Opportunistic Encryption: A Trade-off between Security and Throughput in Wireless Networks

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***Abstract*— Wireless network security based on encryption is widely prevalent at this time. However, encryption techniques do not take into account wireless network characteristics such as random bit errors due to noise and burst errors due to fading. We note that avalanche effect that makes a block cipher secure also causes them to be sensitive to bit errors. This results in a fundamental trade-off between security and throughput in encryption based wireless security[†]. Further, if there is an adversary with a certain attack strength present in the wireless network, we see an additional twist to the security-throughput trade-off issue.**

In this paper, we propose a framework called *opportunistic encryption* that uses channel opportunities (acceptable signal to noise ratio) to maximize the throughput subject to desired security constraints. To illustrate this framework and compare it with some current approaches, this paper presents the following: (a) mathematical models to capture the security-throughput trade-off; (b) adversary models and their effects; (c) joint optimization of encryption and modulation (single and multi-rate); (d) the use of Forward Error Correcting (FEC) codes to protect encrypted packets from bit errors; and (e) simulation results for Rijndael cipher. We observe that opportunistic encryption produces significant improvement in the performance compared to traditional approaches [‡].

***Index Terms*— Stochastic Optimization, encryption, wireless security.**

I. INTRODUCTION

WIRELESS communication medium is open to intruders. In a wireless network, an eavesdropper can intercept a communication by listening to the transmitted signal. Hence, encrypting the transmitted packets helps to achieve confidentiality. Traditionally, design of encryption algorithms and their parameters has used only security against an adversary attack as the main criterion. To achieve this goal, the encrypted data, or the cipher is made to satisfy several properties including the *avalanche* effect [17].

The avalanche criterion requires that a single bit change to the plain text or the key must result in significant and random-looking changes to the cipher text. Typically, an average of one half of the decrypted bits should change whenever a single input bit to the decryption device is complemented. This guarantees that there will not be any noticeable resemblance between two cipher texts obtained by applying two neighboring keys for encrypting the same plain text. Otherwise, there would be considerable reduction of the keyspace search by the cryptanalyst.

It is clear that block ciphers that satisfy the avalanche property are very sensitive to bit errors induced by the wireless link. That is, a single bit error in the received encrypted block will lead to an error in every bit of the decrypted block with probability 1/2. Therefore, we have severe error propagation. This leads to a fundamental trade-off between security (w.r.t. brute force attack) and throughput in encryption based wireless security as seen in Fig. 1. In this figure, for a given channel condition, the throughput decreases with the encryption block length whereas the security increases with the block length. With the assumption that the encryption key length is always equal to or greater than the block length, the level of security of an encrypted block is decided by the block length. Throughput (normalized) is given by $(1-P_b)^N$ where P_b is the bit error probability and N is the encryption block length. The security here is defined as $\log_2 N$ (normalized by the maximum). This choice results in a monotonically increasing function capturing the strength of a cipher in a suitable manner and also is a convenience for the optimization. We explore throughput-security trade-off in this paper and investigate a framework called *opportunistic encryption* to optimize it. The term "opportunity" is used to mean channel

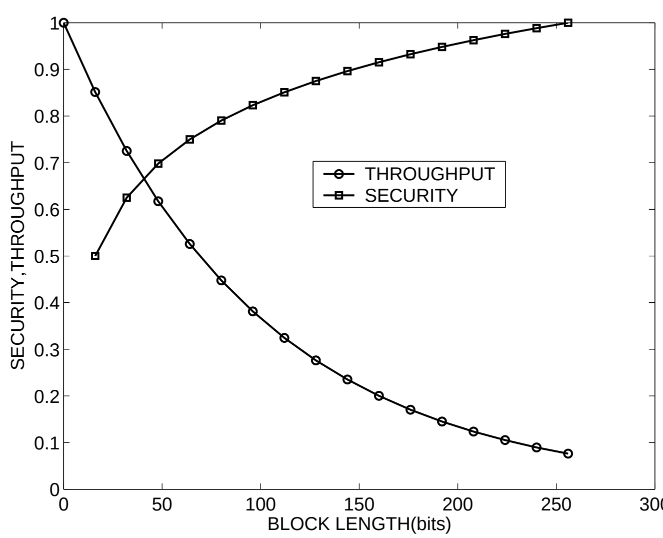

Fig. 1. Throughput (normalized) and security (normalized) as a function of encryption block length at channel bit error probability, $P_b = 10^{-2}$.

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[†] The channel error probability cannot be made zero but can only be made to approach zero asymptotically. Based on Shannon's theorem, one may in theory find a code that can make the error probability to approach zero asymptotically as long as the transmission rate is below the capacity of the channel and if the block length approaches infinity. In practice however, block lengths are finite and the probability of error may never be made zero.

[‡] Part of this work was presented in the 5^{th} international conference on Applied Cryptography and Network Security (ACNS), 2006.

opportunities, i.e., the time durations when channel Signal to Noise Ratio (SNR) is reasonably high (equivalently the bit error rate is low). Note that the channel SNR is a random time-varying parameter. Opportunistic encryption provides a framework that exploits channel opportunities in order to optimize some encryption parameters (e.g., encryption block length) based on the security as well as throughput constraints. It helps to control error propagation due to channel induced bit errors in the received encrypted data. In the process we exploit the variable encryption block length feature offered by Rijndael [16]. In Section I-A to follow different modes of cipher in use are discussed and the specific mode of our interest is explained. Section I-B describes the methods of modelling and measure of the security of a cipher.

A. Different modes in ciphers

There are five basic modes of operation for a block cipher. The Electronic CodeBook (ECB) mode, Cipher Block Chaining (CBC) mode, Cipher FeedBack (CFB) mode, Output FeedBack (OFB) mode and the CounTeR (CTR) mode. The ECB and CBC modes are referred to as block modes as the plaintext is encrypted a block at a time to produce the corresponding ciphertexts. In CFB, OFB and CTR modes, some random value (usually a counter) is encrypted and the resulting ciphertext bits are XORed with the plaintext bits to encrypt the plaintext. Since, the encryption here (CFB, OFB, CTR) can be performed one bit at a time, these modes are considered as stream modes. In the ECB mode every plaintext block is independently encrypted to a ciphertext block. That is, error in one ciphertext block does not propagate to other ciphertext blocks during decryption. However, for lengthy messages ECB mode may not be secure as the cryptanalyst can use structures within the message to break the cipher [15]. In CBC mode, a given plaintext block is XORed with the previous ciphertext block before encryption. This is done to hide the structures within the message, however due to chaining, an error in one ciphertext block will result in errors in multiple decrypted plaintext blocks. Stream modes of operation do not propagate any errors during transmission. Since, the problem of error propagation and the resulting loss of throughput is inherent only to the block modes, in this paper we consider the security - throughput trade off with respect to only the block modes of operation. A problem similar to the one studied in this paper is presented in [25]. In it the authors deal exclusively with the CFB mode of encryption. The overall throughput is formulated as a function of channel bit error rate, encryption block length, and the number of stages in CFB mode. It is shown that, as the number of stages increase the throughput increases up to a peak value and then gradually decreases. The throughput formulation is used to derive the optimal number of stages for a given channel condition.

B. Security of a Cipher

The level of security against cryptanalysis may be measured as the amount of work (computations) required by the adversary to break the cipher. Ideally, a computationally secure encryption system would make it impossible to break the cipher with an exhaustive search approach having exponential order complexity. Nevertheless, practical encryption systems may have vulnerabilities leading to possible short cut attacks making it possible to break the cipher with algorithms of complexities less than an exponential order. Meanwhile, it is reasonable to say that there is no such thing as a completely secure encryption system, and the level of security can only be quantified relative to the strength of the adversary present in the environment. It is possible to model the adversary's "strength" to break a cipher as a random parameter using a probability distribution. It is reasonable to assume that the ability of the adversary to break the cipher becomes less probable as the key length, block length, diffusion etc. increase. In this work, we consider some probability distributions to model the adversary's strength and investigate their effects on the security-throughput trade-off.

