i\right)$$

Karush Kuhn Tucker Conditions:

$$\frac{\partial C}{\partial \Phi_i} = 0 \Rightarrow \Phi_i = -\frac{RP_i}{k\left(\nu + \lambda_i - \mu_i\right)}$$

$\lambda_i\left(\Phi_i - \Phi_{\min}\right) = 0,\ \mu_i\left(\Phi_{\max} - \Phi_i\right) = 0$ (complementary slackness)

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$$\text{Case I: } \lambda_i = 0, \mu_i = 0 \Rightarrow \Phi_{\max} > \Phi_i = -\frac{RP_i}{k\nu} > \Phi_{\min}$$

$$\text{Case II: } \lambda_i = 0, \mu_i \neq 0 \Rightarrow \Phi_i = \Phi_{\max} = -\frac{RP_i}{k(\nu + \lambda_i)} \Rightarrow \lambda_i = -\frac{RP_i}{k\Phi_{\max}} - \nu$$

$$\text{Case III: } \lambda_i \neq 0, \mu_i = 0 \Rightarrow \Phi_i = \Phi_{\min} = -\frac{RP_i}{k(\nu + \mu_i)} \Rightarrow \mu_i = -\frac{RP_i}{k\Phi_{\min}} - \nu$$

The solution should satisfy:

$$\sum_{i=1}^{n'} \max(\Phi_{\min}, \alpha P_i) \wedge \min(\Phi_{\max}, \alpha P_i) = \Phi \text{ where } \alpha = -\frac{R}{k\nu}$$

The solution involves iterations to identify the best set of channels associated with each of the above three cases. In each iteration α satisfies

$$n_1 \Phi_{\min} + n_2 \Phi_{\max} + \sum_{i \in s} \alpha P_i = n\Phi \quad \text{where}$$

s is the set of time slots with $\Phi_{\min} < \Phi_i < \Phi_{\max}$

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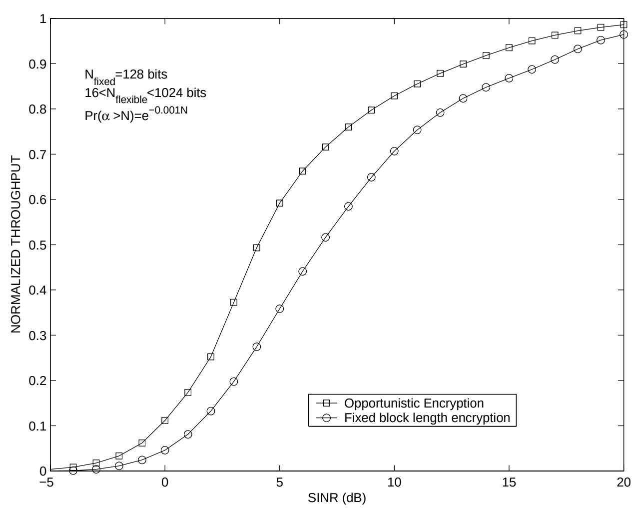
Throughput Gain



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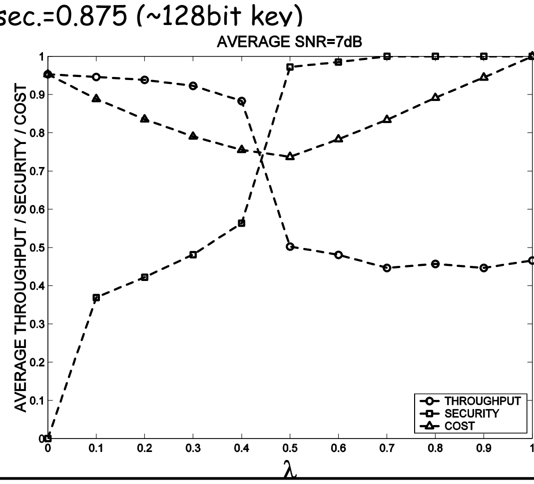
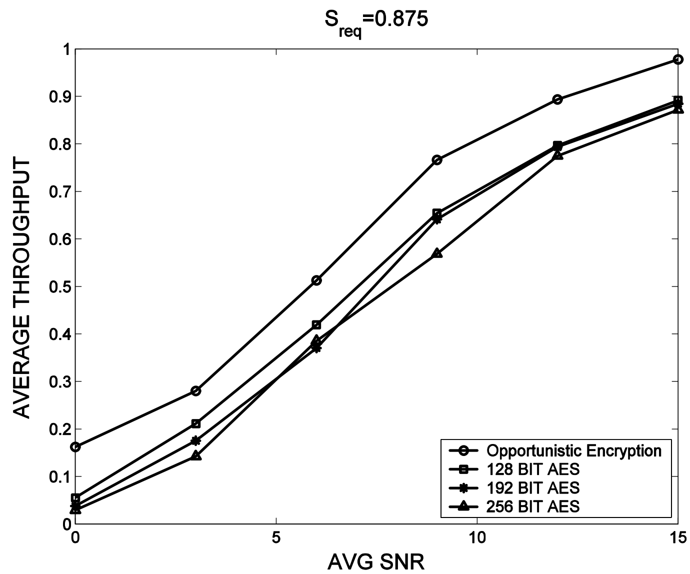
- Uniform distribution: $\Pr(\alpha \geq N_i) = \frac{N_{\max} - N_i}{N_{\max} - N_{\min}}$
- Throughput maximization subject to vulnerability constraint.
  - Re-formulate as fractional knapsack problem.
- Outline of optimal solution:
  - Sort the channel SNR's in decreasing order.
  - Allocate minimum block lengths so that $\Phi_{\min}$ is achieved.
  - Allocate block lengths to the ordered channels corresponding to $(\Phi_{\max} - \Phi_{\min})$
  - Stop when it cannot be done anymore.

