An Efficient ARQ Protocol for Adaptive Error Control over Time-Varying Channels *

[1]Hlaing Minn, [2]Mao Zeng, [3]Annamalai Jr. Annamalai and [1]Vijay K. Bhargava
[1] *Department of Electrical and Computer Engineering, University of Victoria, Victoria, B.C., Canada V8W 3P6*
[2] *Motorola Inc., U.S.A.;* [3] *Bradley Department of Department of Electrical and Computer Engineering, Virginia Tech, U.S.A.*
E-mail: bhargava@ece.uvic.ca

Abstract. In this paper, a simple and efficient stop-and-wait (SW) automatic repeat-request (ARQ) scheme with adaptive error control is investigated. In this scheme, the channel state information (CSI) is extracted by monitoring the contiguous positive acknowledgment (ACK) or negative acknowledgment (NAK) messages. Exploiting this CSI, we adapt the coding strategy to the changes in the channel condition, and thus improve the throughput efficiency. In order to facilitate the throughput analysis and parameters optimization, we model the adaptive system by a Markov chain. Using this analytical model and assuming a static channel, an exact throughput expression for the adaptive ARQ protocol is derived and suboptimal adaptive system parameters are obtained. These design parameters are applied for the adaptive system in a typical time-varying mobile radio channel characterized by Rayleigh multipath fading on top of lognormal shadowing. The throughput performance of the proposed adaptive SW-ARQ scheme in such a time-varying fading channel is evaluated by computer simulation. For slow fading channels, the proposed adaptive system can track the channel variations very well, hence much throughput improvement can be achieved over conventional nonadaptive SW-ARQ schemes for almost all SNR values considered. The simulation results also confirm the applicability of the adaptive system parameters so-obtained by the throughput analysis in static channel, to a time-varying mobile radio channel.

Keywords: adaptive error control, automatic repeat request, channel state estimation, time-varying mobile radio channels

1. Introduction

For communications services where very high system performance is of primary requirement and delay is not a major concern, ARQ and hybrid ARQ error control strategies are usually incorporated in system design to achieve the high system reliability. However, the inherent disadvantage of these schemes is that its throughput declines rapidly

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as channel error rate increases. In mobile wireless communications, radio channels induce a time-varying response with bursty errors due to multipath fading and shadowing effects. During the fades the channel becomes too noisy and at the other times it well-behaves. For such a time-varying channel, it is clear that the use of a single error control strategy will not yield the optimal throughput. Therefore, in order to provide a reliable packet data transmission, the use of different error control strategies for different channel conditions are highly desired, since it can provide high throughput under a wide range of error rate conditions.

Recently, there has been considerable interest in adaptive ARQ scheme [2]-[6]. The basic idea is by dynamically changing the protocol operation mode according to channel state information, the higher throughput is realized over a wide range of channel conditions. For real-time implementation, the channel state information needs to be estimated reliably and effectively. That means in order to track channel variations closely, reliable estimation of the channel state information should be carried out within short enough intervals (which may involve accurate estimation of the signal strength via signal power measurement or with pilot tone transmission, and in turn give rise to high implementation complexity).

Several indirect methods have been proposed in order to address this issue [2]-[6]. Since the frequency of the retransmission requests provide a natural source of CSI, no additional circuitry is required for estimating the channel state condition. In most of the indirect methods, the channel is monitored typically by counting the number of retransmissions during a fixed observation interval and comparing that number with a set of threshold to determine the channel condition. However, the fixed sample size method usually requires a large observation interval to obtain a reliable CSI decision. This will cause the delay in reacting to a change in the channel and thus result in a reduction in the efficiency of the system.

In [4], a simple channel state estimator (CSE) based on the count of contiguous ACKs and/or NAKs messages is proposed. This method can be treated as a variable observation interval method with weighted success or error events. This ensures that the influence of the most recent errors is the largest. In the performance analysis of [4], the adaptive GBN-ARQ scheme was modeled using a simple two-state Markov chain. However, this representation becomes void if the design variables (see Figures 1 and 2) are selected to be larger than unity because now the present state probabilities will be dependent on a specified number of previous state values. In this paper, we refine the analytical model in [4] and derive an exact expression for the throughput efficiency. By using the proposed method, we will investigate the performance of an efficient and simple SW-ARQ protocol with adaptive error control strategies. In our system, the variable observation interval method with weighted success or error events is employed for channel state estimation.

The paper is organized as follows. Section 2 details the operation of the proposed mixed-mode SW-ARQ protocol. In Section 3, an accurate throughput efficiency expression for the adaptive SW-ARQ scheme is derived for a stationary channel. Subsequently, the optimal design of the adaptive system is discussed in Section 4 and the computational results of the suboptimal design parameters are discussed in Section 5. Then the throughput performance of the proposed scheme in a time-varying mobile radio channel is investigated by computer simulation in Section 6. Finally, the conclusions are drawn in Section 7.

2. System Description

For the sake of illustration, let us consider a stop-and-wait ARQ scheme which can operate in one of its three operation modes, namely mode L, mode M and mode H. The difference of the three operation modes is that different error control strategies are used. The decision regarding the transitions between different operation modes is made based on the received acknowledgment messages as illustrated in Figure 1. The system assumes that the channel is transiting from the low error rate to the medium error rate condition upon receiving α contiguous NAKs while in mode L, and consequently will change its operation mode to mode M. Likewise, if the system which is operating in mode M receives γ contiguous NAKs, then the system would consider that the channel is further deteriorated to the high channel error rate condition, and correspondingly a switching to mode H will be executed. On other hand, if the system receives β contiguous ACKs at operation mode M, the system will switch back to mode L. When the system is operating in mode H, an operation switch to mode M will be executed only when λ contiguous ACKs have been received, since in this case the system would consider that the channel condition is getting better.