In the sequel, first we discuss mathematical models to capture the security versus throughput trade-off. Then, maximization of throughput subject to a security constraint is setup formally as an optimization problem. Several scenarios are considered in the formulations. The effect of modulation and coding on the security-throughput trade-off is studied. At the receiver side the problem is modelled as a Markov Decision Process (MDP). The proposed analytical techniques are applied and tested on Rijndael cipher using computer simulations. Detailed comparison with a traditional approach is presented.

The rest of the paper is organized as follows. Section II discusses the channel model and measures of security used in this work. The concept of opportunistic encryption is introduced in Section III. In Section IV we discuss the use of FEC with and without opportunistic encryption. In section V we propose solutions with limited knowledge of channel. Conclusions are presented in Section VI.

II. Channel Model and Security Measure

There are several ways in which one can quantify the strength of an encryption scheme [19]. One way is to measure the work involved in breaking it by the best known cryptanalysis method (or shortcut attack). In the absence of any shortcut attacks (e.g., 10 round Advanced Encryption Standard (AES) [16] cipher), the only way to crack the encryption key is to use the brute force technique (i.e., for a given ciphertext, try decrypting with all possible encryption keys until it decrypts to the corresponding plaintext). Let us consider a simple example. For an AES cipher with key length of 128 bits, there are 2^{128} possible key combinations. Assuming unit complexity for testing one key (single decryption), the complexity involved in cracking 128 bit AES cipher is 2^{128}. Note however, this is the worst case complexity. This motivates a choice of a security measure (w.r.t. brute force attacks) to be $S(N) = \log_2(N)$ where N is the encryption block length. Note that in many practical encryption schemes the block length and key length are equal. We will exploit this fact throughout in this paper. With the maximum block length of N_{max}, we define the normalized security level as $s(N) = \frac{\log_2 N}{S_{max}}$ where $S_{max} = \log_2 N_{max}$.

A. Why we need one key per block length

In this paper, we propose to use a different encryption key for each possible block length in the block cipher. If a common key is to be used for all the block lengths, then an attack on the smaller block length would reveal a part of the key. After a part of the key is revealed, increasing the block length would not exponentially increase the security of the cipher. Since, keys are changed only once in every session and thousands of encryption operations are performed before each key change, we expect minimal impact on the complexity of key management due to our requirement of having a separate encryption key per block length.

B. Security Quantification for a Brute Force Attack

Packet mode communication can be of fixed frame length or variable frame length. In either case, frame lengths are in general several times as large as encryption block lengths. We assume that each frame has a length (bits) that is equal to an integer multiple of encryption block length used in the frame. The security level of a frame is determined by the block length used in the encryption. Let, a message consists of n frames with encrypted block length N_i bits for frame $i = 1, \cdots, n$. N_i is selected by the optimization procedure based on the channel condition. With the block fading [22] assumption of wireless channel, all the information bits in a frame are encrypted using the same encryption block length since the quality of the channel is assumed to be fixed over the frame duration. We make the assumption that every frame of the message (sequence of frames) is equally important to decode the message. In other words one cannot decode the message unless every frame is decrypted. This applies to a scenario such as encryption of compressed image. Then a reasonable measure is the mean of the security levels achieved by the individual frames. Thus we have here,

$$\bar{s} = \frac{1}{nS_{max}} \sum_{i=1}^{n} \log_2 N_i \tag{1}$$

where $N_i \in Q_N$, the set of possible discrete encryption block lengths. Note $0 \leqslant \bar{s} \leqslant 1$.

C. Security Quantification with an Adversary Model

In addition to the discussion on the measure of security in Section II-B, in this section we propose a measure of *vulnerability* having an inverse relationship to security, to be used in the optimization process with a probabilistic adversary model. As in the previous case, the amount of work needed to crack a cipher with brute force attack decides the security of a cipher. However in this case, instead of a security measure based solely on the encryption parameters, we include in it, the attacker's behavior. In particular, the attacker's capability to crack a cipher of certain block length is associated with a Probability Mass Function (PMF). Thus we define the parameter "attacker strength" (denoted by α) having the dimension of block length, and write the probability of cracking a cipher of block length N as $Pr(\alpha = N)$. The attacker with strength α has the capability to crack any cipher with block length $\leq \alpha$ within the useful time of the encrypted information and with a cost less than the value of it.

Let, there be n frames of length $L_i, i = 1, \cdots, n$ in the message to be transmitted. A frame i is to be encrypted using block length N_i. In the discussion to follow, we assume that there is a fixed integer multiple c of encrypted blocks in a given frame, thus $L_i = cN_i$. The approach can be easily extended to other cases. Hence, We define the *vulnerability* (which increases as the encryption block length is decreased) $0 \leqslant \Phi \leqslant 1$ of a message as the expected fraction of the total message being successfully cracked by the adversary. Let the frames be arranged in the ascending order of the respective encryption block lengths. If the adversary's attack strength is α bits, then the adversary can successfully crack all the data frames with encryption block length less than or equal to α. Assume that there are $K (\leqslant n)$ distinct encryption block lengths being used and n_k be the number of frames with encryption block length less than or equal to $N_k, k = 1, \cdots, K$, and $Pr(\alpha = N_k)$ be the probability that the attacker's strength α is N_k. Note that $Pr(\alpha = N_k)$ also is the probability with which the n_k frames (in the ordered list) would be cracked by the adversary resulting in the leakage of a fraction $x_k = \sum_{i=1}^{n_k} l_i$ of the total message, where l_i is the frame length normalized by message length ($l_i = \frac{L_i}{\sum_{j=1}^{n} L_j}$). Thus we can define the vulnerability Φ of the message as the expected leakage given by,

$$\Phi = \sum_{k=1}^{K} x_k P(x_k) \tag{2}$$

where $P(x_k) = Pr(\alpha = N_k)$ is the probability of exposing a fraction x_k of the total message. From a known result in probability theory, this is equivalent to

$$\Phi = \sum_{k=1}^{K} Pr(x \geqslant x_k). \tag{3}$$

Further, if each frame is encrypted with a distinct block length we have $K = n$ and the above equation reduces to

$$\Phi = \sum_{i=1}^{n} Pr(\alpha \geqslant N_i) \tag{4}$$

III. Optimizing Security-Throughput Tradeoff

As discussed in the introduction, avalanche effect causes one or more errors within an encryption block to propagate within the particular encryption block. Therefore a single bit error in the received encrypted block will cause the loss of entire block due to error propagation after decryption. Nevertheless, other blocks in the frame are not effected. Therefore, we make the assumption that a frame is not discarded due to errors in individual encryption blocks in that frame. The problem then is to maximize the overall throughput while guaranteeing a minimum and/or an average security level(s) for the message. The throughput per block and hence a frame is given by $R_i(1-P_i)^{N_i} \approx R_i(1 - N_i P_i)$ for $P_i << 1$ and for a given and fixed N_i where R_i and P_i are respectively the transmission rate selected for the frame and the channel bit error probability. The throughput of the message (sequence of frames) can therefore be expressed as

$$T = \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 - N_i P_i) \quad (5)$$

Here the throughput is normalized by the maximum transmission rate $R_{max} = \max_i \{R_i\}$. The discussions on the optimization to follow assume exact channel knowledge over the sequence of frames (message). Let the channel SNR γ_i be known for the frames $i = 1, \cdots, n$. We present here the optimization problems for the two different attack models given in Section II. The essence of the procedure is to optimally choose the encryption block lengths based on the channel condition as well as required security.