Case 2: Average Channel SNR Known

- Define cost function: $C(\gamma, N) = (1-\lambda)D(\gamma, N) + \lambda S(N)$
- Rijndael cipher; N={128,160,192,224,246}
- Average SNR = 7dB.
- Min. sec.=0.875 (~128bit key)





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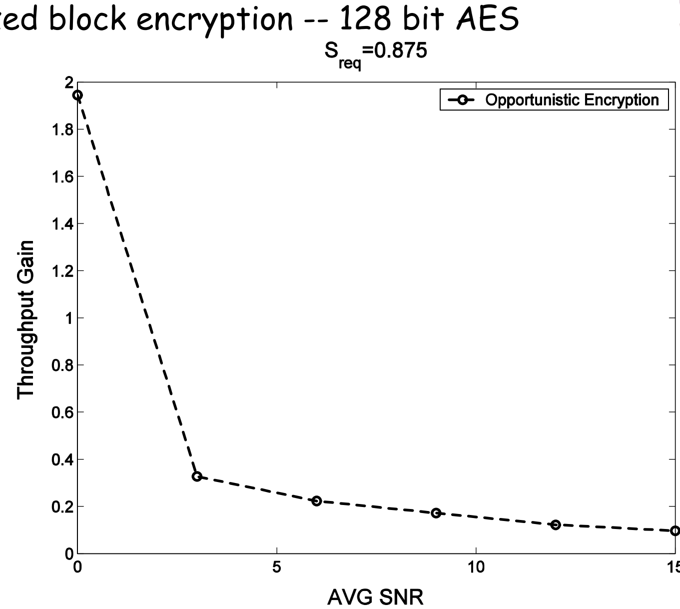
Fixed block encryption -- 128 bit AES



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Case 3: Finite State Markov Channel Model

- Channel SNR is quantized to finite set of states.
- Channel jumps from one state to another as a Markov process.
- Each state corresponds to a range of bit error rates.
- State transition probabilities are functions of various physical layer parameters.

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A Markov Decision Process (MDP) Model (I)

- Define state of the MDP as: $\{(c_s, b_t), s = 1...r; t = 1...q\}$
- r-number of channel states.
- q-capacity of receiver buffer.
- Assume ACK/NAK sent to transmitter.
- Q_n : set of available encryption block lengths (action set). $|Q_n|$=k.
- Buffer occupancy: $b_t = \sum_{a=1}^{k} m_a N_a$
  where m_a blocks of lengths N_a were successfully transmitted.

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A Markov Decision Process (MDP) Model (II)

- MDP state transition probability:

$$P_{ij}(a) = P(c(n+1) = c_{s_j}, b(n+1) = b_{t_j} \mid c(n) = c_{s_i}, b(n) = b_{t_i}, a)$$

- Reward function of MDP:

$$r(i,a) = b_i + N_a(1 - P_{bl,a}(c_{s_i}))$$

- Bellman's equation (dynamic program):

$$v_{\alpha,T}(i) = \max_a \{r(i,a) + \alpha \sum_j P_{ij}(a) v_{\alpha,T-1}(j)\}$$

$v_{\alpha,T}(.)$: Optimum function value T steps into future

$0 < \alpha < 1$: discount factor

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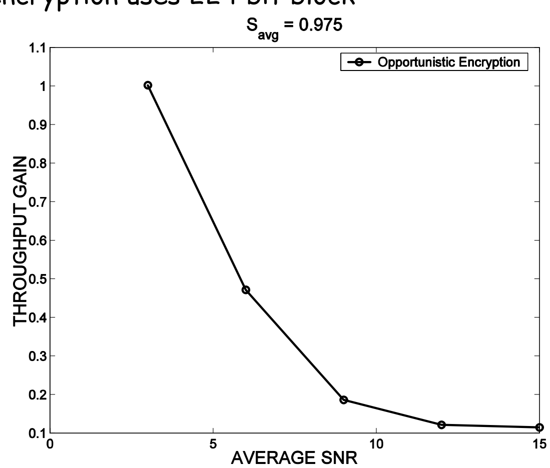
Throughput Gain

- N_a={128,160,192,224,256}
- r =8 (no. of channel states)
- T=1000; $\alpha = 0.5$
- Fixed encryption uses 224 bit block



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Conclusions

- Link state adaptive encryption (opportunistic encryption) results in significant throughput increase for a wide range of channel SNR.
- Opportunistic encryption performs well with varying degrees of side information about the channel conditions.
- Provides a framework to model security vs. throughput trade-off.

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