Clearly, we can characterize the adaptive mixed-mode ARQ system by an $(\alpha + \beta + \gamma - 1 + \lambda)$-state Markov chain as shown in Figure 2. The state space of the Markov chain can be partitioned into three groups of α, $\beta + \gamma - 1$ and λ states which correspond to the three different operation modes respectively. Based on this Markov chain representation, we will analyze the throughput efficiency of the adaptive system in the following section.

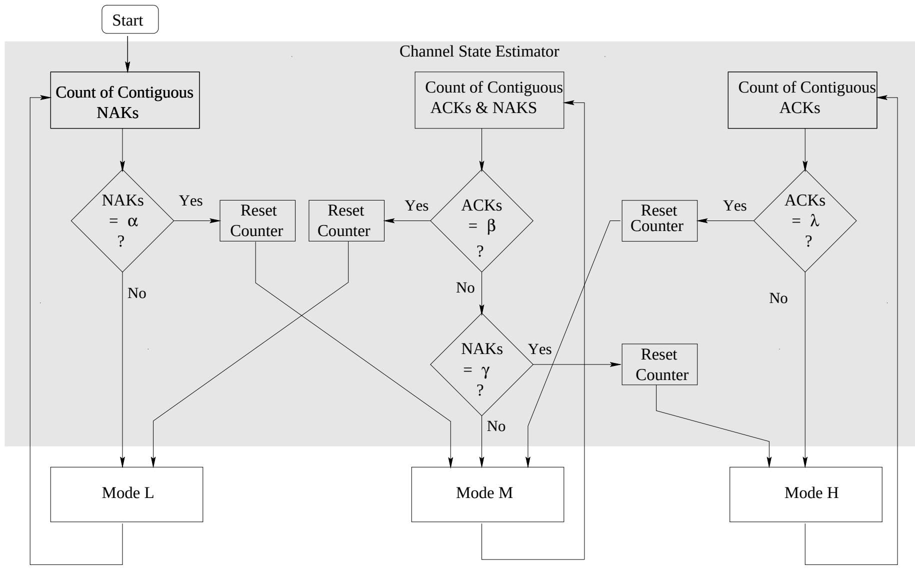

Figure 1. System description of an adaptive SW-ARQ protocol with sliding observation interval and three operation modes.

3. Throughput Analysis

The performance of an ARQ scheme is generally measured in terms of its throughput efficiency and its delay characteristics. In this section, we focus on the throughput efficiency, which is defined as the ratio of the number of information bits delivered to the total number of bits that transmitter could have transmitted. For simplicity, we made the following assumptions in the evaluation of the throughput.
1). All acknowledgment messages (ACK/NAK) are received error-free at the transmitter, i.e., the feedback channel of the system is noiseless;
2). Transmission errors in consecutive packets occur independently.

We conduct our study of the ARQ scheme introduced in the previous sections under assumption of a stationary channel. The analytical results can provide fundamental insights into how the system parameters interact and determine the performance, and also enable us to design the system for time-varying channels.

3.1. Steady-state Probabilities

When we assume the channel is stationary, the transition probabilities in Figure 2 do not vary with the time. Thus, the Markov chain is stationary and the steady-state probabilities exist. Since these steady-state probabilities are required to estimate the throughput of the investigated adaptive ARQ system, we will derive them in the following.

From Figure 2, it is straightforward to construct the $(\alpha+\beta+\gamma-1+\lambda)$-state transition matrix. Thus, the steady-state probabilities must satisfy the following equations.

$$\begin{aligned}
P_{L_1} &= (1-P_{2e})P_{M_\beta} + (1-P_{1e})\textstyle\sum_{k=1}^{\alpha} P_{L_k} \\
P_{L_i} &= P_{1e}^{i-1}P_{L_1}, \qquad i=2,\ldots,\alpha; \\
P_{M_1} &= P_{1e}^{\alpha}P_{L_1} + (1-P_{3e})^{\lambda}P_{H_1}; \\
P_{M_2} &= (1-P_{2e})(P_{M_1}+P_{m_2}+P_{m_3}+\ldots+P_{m_\gamma}) \\
P_{M_i} &= (1-P_{2e})^{i-2}P_{M_2}, \qquad i=3,\ldots,\beta; \\
P_{m_2} &= P_{2e}(P_{M_1}+P_{M_2}+\ldots+P_{M_\beta}) \\
P_{m_i} &= P_{2e}^{i-2}P_{m_2}, \qquad i=3,\ldots,\gamma; \\
P_{H_1} &= P_{2e}P_{m_\gamma} + P_{3e}(P_{H_1}+\ldots+P_{H_\lambda}); \\
P_{H_i} &= (1-P_{3e})^{i-1}P_{H_1}, \qquad i=2,\ldots,\lambda; \\
&\textstyle\sum_{k=1}^{\alpha} P_{L_k} + \sum_{k=1}^{\beta} P_{M_k} + \sum_{k=2}^{\gamma} P_{m_k} + \sum_{k=1}^{\lambda} P_{H_k} = 1.
\end{aligned} \tag{1}$$

where P_{1e}, P_{2e} and P_{3e} denote the message packet error probabilities of operation modes L, M and H, respectively. After some mathematical manipulations, we can obtain the steady-state probabilities as follows.

$$\begin{aligned}
P_{L_i} &= \mathcal{C}P_{1e}^{i-1}P_{2e}(1-P_{2e})^{\beta-1}(1-P_{2e}^{\gamma})(1-P_{3e})^{\lambda};\ i=1,2,\ldots,\alpha; \\
P_{M_1} &= \mathcal{C}P_{1e}^{\alpha}[P_{2e}^{\gamma} - P_{2e}^{\gamma}(1-P_{2e})^{\beta-1} + P_{2e}(1-P_{2e})^{\beta-1}](1-P_{3e})^{\lambda}; \\
P_{M_i} &= \mathcal{C}P_{1e}^{\alpha}P_{2e}(1-P_{2e})^{i-2}(1-P_{2e}^{\gamma})(1-P_{3e})^{\lambda};\ i=2,3,\ldots,\beta; \\
P_{m_i} &= \mathcal{C}P_{1e}^{\alpha}P_{2e}^{i-1}(1-(1-P_{2e})^{\beta})(1-P_{3e})^{\lambda};\ i=2,3,\ldots,\gamma; \\
P_{H_i} &= \mathcal{C}P_{1e}^{\alpha}P_{2e}^{\gamma}(1-(1-P_{2e})^{\beta})(1-P_{3e})^{i-1};\ i=1,2,\ldots,\lambda.
\end{aligned} \tag{2}$$

where $\mathcal{C}$ is a constant.