Any strategy for optimum block length allocation depends on the knowledge of channel conditions. Further, there should be a mechanism for the receiver to know the encryption block length used during the transmission of each frame. The straightforward approach to achieve this is to include the block length information as clear text payload in the frame. An alternative would be for the receiver to compute it from the security constraints and the channel state during the reception of the frame. This is feasible as the security constraints are agreed upon apriori, and the receivers usually have the capability to estimate the forward channel. Nevertheless there could be computational overheads at the receiver. In the case where the frame length is a fixed integer multiple (known to receiver) of the block length, it is trivial for the receiver to compute the block length from the frame length.

The channel adaptive encryption methods presented in this paper heavily depend on the ability to know the channel quality in terms of SNR or the channel Bit Error Rates (BER) in advance. Although beyond the scope of this paper, the sensitivity of the performance to errors in channel knowledge has to be studied. Nevertheless, we mention here published work on channel estimation, tracking, and prediction. Channel estimation techniques for Orthogonal Frequency Division Multiplexing (OFDM) is discussed for instance in [26]. A technique for the prediction of channel in the short term for multiuser OFDM scenario can be found in [27]. Similarly [28] present the methods for long range channel prediction for OFDM systems.

A. Bruteforce Attack Model

We are required to maximize the throughput subject to an overall security requirement over a finite horizon. This can be stated as a constrained optimization problem given by

$$\begin{aligned} &\max_{\{N_i\}} \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 - N_i P_i) \\ &\textit{such that} \quad \frac{1}{nS_{max}} \sum_{i=1}^{n} \log_2 N_i = s_{req} \end{aligned} \quad (6)$$

Note that $P_i = P_i(\gamma_i, R_i)$ is a function of channel SNR γ_i and the transmission rate used for the frame R_i, and s_{req} is the required level of security. As shown in the appendices, the optimal block lengths are given by

$$N_i^* = \frac{\left(\prod_{i=1}^{n} R_i P_i\right)^{\frac{1}{n}}}{R_i P_i} e^{(S_{max} s_{req}) \log_e 2} \quad (7)$$

In the case where the transmission rate is fixed, the above result reduces to

$$N_i^* = \frac{\left(\prod_{i=1}^{n} P_i\right)^{\frac{1}{n}}}{P_i} e^{(S_{max} s_{req}) \log_e 2} \quad (8)$$

Clearly we see that the optimal encryption block lengths as computed above are inversely proportional to the *probability of channel bit error*. This implies that "opportunistically" allocating larger block lengths for better channels and vice versa is the best strategy in the case of fixed rate.

First we consider transmission with a fixed rate namely Binary Phase Shift Keying (BPSK). Thus the maximum achievable throughput is 1 bit/symbol. The bit error probability of BPSK signaling is given by

$$P_i = \frac{1}{2} \text{erfc}(\sqrt{\gamma_i})^{\S} \quad (9)$$

The assumption of a "flat fading" wireless channel with a Rayleigh probability density function (pdf) for signal envelop and thus an exponential pdf for received SNR we have

$$p(\gamma_i) = \frac{1}{\bar{\gamma}} e^{\frac{\gamma_i}{\bar{\gamma}}} \quad (10)$$

where $\bar{\gamma}$ is the average SNR.

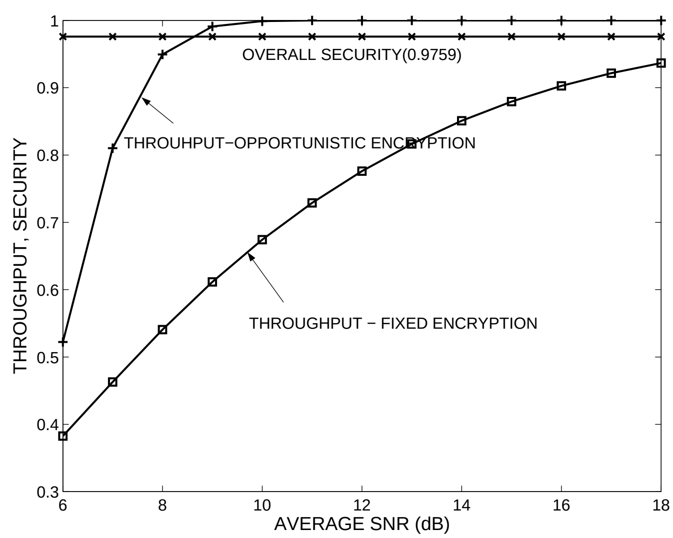

Fig. 2. Normalized throughput and security with opportunistic and fixed block size encryption for known channel SNR sequence and BPSK modulation.

Comparison of the throughput observed in simulations using opportunistic encryption block lengths computed from (8) and fixed block size encryption is shown in Fig. 2. For the purpose of illustrating the optimization process, we let the block length to assume any positive integer value. In the sequel however, we adopt block lengths as per to Rijndael cipher with practically useful block lengths.The overall security requirement setting

§ $\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt$

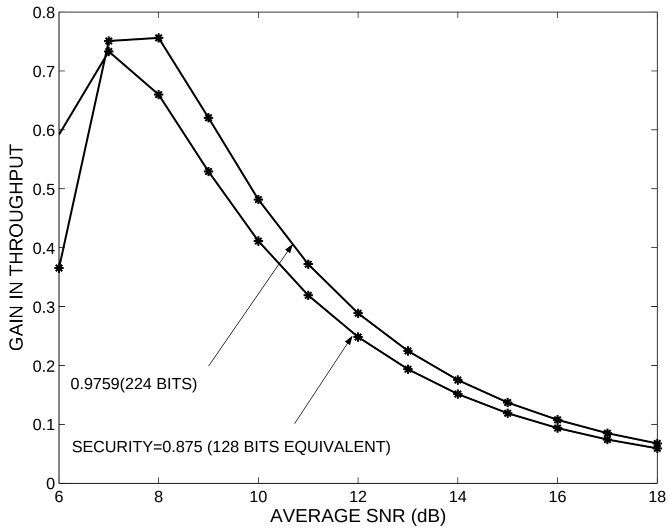

Fig. 3. Throughput gain with opportunistic encryption for known channel SNR sequence and BPSK.

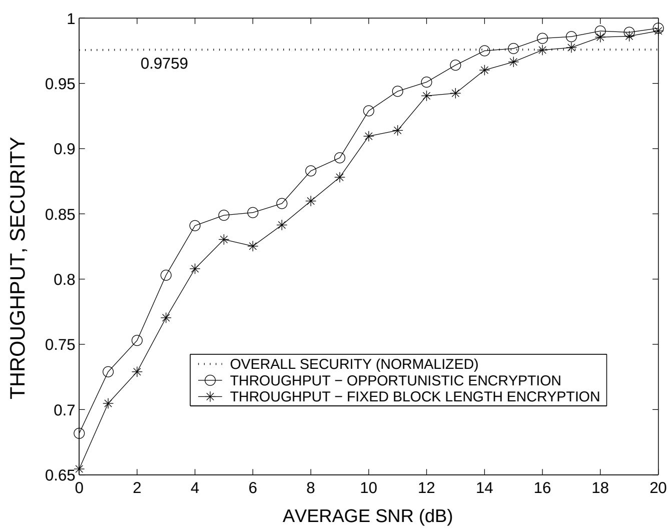

Fig. 4. Throughput comparison of opportunistic and fixed block length Rijndael encryption using BPSK modulation.

for this result is $s_{req} = 0.9759$, which is equivalent to the security of a 224 bit fixed block encryption and $S_{max} = \log_2(256) = 8$. The gain in throughput was computed as $\frac{T_{opt}-T_{fixed}}{T_{fixed}}$, where T_{opt} and T_{fixed} are throughput of optimum and fixed block length allocations. Shown in Fig. 3 are gains for two different settings of overall security values of 0.875 and 0.9759. We observe that the gain varies over the range of average SNR values. Maximum gain of about 73% is observed around 7 dB average SNR with $s_{req} = 0.875$. The decline in gain above 7dB average SNR is explained by the low bit error probabilities in this range. The throughput is close to the maximum for all values N_i under consideration. At lower SNR the bit error rates are high and in (8), the factor $\frac{\left(\prod_{i=1}^{n} P_i\right)^{\frac{1}{n}}}{P_i}$ approaches unity. Therefore $N_i \rightarrow e^{(S_{max} s_{req}) \log_e 2}, i = 1, \cdots, n$ which is the fixed block length corresponding to the security level. Hence the gain in throughput w.r.t. fixed block length encryption approaches zero.

Fig. 4 compares the throughput of opportunistic and fixed block length Rijndael [16] encryption. For the opportunistic encryption, the encryption block lengths were selected from the set $Q_N = \{128, 160, 192, 224, 256\}$ (bits) and the plaintext block size for fixed block length encryption was 224 bits. It is seen in this figure that the observed throughput gain is smaller than the theoretical gain. This is due to the fact that the number of available block sizes in Rijndael cipher is small. Next we consider an example with multiple transmission rates including BPSK and higher order Quadrature Amplitude Modulation (QAM) schemes . The probability of bit error of M-ary QAM signal is given by the well known approximation [2] by

$$P_i \approx \frac{\sqrt{M}-1}{\sqrt{M}\log_2\sqrt{M}}\text{erfc}\left[\sqrt{\frac{3\log_2 M}{2(M-1)}\gamma_i}\right] \quad (11)$$

where M is the constellation size. We use BPSK and the set $Q_M = \{4, 16, 64\}$ in this work. Correspondingly the set of maximum achievable throughput values are $Q_R = \{1, 2, 4, 6\}$ bits/symbol.

Fig. 5 shows the gain in throughput with variable rates. A gain of 109% is observable around 9 dB average SNR. Fluctuation in the gain is observed with increasing SNR, and this is due to the discrete rate control.

B. Adversarial Attack

For the discussion in this section, we consider two probability distributions namely uniform and exponential to model the adversary strength. We show in the sequel that with uniform distribution, the optimization problem is equivalent to “fractional knapsack” problem and therefore the optimum algorithm has linear execution time. With the exponential distribution, the optimal solution resembles “water-filling” algorithm. As before we assume that the frames are not discarded due to bit errors in some encryption block in the frame.

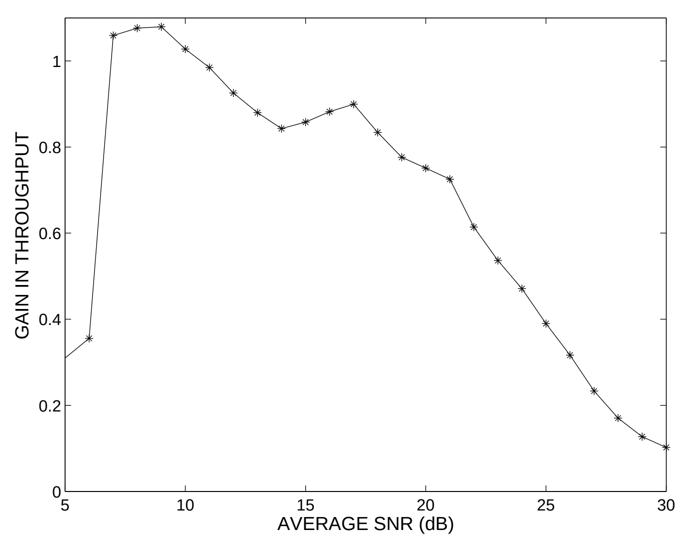

Fig. 5. Gain in throughput of opportunistic encryption with respect to fixed block length encryption against average SNR for multiple rate case.

1) Linear Adversary Strength Model: Let the probability mass function describing an adversary's strength has uniform distribution, *i.e.*, $\Pr(\alpha = N_i) = \frac{1}{N_{max} - N_{min}}$ for $i = 1, \cdots, n$ where N_{min} and N_{max} are the minimum and maximum block lengths available in the crypto system. That is, the probability that the adversary can successfully attack a ciphertext block (key) length N_i is uniformly distributed. This conclusion leads to

$$\phi_i = \Pr(\alpha \geqslant N_i) = \frac{N_{max} - N_i}{N_{max} - N_{min}}, i = 1, \cdots, n. \quad (12)$$

Now we are required to maximize the throughput given by

$$T = \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 - P_i(N_{max} - (N_{max} - N_{min})\phi_i)) \quad (13)$$

subject to the conditions

$$\phi_{min} \leqslant \phi_i \leqslant \phi_{max}, i = 1, \cdots, n$$
$$\frac{1}{n} \sum_{i=1}^{n} \phi_i \leqslant \Phi_0 \quad (14)$$

Φ_0 is the maximum allowable average vulnerability level, and ϕ_{min} and ϕ_{max} are the corresponding minimum and maximum allowable values for a frame. It is easily seen that the optimal solution is achieved with equality in the condition (14). By expanding (13) and omitting the terms that are independent of $\phi_i, \forall i$, the problem reduces to the following.

$$\max_{N_i} T' = \sum_{i=1}^{n} w_i \phi_i \quad (15)$$

where, $w_i = P_i R_i$. This problem is a special case of *fractional knapsack problem* which is solvable in polynomial time. It can be seen that selecting the ϕ_is in the non-increasing order of maximum w_i maximizes T' and hence T [23]. Observe that for every frame i we should allocate a minimum vulnerability level, ϕ_{min} corresponding to the maximum encryption block length, N_{max}. Therefore the formulation can be modified such that the optimization problem is

$$\max_{\phi_1, \cdots, \phi_n} \sum_{i=1}^{n} w_i \phi_i \textit{ such that}$$
$$\frac{1}{n} \sum_{i=1}^{n} \phi_i \leqslant \Phi_0'; 0 \leqslant \phi_i \leqslant \phi_{max} - \phi_{min} \quad (16)$$

where $\Phi_0' = \Phi_0 - n\phi_{min}$. The following algorithm solves the problem optimally [24].

1) *Initialization*: Allocate a vulnerability level of ϕ_{min} for all frames $i, i = 1, \cdots, n$.
2) Sort the frames in the non-increasing order of $w_i = P_i R_i, i = 1, \cdots, n$.
3) Allocate the additional maximum allowed vulnerability level less than or equal to $\phi_{max} - \phi_{min}$ for each frame i in the sorted order, i.e., $w_i > w_{i+1}$. That is, allocate $\phi_{max} - \phi_{min}$ units to frames $i = 1, \cdots, j^* - 1$ for some j^*, and fewer than $\phi_{max} - \phi_{min}$ or 0 for frame $i = j^*$ with the sum total of the additional allocation equal to Φ_0'. Frames $i = j^* + 1, \cdots, n$ get no additional allocation above ϕ_{min}.

2) Exponential Adversary Strength Model: Let the attacker strength be given by:

$$\phi_i = \Pr(\alpha \geqslant N_i) = e^{-kN_i} \quad (17)$$

where $k > 0$ is a constant. We are required to maximize the throughput given by

$$T = \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 + \frac{P_i}{k} \log_e \phi_i) \quad (18)$$

subject to the conditions

$$\phi_i - \phi_{min} \geqslant 0, i = 1, \cdots, n \quad (19)$$
$$\phi_{max} - \phi_i \geqslant 0, i = 1, \cdots, n \quad (20)$$
$$\Phi_0 - \frac{1}{n} \sum_{i=1}^{n} \phi_i = 0 \quad (21)$$

where Φ_0 is the maximum allowable overall vulnerability level. The equality in (21) results from the observation that maximum of T is achieved by using the maximum allowed overall vulnerability. The augmented objective function can then be written as,

$$C = \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 + \frac{P_i}{k} \log_e \phi_i) + \nu(n\Phi_0 - \sum_{i=1}^{n} \phi_i) + \sum_{i=1}^{n} \lambda_i(\phi_i - \phi_{min}) + \sum_{i=1}^{n} \mu_i(\phi_{max} - \phi_i) \quad (22)$$

where $\nu, \lambda_i, \mu_i, i = 1, \cdots, n$ are constants (Lagrange multipliers). The Karush Kuhn-Tucker Conditions (KKC) [6] for this problem are obtained by considering the vanishing point of the first order derivative of C w.r.t. ϕ_i and also from the complimentary slackness. Thus we have,

$$\phi_i = \frac{R_i P_i}{knR_{max}(\mu_i + \nu - \lambda_i)}$$
$$\lambda_i(\phi_i - \phi_{min}) = 0$$
$$\mu_i(\phi_{max} - \phi_i) = 0$$
$$\lambda_i \geqslant 0$$
$$\mu_i \geqslant 0$$
$$\Phi_0 - \sum_{i=1}^{n} \phi_i = 0$$
$$\nu \geqslant 0 \quad (23)$$

for $i = 1, \cdots, n$. Therefore the optimal value of ϕ_i, for $i = 1, \cdots, n$ is found from one of the following three cases.