3.2. Throughput Estimation

In SW-ARQ schemes, the transmitter sends out a packet and waits for an acknowledgment. Once the receiver has processed the packet, it responds by sending a positive acknowledgment (ACK) if the packet can be successfully decoded, otherwise, it sends a retransmission request. Therefore, a new packet will be transmitted only after a positive acknowledgment for the previous packet has been received. This means that, in the Markov chain representation as shown in Figure 2, the first

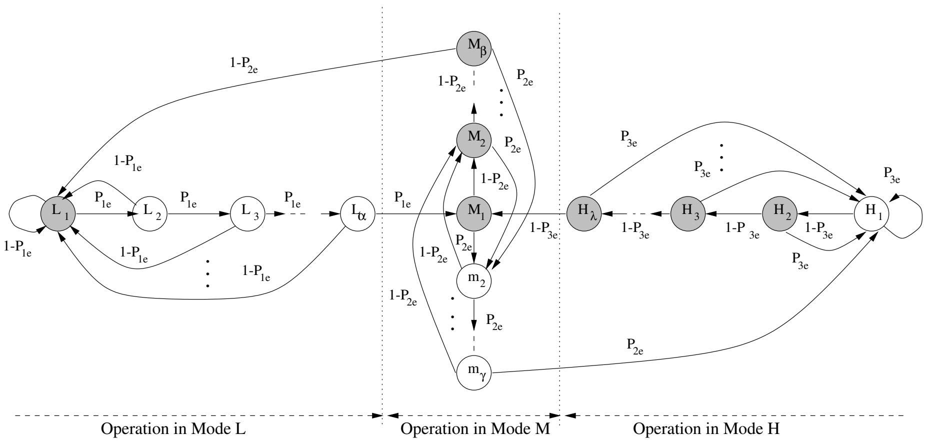

Figure 2. Markov chain representation for the proposed adaptive SW-ARQ protocol.

transmission of a new packet can only start from the states which can be reached in one-step with a ACK, i.e., states L_1, M_i, $i = 1, 2, \ldots, \beta$, H_j, $j = 2, 3, \ldots, \lambda$. For convenience of presentation, we define a state variable X, which denotes a state where a new packet is oriented. We denote f as the number of transmissions (including the original transmission and retransmissions) required for a successful packet. Then, for a packet oriented from state X to be successfully accepted by the receiver, the average number of bits that the transmitter could have transmitted can be calculated as follows.

a). When the packet is oriented from state L_1, it can be seen from Figure 2 that if the number of (re)transmissions is less than α, all the transmissions are sent in mode L. However, after more than α and less than $\alpha + \gamma$ consecutive failures in transmission attempts for that packet, the transmitter will operate in mode M during the following possible retransmissions. When the number of transmission failures for the packet is larger than $\alpha + \gamma$, the transmitter will finally operate in mode H. Therefore, the conditional probability of $P(f = k|X = L_1)$ can be calculated as

$$P(f = k|X = L_1) = \begin{cases} P_{1e}^{k-1}(1 - P_{1e}); & k \leq \alpha \\ P_{1e}^{\alpha} P_{2e}^{\gamma} P_{3e}^{k-\alpha-\gamma-1}(1 - P_{3e}); & k > \alpha + \gamma \\ P_{1e}^{\alpha} P_{2e}^{k-\alpha-1}(1 - P_{2e}); & others \end{cases} \qquad (3)$$

Consequently, the average number of bits that the transmitter could have transmitted for the packet to be successfully received and acknowledged is

$$\begin{aligned} T_{L_1} &= \sum_{k\le\alpha} k(n_1+R\tau)P(f=k|L_1) \\ &+ \sum_{\alpha<k\le\alpha+\gamma} [\alpha(n_1+R\tau)+k(n_2+R\tau)]P(f=k|L_1) \\ &+ \sum_{k>\alpha+\gamma} [\alpha(n_1+R\tau)+\gamma(n_2+R\tau)+k(n_3+R\tau)]P(f=k|L_1) \\ &= (1-P_{1e}^{\alpha})\frac{n_1+R\tau}{1-P_{1e}} + P_{1e}^{\alpha}(1-P_{2e}^{\gamma})\frac{n_2+R\tau}{1-P_{2e}} + P_{1e}^{\alpha}P_{2e}^{\gamma}\frac{n_3+R\tau}{1-P_{3e}} \end{aligned} \tag{4}$$

where n_1, n_2 and n_3 are the numbers of bits in a packet transmitted in mode L, mode M and mode H respectively, τ is the idle time from the end of transmission of one packet to the beginning of transmission of the next, and R is the transmission rate in bits per second.