Case 1: $\lambda_i = 0, \mu_i = 0 \Rightarrow \phi_{min} < \phi_i < \phi_{max}$ and we have $\phi_i = \alpha w_i$ with $\alpha = \frac{1}{k\nu nR_{max}}, \nu > 0$ and $w_i = R_i P_i$

Case 2: $\lambda_i = 0, \mu_i \neq 0 \Rightarrow \phi_i = \phi_{max}$

Case 3: $\lambda_i \neq 0, \mu_i = 0 \Rightarrow \phi_i = \phi_{min}$

The following iterative algorithm provides the optimal solution. Any value of $\phi_i, i = 1, \cdots, n$ computed complies with one of the three cases above.

1) Sort the channels in the non-increasing order of $w_i, i = 1, \cdots, n$; let $j = 1$
2) Compute $\alpha = \frac{\phi_{min}}{w_j}$
3) Compute $\phi_i = \alpha w_i$ for $i = 1, \cdots, n$; if $\phi_i < \phi_{min}$ set $\phi_i = \phi_{min}$; if $\phi_i > \phi_{max}$ set $\phi_i = \phi_{max}$
4) If $n\Phi_0 > \sum_{k=1}^{n} \phi_i$ set $j = j + 1$ and goto step 2); else goto step 5)
5) If $n\Phi_0 = \sum_{k=1}^{n} \phi_i$ the current set of $\phi_i, i = 1, \cdots, n$ are optimal; else goto step 6)
6) The optimum α is in between the two values say α_j and α_{j-1} computed in the last two iterations. Fine tune as follows. Default to the allocation corresponding to $\alpha = \alpha_{j-1}$. Let l be the index of the largest $w_i, i = 1, \cdots, n$ such that $\phi_i < \phi_{max}$, and i_{min} is the index of smallest w_i such that $\phi_i > \phi_{min}$
7) Set $\alpha = \frac{\phi_{max}}{w_l}$; if $\alpha < \frac{\phi_{min}}{w_{i_{min}+1}}$ set $\phi_i = \alpha w_i, i = 1, \cdots, n$; $\phi_i(\phi_i < \phi_{min}) = \phi_{min}$; $\phi_i(\phi_i > \phi_{max}) = \phi_{max}$; goto the step (8); else set $l = l - 1$ and goto step (9)
8) If $\sum_{i=1}^{n} \phi_i = n\Phi_0$ optimal values are found; else if $\sum_{i=1}^{n} \phi_i < n\Phi_0$ set $l = l + 1$ and goto step (7); else set $l = l - 1$; goto step (9)
9) The optimal α is found from $\alpha = \frac{1}{\sum_{i=i_{min}}^{l} w_i}(n\Phi_0 - (n - i_{min})\phi_{min} + (l - 1)\phi_{max})$; set $\phi_i = \alpha w_i, i = 1, \cdots, n$, $\phi_i(\phi_i < \phi_{min}) = \phi_{min}$, and $\phi_i(\phi_i > \phi_{max}) = \phi_{max}$

Appendices provide an explanation as to how this algorithm indeed provides the optimal solution.

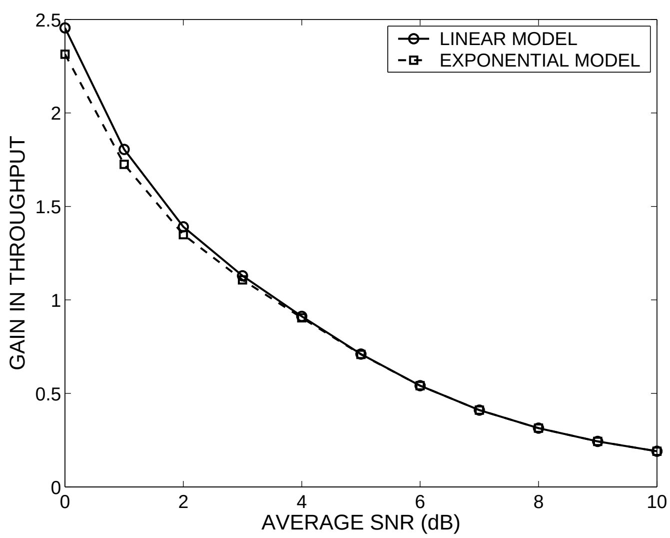

Fig. 6. Throughput gain due to proposed channel adaptive encryption compared to fixed block length encryption for single rate (BPSK) transmission. Both linear and exponential adversary attack models are shown.

We carried out computations of sample performance curves with certain parameter settings. A case with fixed transmission rate namely BPSK and multi-rate namely MQAM were considered. Block length equivalents of the target, minimum, and maximum security levels for this computation are respectively 128, 16 and 1024 bits. For the adversary model with exponential probability distribution, the decay constant k_i was

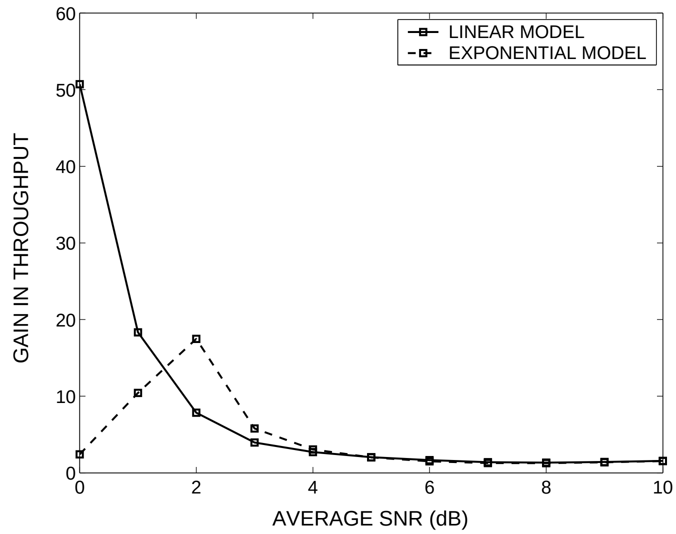

Fig. 7. Throughput gain due to proposed channel adaptive encryption compared to fixed block length encryption for multi- rate (MQAM) transmission. Both linear and exponential adversary attack models are shown.

set to 0.0001 for all $i = 1, \cdot, n$. It was assumed that the channel gain remains fixed during the transmission of a frame. For the optimization, $n = 5000$ channel samples were drawn using a Rayleigh distribution with a given average SNR. The optimum encryption block lengths were assigned based on the algorithm for each of the adversary models. The throughput was computed with optimum allocation of block lengths and with fixed block length of 128 bits.

Fig. 6 shows the gain in throughput with respect to fixed block length encryption. The results are given for the two different probabilistic models of the attacker and for single rate (BPSK) signaling. As seen in the results, a throughput gain of 2.5 fold is observable at $\bar{\gamma} = 0dB$. Note in the example that the performance when the adversary is modelled with exponential distribution is slightly inferior to that of uniform distribution at low average SNR, in all cases. With exponential model, adversary has a larger probability of breaking the encryption with smaller encryption block length compared to a larger block length. Thus the optimization process has a tendency to allocate larger block lengths to a larger fraction of frames compared to the case with uniform distribution. Therefore higher frame error rates results more frequently with exponential probability distribution than in the case of uniform distribution of adversary strength.

Fig. 7 shows the performance with multi-rate (MQAM) transmissions. It is seen that with exponential model, the gain has a peak at moderate average SNR values. This is akin to the fact that with exponential model, the optimization algorithms have a tendency to select larger encryption block lengths for a larger fraction of channel instantiations compared to the case with linear model. The fact that transmission rates are optimally selected for the channels, and encryption block lengths mostly large regardless of the channel conditions brings the throughput performance close to that of fixed block length encryption. However, there is a range of SNR in which the optimization process has higher gains.

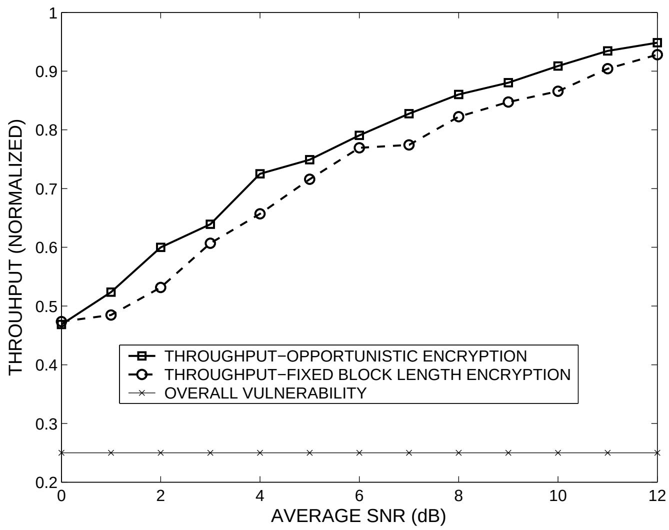

Fig. 8. Throughput comparison of opportunistic encryption and fixed block length encryption for single rate (BPSK) with linear probability model of attacker strength and Rijndael cipher.

The throughput performance with the probabilistic models of attacker for finite set of encryption block sizes available in the Rijndael cipher is shown in Fig. 8. As with the deterministic models in the previous cases, we observe marginal gain in throughput due to limited flexibility in the encryption block length sizes.

IV. Forward Error Correction Codes

In order to investigate the performance of opportunistic encryption compared to concatenated encryption and forward error correction codes with fixed block length encryption, we used Read-Solomon (RS) code. In RS coding redundancy is added to a k symbols of information block to achieve a n symbol codeword leading to (n, k) code. In a $q - ary$ RS code with error correction capability of t symbols, we have $n = q - 1$ and $k = q - 1 - 2t$. Setting the leading l symbols to zero does not change the error correction capability. Thus deleting this leading l symbols, we obtain the shortened $(q - 1 - l, q - 1 - 2t - l)$ RS code with an error correction capability of t symbols [21]. In the cipher system we consider in this work, information is processed in bytes. Therefore an RS code with $q = 2^8$ is an appropriate choice. Thus we adopt a code capable of handling blocks of 255 bytes or less as input. The post-decoding bit error probability of this code can be approximated by

$$P_{bc} \approx \frac{1}{8k} \left(1 - \sum_{i=0}^{t} \binom{255 - l}{i} P_s^i (1 - P_s)^{255-i-l} \right) \quad (24)$$

$P_s = 1 - (1 - P_b)^8$ here is the byte error probability without coding and P_b is the bit error probability.

The throughput performance for fixed block length encryption and opportunistic encryption with BPSK with and without FEC (RS code) with $t = 15$ is illustrated in Fig. 9. This result

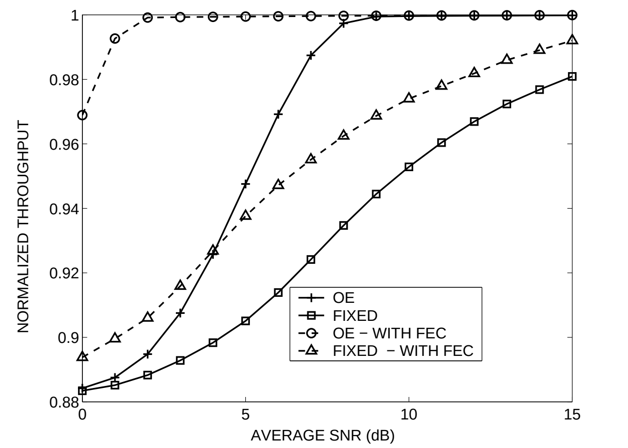

Fig. 9. Throughput of opportunistic encryption and fixed block length encryption with and without FEC (RS code with $t = 15$) as average SNR varies.

was obtained with the optimization technique based on the deterministic measure of security as presented in section III-A. It is seen that at low SNR values, the throughput performance of fixed block length encryption with FEC outperforms opportunistic encryption. As the SNR increases the opportunistic encryption without FEC tends to significantly outperform fixed block length encryption with FEC. At low SNR values the reduction in block error rate due to FEC has larger effect than the benefit of adaptive block length selection. However as the SNR is increased, the opportunistic encryption achieves higher flexibility to optimize the throughput using the large dynamic range in encryption block lengths with minimal effect on throughput.

V. Opportunistic Encryption as Stochastic Optimization

Optimal block length selection for encryption with a known sequence of channel gain serves as the way to derive the optimal tradeoff in security and performance. Such an approach may be applicable if the current and future channel states are known exactly. In the absence of such knowledge, optimization under uncertainty may be essential. In this section we present stochastic optimization approaches with two different levels of channel knowledge.

A. Optimization Based on Finite State Markov Channel Model

In this section we present a method applicable when the channel state transitions can be modelled by a *Finite State Markov Chain* (FSMC) [7]. It is assumed that the actual state of the current channel is known prior to each transmission. Then the selection of encryption block lengths can be considered as the control decisions considering the current and future channel states with the formulation of a finite horizon discrete time Markov decision process [9]. To this end we are required to define the state space, the transition probabilities, and the control actions.

1) Finite State Markov Chain Model for the Wireless Channel: For the model, the fading is assumed to be sufficiently slow such that the channel is assumed to remain constant during the transmission of a data frame. The signal power and hence the SNR, γ of Rayleigh fading channel has an exponential probability density function given by (10). The bit error probability of BPSK signaling as a function of received SNR is given by (9).Thus the steady state probability of a state i is defined by a range of SNR from γ_i to γ_{i+1} as [7],

$$p_i = \int_{\gamma_i}^{\gamma_{i+1}} \frac{1}{\bar{\gamma}} e^{\frac{\gamma}{\bar{\gamma}}} d\gamma = e^{-\frac{\gamma_i}{\bar{\gamma}}} - e^{-\frac{\gamma_{i+1}}{\bar{\gamma}}} \quad (25)$$

and the probability of bit error, or the crossover probability in state i, is

$$P_b^{(i)} = \frac{[\int_{\gamma_i}^{\gamma_{i+1}} e^{-\frac{\gamma}{\bar{\gamma}}} \text{erfc}(\sqrt{\gamma}) d\gamma]}{[\int_{\gamma_i}^{\gamma_{i+1}} e^{-\frac{\gamma}{\bar{\gamma}}} d\gamma]} \quad (26)$$

The probability of transition from state i to state $i+1$ (for $i = 1, \cdots, r-1$) is approximately given by,

$$P_{i,i+1} \approx \frac{K_{i+1}}{R_{bl} p_i} \quad (27)$$

whereas the probability of transition from state i to state $i-1$ (for $i = 2, \cdots, r$) is by,

$$P_{i,i-1} \approx \frac{K_i}{R_{bl} p_i} \quad (28)$$

Here R_{bl} is the transmission rate in number of frames per second, and p_i is the probability the channel is in state i as in (25). K_{i+1} is the expected number of level crossing per second and is a function of maximum *Doppler frequency*, f_m and the SNR level, γ_i given by

$$K_i = \sqrt{\frac{2\pi\gamma_i}{\bar{\gamma}}} f_m e^{-\frac{\gamma_i}{\bar{\gamma}}} \quad (29)$$

The maximum Doppler frequency is defined as $f_m = \frac{v}{\lambda}$ with v, the speed of the vehicle and λ, the wavelength of the carrier. As is the case with practical scenarios, we assume that the probabilities of transition to states other than adjacent are negligible and therefore we have

$$P_{i,i} = 1 - P_{i,i+1} - P_{i,i-1} \quad (30)$$

one step transition to states other than self and adjacent states is not possible.