b). When the packet is oriented from state M_i, $i=1,2,\ldots,\beta$, the first γ transmissions, if necessary, are in mode M. However, if the number of retransmissions is larger than γ, then all possible retransmissions after γ retransmissions will be in mode H. Similar to the case of $X=L_1$, we have

$$P(f=k|X=M_i) = \begin{cases} P_{2e}^{k-1}(1-P_{2e}); & k\le\gamma \\ P_{2e}^{\gamma}P_{3e}^{k-\gamma-1}(1-P_{3e}); & k>\gamma \end{cases} \tag{5}$$

and the average number of bits that the transmitter could have transmitted is

$$\begin{aligned} T_{M_i} &= \sum_{k\le\gamma} k(n_2+R\tau)P(f=k|M_i) \\ &+ \sum_{k>\gamma}[\gamma(n_2+R\tau)+k(n_3+R\tau)]P(f=k|M_i) \\ &= (1-P_{2e}^{\gamma})\frac{n_2+R\tau}{1-P_{2e}} + P_{2e}^{\gamma}\frac{n_3+R\tau}{1-P_{3e}}. \end{aligned} \tag{6}$$

c). When the packet is oriented from state H_i, $i=2,\ldots,\lambda$, all the (re)transmissions will be operated in mode H. Therefore, we simply have

$$T_{H_i} = \frac{n_3+R\tau}{1-P_{3e}} \tag{7}$$

It is useful to define a new parameter p_X, which dictates the conditional probability that when there is a new packet to be transmitted, the packet is transmitted at state X. From the steady-state probabilities of the adaptive system, we can obtain the probability that there is a new packet to be transmitted as

$$P_{new} = P_{L_1} + P_{M_{1H}} + \sum_{i=2}^{\beta} P_{M_i} + \sum_{j=2}^{\lambda} P_{H_j} \tag{8}$$

where $P_{M_{1H}} = P_{2e}^{\gamma-1}\ P_{m_2}$. Then the conditional probability p_X can be calculated as

$$p_X = \frac{P_X}{P_{new}}, \tag{9}$$

where $X = L_1,\ M_{1H},\ M_i,\ (i = 2, \ldots, \beta)$ or $H_j,\ (j = 2, 3, \ldots, \lambda)$.

Therefore, the average number of bits required for a packet of K information bits to be successfully received and acknowledged is

$$\bar{T} = T_{L_1} p_{L_1} + T_{M_1} p_{M_{1H}} + \sum_{i=2}^{\beta} T_{M_i} p_{M_i} + \sum_{j=2}^{\lambda} T_{H_j} p_{H_j}, \tag{10}$$

and the throughput efficiency of this adaptive scheme can be obtained by

$$\eta = \frac{K}{\bar{T}}. \tag{11}$$

4. Throughput Optimization

As illustrated in Section 3, the throughput efficiency of the adaptive system depends on the parameters $(\alpha, \beta, \gamma, \lambda)$. Thus, it requires a careful selection of these parameters to optimize the system performance. In the following, we discuss the optimal design of the investigated adaptive system in terms of throughput efficiency. First, we start with an investigation on some properties of the system.

Proposition I: Upper bound of the throughput efficiency

The throughput efficiency of the adaptive mixed-mode ARQ system is upper bounded by η^*, which is defined as

$$\eta^* = \begin{cases} \eta_L & 0 < P_S \leq P_{co}^{(1)} \\ \eta_M & P_{co}^{(1)} < P_S \leq P_{co}^{(2)} \\ \eta_H & P_{co}^{(2)} < P_S < 1 \end{cases} \tag{12}$$

where $P_{co}^{(1)}$ is the throughput crossover probability of the systems operating in single mode L and mode M, $P_{co}^{(2)}$ is the throughput crossover probability of the systems operating in single mode M and mode H, and P_S is the symbol error probability.

From *Proposition I*, it can be seen that the throughput performance of the proposed adaptive system can be upper bounded by one of its operation modes in different ranges of symbol error probability. Furthermore, we can obtain the asymptotic properties of the system as follows.

Proposition II: The asymptotic properties of the throughput efficiency

1). If $\lim_{\alpha,\,\beta\to\infty} \frac{\alpha}{\beta-1} > \frac{\ln(1-P_{2e})}{\ln(P_{1e})}$ and $\lim_{\gamma,\,\lambda\to\infty} \frac{\gamma-1}{\lambda-1} > \frac{\ln(1-P_{3e})}{\ln(P_{2e})}$,

$$then \quad \lim_{\alpha,\,\beta,\,\gamma,\,\lambda\to\infty} \eta = \eta_L; \tag{13}$$

2). If $\lim_{\alpha,\,\beta\to\infty} \frac{\alpha}{\beta-1} < \frac{\ln(1-P_{2e})}{\ln(P_{1e})}$ and $\lim_{\gamma,\,\lambda\to\infty} \frac{\gamma-1}{\lambda-1} < \frac{\ln(1-P_{3e})}{\ln(P_{2e})}$,

$$then \quad \lim_{\alpha,\,\beta,\,\gamma,\,\lambda\to\infty} \eta = \eta_H; \tag{14}$$

3). If $\lim_{\alpha,\,\beta\to\infty} \frac{\alpha}{\beta-1} < \frac{\ln(1-P_{2e})}{\ln(P_{1e})}$ and $\lim_{\gamma,\,\lambda\to\infty} \frac{\gamma-1}{\lambda-1} > \frac{\ln(1-P_{3e})}{\ln(P_{2e})}$,

$$then \quad \lim_{\alpha,\,\beta,\,\gamma,\,\lambda\to\infty} \eta = \eta_M; \tag{15}$$

By choosing set of $(\alpha, \beta, \gamma, \lambda)$ to satisfy that

$$\begin{aligned} \frac{\alpha}{\beta-1} &= \frac{\ln(1-P_{2e}(P_{co}^{(1)}))}{\ln P_{1e}(P_{co}^{(1)})}, \\ \text{and} \quad \frac{\gamma-1}{\lambda-1} &= \frac{\ln(1-P_{3e}(P_{co}^{(2)}))}{\ln P_{2e}(P_{co}^{(2)})}; \end{aligned} \tag{16}$$

it can be easily verified that the conditions in 1), 2) and 3) will be satisfied when the symbol error probability P_S takes value from the intervals $(0, P_{co}^{(1)})$, $(P_{co}^{(1)}, P_{co}^{(2)})$ and $(P_{co}^{(2)}, 1)$, respectively. Therefore, *Proposition II* shows that the throughput of the proposed system has an optimum in $\alpha \times \beta \times \gamma \times \lambda$ space, which is the upper limit η^* imposed by *Proposition I*. It also implies that the optimum $(\alpha^*, \beta^*, \gamma^*, \lambda^*)$ lies in the infinite space. However, in practical applications, we may prefer to smaller α, β, γ and λ since this will reduce the delay in reacting to a change in the channel and thus improve the adaptability of the system.

Using *Proposition I* and *II*, we can now formulate an objective function to determine the suboptimal design parameters such that the throughput of the adaptive ARQ scheme, η best approximates η^* in the sense that the mean square error (MSE) is minimized, i.e.,

$$\begin{aligned} E(\alpha,\beta,\gamma,\lambda) &= \int_0^1 w[\eta(P_S) - \eta^*(P_S)]^2 dP_S \\ &= \Delta \sum_{k=1}^{L} w_k [\eta(P_S^{(k)}) - \eta^*(P_S^{(k)})]^2 \\ \text{subject to:} \quad & d_{min} < (\alpha,\beta,\gamma,\lambda) < d_{max} \end{aligned} \tag{17}$$

where L and $P_S^{(k)}$ denote the sample size and symbol error probability of the kth sample, respectively. w_k is a pre-defined weight sequence that provides additional flexibility in matching different data points with varying accuracy, and the optimization variables can assume any values from set Z, which consists of positive integers.

Discrete determination of the MSE $E(\alpha,\beta,\gamma,\lambda)$ is valid if the step size Δ between the consecutive data points is selected to be relatively small. In addition, the boundary constraints to the design parameters (which will be specified by the channel behavior) are introduced to achieve a good compromise between the ability to react to channel fluctuation rate (in a time-varying channel) and the switching reliability criterion (i.e., the MSE value). In the minimization problem Equation 17, the boundary constraints can be eliminated via transformation $y = \tanh(z)$ or alternatively $y = 2\arctan(z)/\pi$.

5. Computational Results and Remarks

In this subsection, we present a few examples to illustrate the system design and the parameter optimization for the CSE algorithm. In our examples, we assume that one data packet contains only one codeword. All the codes of differernt modes contain the same length of information bits. In mode L, which corresponds to low error rate mode, only CRC is used for error detection. Besides CRC, in mode H and M, which correspond to high error rate mode and moderate error rate mode, a Reed-Solomon code RS(31,15) and a punctured RS code (21,15) are used for error correction respectively. The round-trip delay of 2 RS symbol intervals is assumed. In throughput evaluation, perfect error detection of CRC is assumed and the CRC parity bits are not included in throughput calculation.

Table I depicts the suboptimal design parameters (obtained via quasi-Newon method) and their corresponding switching reliability criterion for the proposed adaptive SW-ARQ system. The weight sequence w_k in Equation 17 can be defined according to the fading channel

Table I. Suboptimal Design Parameters($d_{min} = 1$)

d_{max}	$(\alpha, \beta, \gamma, \lambda)$	MSE
5	(1,5,2,5)	4.20×10^{-4}
10	(2,10,3,10)	1.75×10^{-4}
15	(2,15,3,15)	1.10×10^{-4}
20	(2,20,3,20)	9.55×10^{-5}
25	(2,21,3,25)	9.50×10^{-5}
30	(3,30,4,30)	7.40×10^{-5}

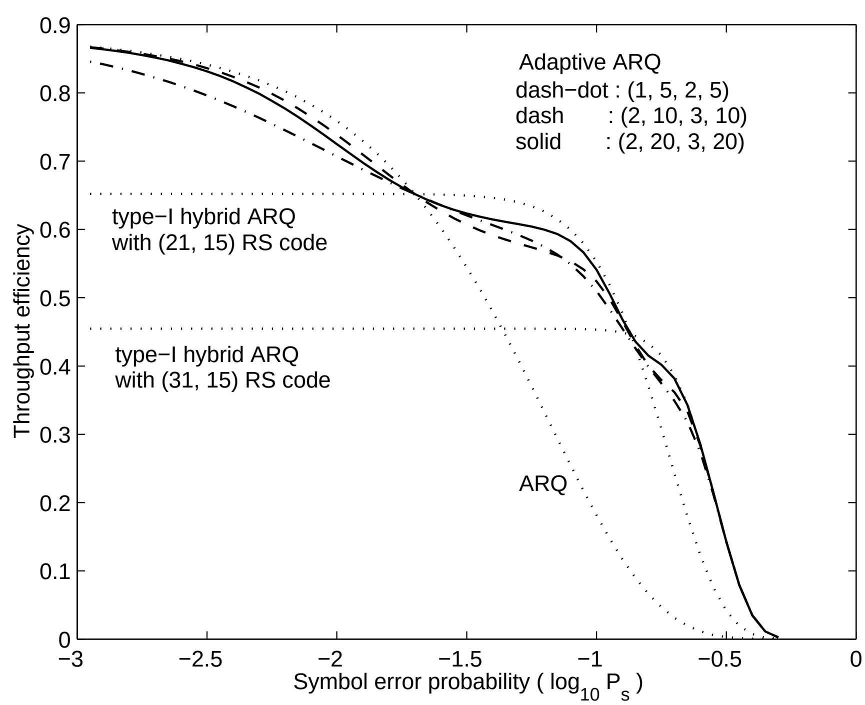

Figure 3. Performance comparison of the proposed adaptive ARQ system with different sets of design parameters $(\alpha, \beta, \gamma, \lambda)$