2) Markov Decision Process (MDP) Formulation: We define the state of the system by a combination of channel state and the amount of data successfully transmitted. Thus a state is given by the a tuple $i \in \{(c_i, b_i)|c_i = 1, \cdots, r; b_i = 1, \cdots, q\}$ where c_i, b_i, r, and q are respectively the channel state, the number of bits successfully transmitted, the number of channel states, and the capacity of the receiver buffer in number of bits. Note that two distinct system states i and j such that $i \neq j$, does not imply $c_i \neq c_j$ or $b_i \neq b_j$. However if $c_i = c_j$ and $b_i = b_j$ then $i \equiv j$. Following a transmission, the success/failure of the correct reception is feeded back to the transmitter by an ACK/NACK signal. We define the set of actions as the available encryption block lengths. Then we can write the receiver buffer occupancy b_i as a sum of a combination of encryption block lengths. Thus $b_i = \sum_{a=1}^{k} m_a N_a$ where there are k different possible encryption block lengths, and m_a blocks of length N_a were successfully transmitted. It should be noted that there are more than one possible combinations of encryption block lengths resulting in the same b_i. A transition from state i to state j implies that the channel has changed from state c_i to c_j and the total number of bits transmitted has changed from b_i to b_j. When the channel is statistically stationary, the probability of transition from a state i to state j under action a is independent of the time n and can be expressed as

$$\begin{aligned} P_{ij}(a) = Pr(c(n+1) = c_j, \\ b(n+1) = b_j | c(n) = c_i, b(n) = b_i, a) \end{aligned} \quad (31)$$

where the action a represents the selection of corresponding encryption length N_a. We observe from (27) and (28) that the channel state transition probabilities depend on the frame rate R_{bl}. We discuss here a scenario where the frame length is same as the encryption block length, N_a, and the extension to the case with fixed frame length is straightforward. Note that the frame rate is inversely proportional to N_a. It is easy to see that (31) can be re-written as:

$$P_{ij}(a) = \begin{cases} Pr(c(n+1) = c_j | c(n) = c_i)(1 - P_{bl,a}(c_i)), \\ b_j = b_i + N_a, |c_j - c_i| \leqslant 1 \\ Pr(c(n+1) = c_j | c(n) = c_i) P_{bl,a}(c_i), \\ b_j = b_i, |c_j - c_i| \leqslant 1 \\ 0 \quad \text{otherwise.} \end{cases} \quad (32)$$

where $Pr(c_{n+1} = c_j | c_n = c_i)$ is the channel transition probability, and the block error probability $P_{bl,a}(c_i)$ in channel state c_i under action a is given by

$$P_{bl,a}(c_i) = 1 - (1 - P_b(c_i))^{N_a} \quad (33)$$

Here $P_b(c_i)$ is the channel *bit error probability* in channel state c_i. Equation (32) is written considering the fact that the total number of transmitted bits will increase with number of successfully transmitted frames and remain the same with failures.

Substituting from (27)-(30) and (33) into (32) along with the use of the expression for block rate, $R_{bl,a} = \frac{R_b}{N_a}$ in terms of the bit rate R_b and encryption block length, N_a, we get

Having defined the state space, the action set, and the transition probabilities, the iterative *value function* of the MDP is given by the Bellman's equation and can be written as

$$v_{\alpha,T}(i) = \max_a \left\{ r(i,a) + \alpha \sum_j P_{ij}(a) v_{\alpha,T-1}(j) \right\} \quad (35)$$

where $v_{\alpha,T}(i)$ the optimal *function value* computed using T steps into the future, is the optimal *reward*. We define the reward for taking the action a at state i as $r(i,a) = b_i + N_a(1 - P_{bl,a}(c_i))$. Here the first term is the reward for the

$$P_{ij}(a) = \begin{cases} \sqrt{\frac{2\pi\gamma_{i+1}}{\bar{\gamma}}} f_m e^{-\frac{\gamma_{i+1}}{\bar{\gamma}}} \frac{N_a(1-P_b(c_i))^{N_a}}{R_b p_i}, & b_j = b_i + N_a, c_j = c_i + 1 \\ \sqrt{\frac{2\pi\gamma_i}{\bar{\gamma}}} f_m e^{-\frac{\gamma_i}{\bar{\gamma}}} \frac{N_a(1-P_b(c_i))^{N_a}}{R_b p_i}, & b_j = b_i + N_a, c_j = c_i - 1 \\ [1 - (\sqrt{\frac{2\pi\gamma_{i+1}}{\bar{\gamma}}} e^{-\frac{\gamma_{i+1}}{\bar{\gamma}}} + \sqrt{\frac{2\pi\gamma_i}{\bar{\gamma}}} e^{-\frac{\gamma_i}{\bar{\gamma}}}) f_m] \frac{N_a(1-P_b(c_i))^{N_a}}{R_b p_i}, & b_j = b_i + N_a, c_j = c_i \\ \sqrt{\frac{2\pi\gamma_{i+1}}{\bar{\gamma}}} f_m e^{-\frac{\gamma_{i+1}}{\bar{\gamma}}} \frac{N_a(1-(1-P_b(c_i))^{N_a})}{R_b p_i}, & b_j = b_i, c_j = c_i + 1 \\ \sqrt{\frac{2\pi\gamma_i}{\bar{\gamma}}} f_m e^{-\frac{\gamma_i}{\bar{\gamma}}} \frac{N_a(1-(1-P_b(c_i))^{N_a})}{R_b p_i}, & b_j = b_i, c_j = c_i - 1 \\ [1 - (\sqrt{\frac{2\pi\gamma_{i+1}}{\bar{\gamma}}} e^{-\frac{\gamma_{i+1}}{\bar{\gamma}}} + \sqrt{\frac{2\pi\gamma_i}{\bar{\gamma}}} e^{-\frac{\gamma_i}{\bar{\gamma}}}) f_m] \frac{N_a(1-(1-P_b(c_i))^{N_a})}{R_b p_i}, & b_j = b_i, c_j = c_i \\ 0, \quad \text{otherwise.} \end{cases} \tag{34}$$

total number of bits successfully transmitted. The second term is the reward of achieved encryption strength (on successful transmission). $0 < \alpha < 1$ is a discount factor to give a desired weight to the future rewards. We do not assume a termination reward. The computation of optimal function values along with the optimal action is performed recursively.