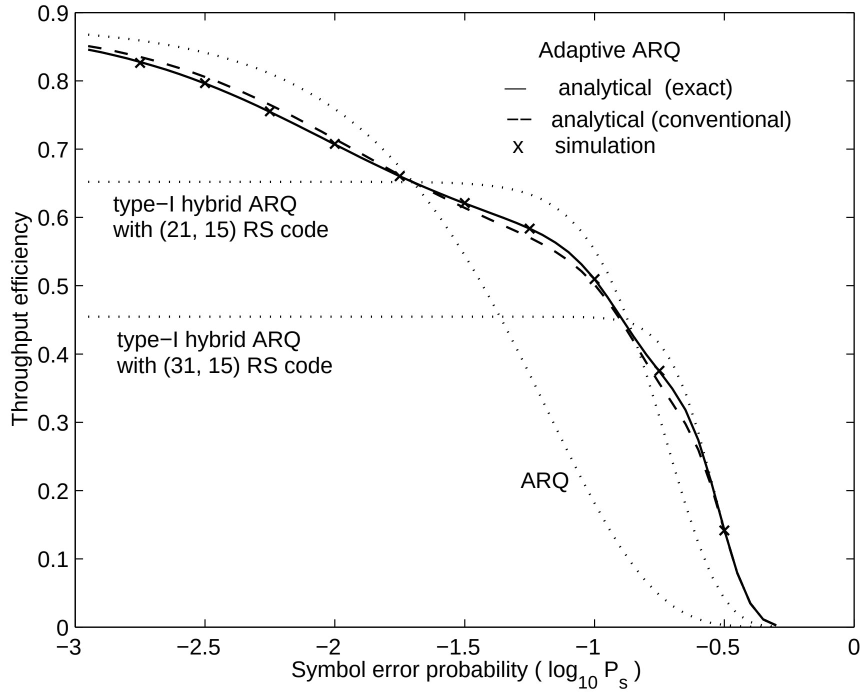

Figure 4. Throughput versus symbol error probability. Adaptive ARQ parameters: $(\alpha = 1, \beta = 5, \gamma = 2, \lambda = 5)$

statistics and SNR operation point of the system. However, in order to observe the generality and robustness of the adaptive system parameters, no specific weight sequence is applied in our optimization, i.e., $w_k = 1$ for all k. In other words, no channel statistics and no particular SNR operation point of the system are assumed in our optimization. From this table, we found that for the suboptimal points, the parameters β and λ are always much larger than α and γ as predicted by our Proposition II in Section 4. It is also seen that the MSE decreases as the ratio of suboptimal design variables β/α or λ/γ increases.

Figure 3 illustrates the throughput performance of a mixed-mode SW-ARQ scheme for three different sets of suboptimal design parameters. It is clear that the adaptive scheme yields much higher throughput than other comparable nonadaptive ARQ schemes over a wide range of error rates. Moreover, it is seen that with the design parameters $(\alpha, \beta, \gamma, \lambda)$=(2,20,3,20), which has the largest ratios of β/α and λ/γ among the three sets, its actual throughput efficiency is the closest to the desired performance curve among the three sets, as discussed previously. This trend holds for stationary channels, but in practical applications in time-varying channels, we may prefer to smaller α, β, γ and λ since this will reduce the delay in reacting to a change in the channel and thus improve the adaptability of the system.

The throughput of adaptive ARQ scheme is conventionally calculated as a simple average of the throughput values of each distinct operation modes, namely, $\eta = \sum P_i \eta_i$. However, it should be noted that this conventional throughput calculation is not exact. For the adaptive system investigated in this paper, comparisons between throughput performance obtained by the conventional approach and that developed in this paper are shown in Figure 4 for an adaptive SW-ARQ scheme with $(\alpha, \beta, \gamma, \lambda) = (1, 5, 2, 5)$. We found that the curve obtained by Equation 11 is in good agreement with the throughput values obtained by computer simulations whereas that of the conventional approach shows some small discrepency against simulation results. This observation validates the accuracy of our analytical model.

6. Simulation of the Adaptive ARQ scheme over time-varying channels

In previous section, the throughput performance of adaptive ARQ scheme is analysed assuming a static channel case. However, a practical mobile radio channel is a time-varying environment and consequently the adaptive system becomes a nonstationary Markov process. Furthermore, transmission errors in consecutive packets no longer occur independently due to the time-correlation characteristics of the mobile radio channel. Thus, an exact throughput analysis of an adaptive ARQ scheme in a time-varying mobile radio channel becomes intractable. Hence, simulation approach is adopted here to evaluate the adaptive ARQ scheme performance in a typical mobil radio channel. Particularly, the suboptimal CSE design parameters obtained for stationary channel will be used for time-varying channel and the applicability of these parameters in a practical time-varying channel will be investigated.

6.1. Channel Model

Mobile radio channel is typically characterized by multipath fading and shadowing. In our simulation, multipath fading is modeled with Rayleigh distribution. Doppler spread induced by the motion of a mobile terminal, which corresponds to the time correlation of the fading gain samples, is also included. Jake's Doppler spectrum is assumed and the correlated Rayleigh fading gain samples are generated by using the method of [7]. The shadowing effect which causes slower variation of the

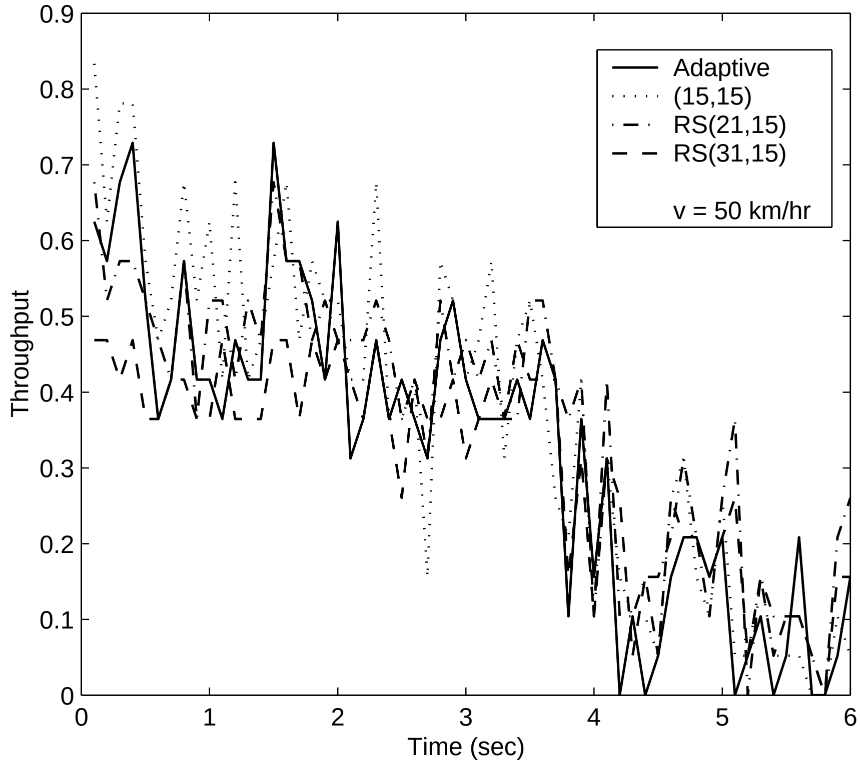

Figure 5. Short-term throughput of the adaptive and nonadaptive ARQ schemes for mobile speed of 50 km/hr and long term SNR of 5 dB

short term median strength of the received signal is usually modeled with lognormal distribution, i.e., the short term median strength $\gamma(t)$ of the received signal can be expressed as

$$\gamma(t) = 10^{-\xi(t)/10}, \tag{18}$$

where $\xi(t)$ is a time-correlated Gaussian random variable. In our simulation, the method of [8] is used for lognormal shadowing where the lognormal shadowing is modeled as a Gaussian white noise process which is filtered with first order lowpass filter. With this model,

$$\xi_{k+1} = \varepsilon \cdot \xi_k + (1 - \varepsilon) \cdot \nu_k, \tag{19}$$

where ν_k is a zero mean white Gaussian random variable with variance Ω_ν, ε is a parameter that controls the spatial correlation of the shadowing and given by

$$\varepsilon = \varepsilon_D^{vT_s/d}. \tag{20}$$

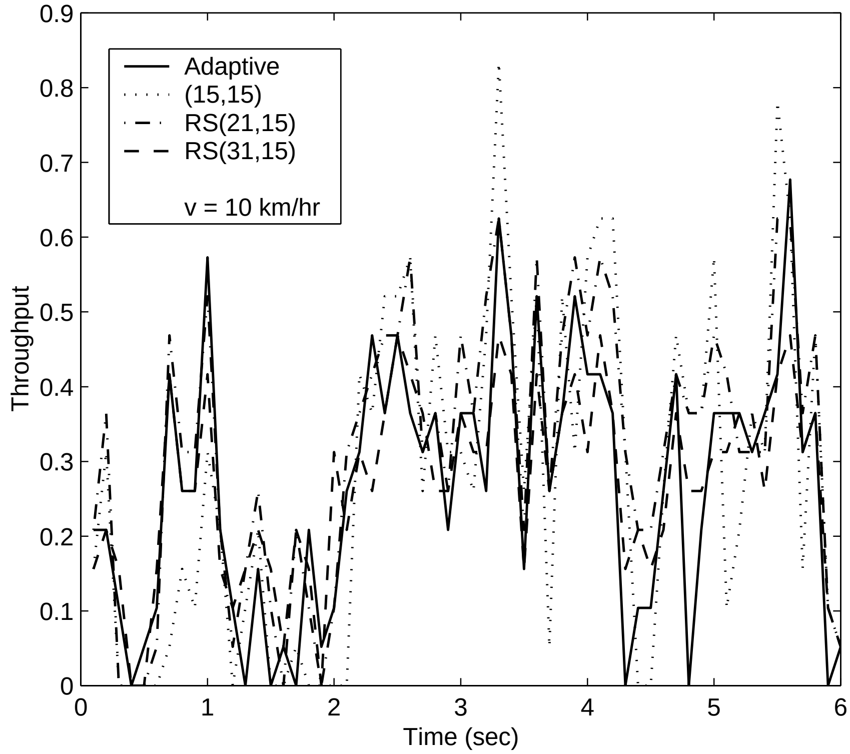

Figure 6. Short-term throughput of the adaptive and nonadaptive ARQ schemes for mobile speed of 10 km/hr and long term SNR of 5 dB

The parameter ε_D is the correlation between two points separated by a spatial distance of D, v is the velocity of the mobile terminal, T_s is the sampling period. For typical suburban propagation at 900 MHz, it has been suggested in [8] that $\Omega_\xi \approx 7.5dB$ with a correlation $\varepsilon_D \approx 0.82$ and D $= 100$.

6.2. Simulation Results and Discussions

In this subsection, the simulation results of the throughput performances of the proposed adaptive ARQ scheme and non-adaptive ARQ schemes in a typical time-varying mobile radio channel for different mobile speeds are presented. The system parameters used in Section 5 are also applied in the simulation and BPSK modulation with coherent detection is considered. The adaptive ARQ parameters of $(\alpha, \beta, \gamma, \lambda) = (1, 5, 2, 5)$ is used in our simulation. The carrier frequency of 900 MHz and data rate of 14.4 kbps are assumed.