TABLE I
CHANNEL STATES AND SNR RANGES AT 10 dB AVERAGE SNR

state	SNR range
1	$-\infty$ - 1.2558
2	1.2558 - 4.5891
3	4.5891 - 6.7210
4	6.7210 - 8.4083
5	8.4083 - 9.9159
6	9.9159 - 11.4186
7	11.4186 - 13.1795
8	13.1795 - ∞

Numerical simulations for the MDP formulation were carried out as follows. The SNR regions for each state was selected with the assumption of equal steady state probabilities for the states. The state transition probability matrix of (34) was computed for the parameter settings, $f_m = 10$Hz, $r = 8$, $\bar{\gamma} = 0, 5, 10$dB, and $p_i = \frac{1}{r}$ for all i. TABLE I shows The SNR ranges corresponding to each state at $\bar{\gamma} = 10dB$ as an example. We have used the Rijndael ciphers with encryption block lengths $N_a \in \{128, 160, 192, 224, 256\}$. The encryption block lengths for various channel instances for the Rijndael cipher were calculated using the MDP based approach, with the set of N_as as the set of control actions and the channel transition probability matrix as discussed above. In the MDP, we set $r = 8$, $q = 30$, $T = 1000$ and $\alpha = 0.5$. As a baseline of comparison we consider a 224 bit fixed block length encryption for all channel instances. We observed that (Fig. 10) using opportunistic encryption and the knowledge of the channel model, we can achieve higher throughput when compared to the present encryption method where the selection of encryption block length is independent of the channel conditions. Fig. 10 gives the comparison of throughput achieved by opportunistic encryption and the fixed block length allocation (224 bit) over a range of average SNR, $\bar{\gamma}$. We can observe a gain in the throughput over all SNR values. Moreover, for low SNR values, the throughput gain using opportunistic encryption is observed to be higher than that at high SNR values which is explained by the optimal selection of smaller block sizes at low SNR.

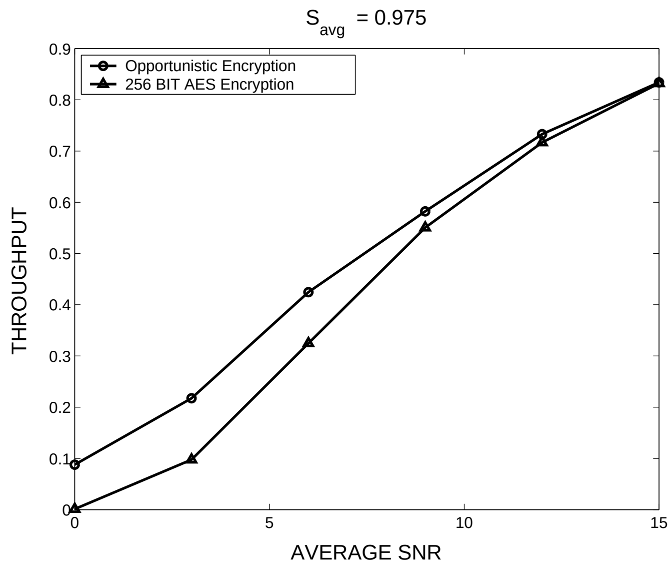

Fig. 10. Throughput comparison between opportunistic encryption and the fixed block length allocation over all average SNRs for a fixed security requirement of $\frac{\log_2(224)}{\log_2(256)} = 0.975$ with the MDP approach.

VI. CONCLUSION

The work presented in this paper shows that opportunistic encryption based on wireless channel states could lead to significant gains in the throughput achieved for a specified security constraint. Three different approaches are presented each with varying levels of channel knowledge. Both analytical and experimental results are presented. For the case where we assume exact channel knowledge and continuous encryption block length we get an improvement of 95% (around 5dB SNR) in the throughput over fixed block length encryption. For the case where only the average SNR and the probability distribution are known we get an improvement of 32% (around 5dB SNR) in the throughput variable block length encryption. Finally, for the case when a Markov channel model is available, using MDP techniques we observe an improvement of 50% (around 5dB SNR) in the throughput over the fixed encryption.

APPENDIX I
OPTIMUM SOLUTION WITH BRUTE FORCE ATTACK

We are required to maximize the throughput subject to an overall security requirement over a finite horizon. This can be stated as a constrained optimization problem given by

$$\max_{\{N_i\}} \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 - N_i P_i)$$
$$\textit{such that} \quad \frac{1}{nS_{max}} \sum_{i=1}^{n} \log_2 N_i = s_{req} \tag{36}$$

Note that $P_i = P_i(\gamma_i, R_i)$ is a function of channel SNR γ_i and the transmission rate used for the frame R_i and s_{req} is the required level of security. This constrained optimization problem can be converted to an unconstrained optimization problem using the Lagrange optimization technique where the object function can be written as

$$C = \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 - N_i P_i) + \lambda \left(\frac{1}{nS_{max}} \sum_{i=1}^{n} \log_2 N_i - s_{req} \right) \tag{37}$$

where the parameter λ is the Lagrange multiplier. Taking partial derivatives of (**??**) w.r.t. N_i and setting them equal to zero we obtain

$$N_i^* = \frac{\lambda}{\log_e 2} \frac{R_{max}}{S_{max}} \frac{1}{R_i P_i}, i = 1, \cdots, n \tag{38}$$

where the superscript $*$ indicates the optimality. Constraint in (36) and Equation (**??**) leads to

$$N_i^* = \frac{\left(\prod_{i=1}^{n} R_i P_i\right)^{\frac{1}{n}}}{R_i P_i} e^{(S_{max} s_{req}) \log_e 2} \tag{39}$$

In the case where the transmission rate is fixed, the above result reduces to

$$N_i^* = \frac{\left(\prod_{i=1}^{n} P_i\right)^{\frac{1}{n}}}{P_i} e^{(S_{max} s_{req}) \log_e 2} \tag{40}$$

APPENDIX II
OPTIMALITY OF THE ALGORITHM UNDER EXPONENTIAL ATTACK MODEL

The following discussion establishes that the algorithm presented in Section III-B.2 is indeed optimal. Consider the quantity to be maximized namely $T = \frac{1}{nR_{max}} \sum_{i=1}^{n} R_i(1 + \frac{P_i}{k} \log_e \phi_i)$ subject to the constraints as in (19)-(21). This is equivalent to maximizing $S = \sum_{i=1}^{n} w_i \log_e \phi_i$ where $w_i = R_i P_i$ with the set of constraints. Each of the summands in S is concave and therefore the optimum allocation of ϕ_i resembles "water-filling" solution [20]. If $y_i = w_i \log_e \phi_i$ then the marginal gain of additional allocation to the ith channel is given by $\frac{\partial y_i}{\partial \phi_i} = \frac{w_i}{\phi_i}$. Let the channels be ordered such that $w_1 \geqslant w_2 \geqslant \cdots \geqslant w_n$. The optimal allocation procedure should first allocate $\phi_i = \phi_{min}$ for $i = 1, \cdots, n$. Next, starting with the first channel in the ordered list, ϕ_1 should be increased from the initial value of ϕ_{min} until the condition $\frac{\partial y_1}{\partial \phi_1} = \frac{\partial y_2}{\partial \phi_2}$ is reached which is equivalent to $\frac{\phi_1}{w_1} = \frac{\phi_2}{w_2}$ with $\phi_2 = \phi_{min}$. From this point onward both ϕ_1 and ϕ_2 should be increased such that $\frac{\phi_1}{w_1} = \frac{\phi_2}{w_2}$ until the common ratio is equal to $\frac{\phi_3}{w_{min}}$. The procedure continues including more and more channels while maintaining equal marginal gains for all channels under consideration. Due to the upper limit of ϕ_{max} on ϕ_i, they may be capped at ϕ_{max} as the procedure continues. The procedure continues until the condition $n\Phi_0 = \sum_{i=1}^{n} \phi_i$ is met. Our formulation of the algorithm is to carry out this allocation process in discrete values for computational efficiency.

The algorithm starts by allocating $\phi_i = \phi_{min}, i = 1, \cdots, n$ and proceeds with the iteration by selecting increasing values for α so as to assign $\phi_i > \phi_{min}$ to more and more channels in the increasing order of w_i until the condition $n\Phi_0 \geqslant \sum_{k=1}^{n} \phi_i$ is achieved. If the equality of constraint is not achieved, the subsequent steps perform fine tuning to achieve the optimal solution.

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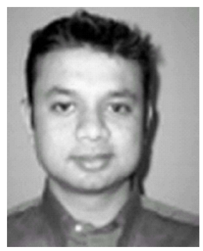

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