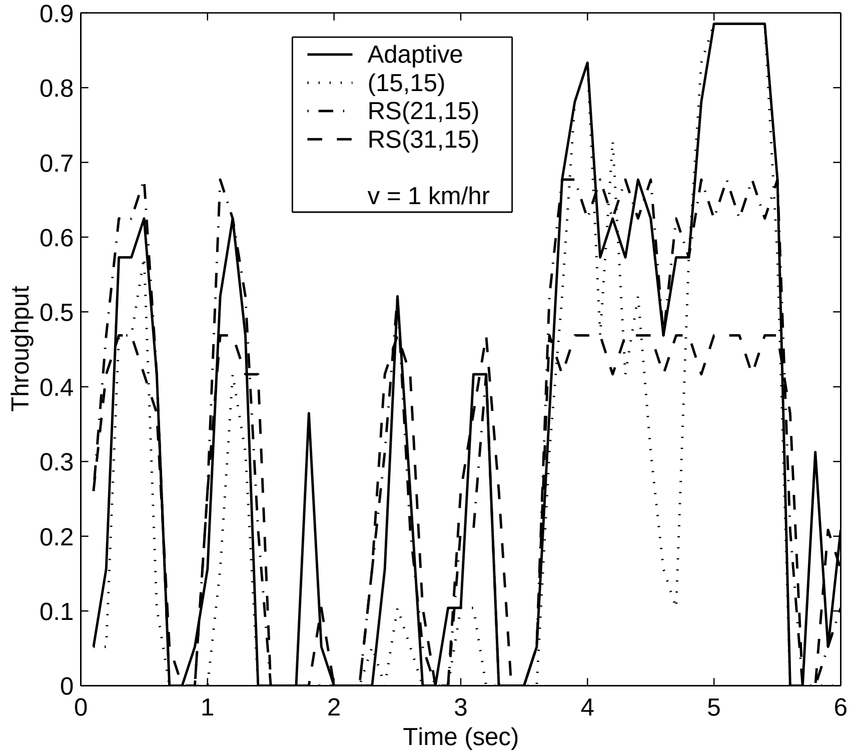

Figure 7. Short-term throughput of the adaptive and nonadaptive ARQ schemes for mobile speed of 1 km/hr and long term SNR of 5 dB

Figures 5, 6 and 7 show, as a function of time, short-term average throughput of the proposed adaptive SW-ARQ scheme and conventional SW-ARQ schemes applying the codes used in adaptive scheme for the mobile speeds of 50 km/hr, 10 km/hr and 1 km/hr respectively. The short-term throughput is obtained by averaging over every 0.1 second interval. From the figures, it is observed that for very slow fading case of v = 1km/hr, the short-term throughput is mainly determined by the multipath fading effect. On the other hand, for faster fading cases of v=10 km/hr and 50 km/hr, the effects of shadowing on throughput performance become prominent. Regarding the tracking capability to channel conditions, it is observed that the adaptive system can track the channel variations quite well for all fading rates considered, especially for slower fading cases. As expected, it can adapt to multipath fading more closely for very slow fading case than faster fading cases. The tracking trends for faster fading cases cannot follow multipath fading quite closely but they follow the shadowing effect.

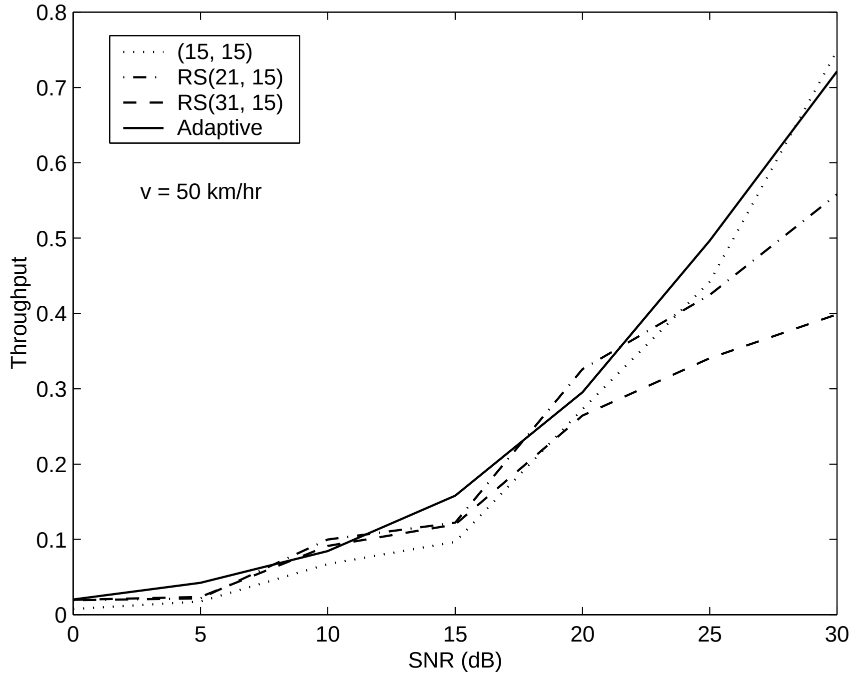

Figure 8. Throughput of the adaptive and nonadaptive ARQ schemes for mobile speed of 50 km/hr

In Figures 8, 9 and 10, the throughput performance of the proposed adaptive SW-ARQ scheme and conventional SW-ARQ schemes which use the codes applied in adaptive system are shown as a function of long term SNR values for the mobile speeds of v = 50 km/hr, 10 km/hr and 1 km/hr respectively. First of all, the throughput performances of ARQ schemes for faster fading rates are observed to be smaller than those for slower fading rates. It is expected since faster fading causes more random channel errors and hence more retransmission and less throughput. The greater throughput performance improvement of adaptive system is observed for slower fading case. As discussed previously, the adaptive system can track multipath fading more closely for slower fading rate case and hence, this brings about the greater improvement. For the cases with mobile speeds of 10 km/hr and 1 km/hr, the adaptive system throughput is considerably higher than any of the conventional SW-ARQ schemes for almost all SNR values considered. The exceptions are at the very high SNR value of 30 dB and the very low SNR value of 0 dB. For very high SNR value, all the packets are received correctly almost all the time. However, occasional packet errors cause the adaptive system to switch the operation mode unnecessarily and because of this

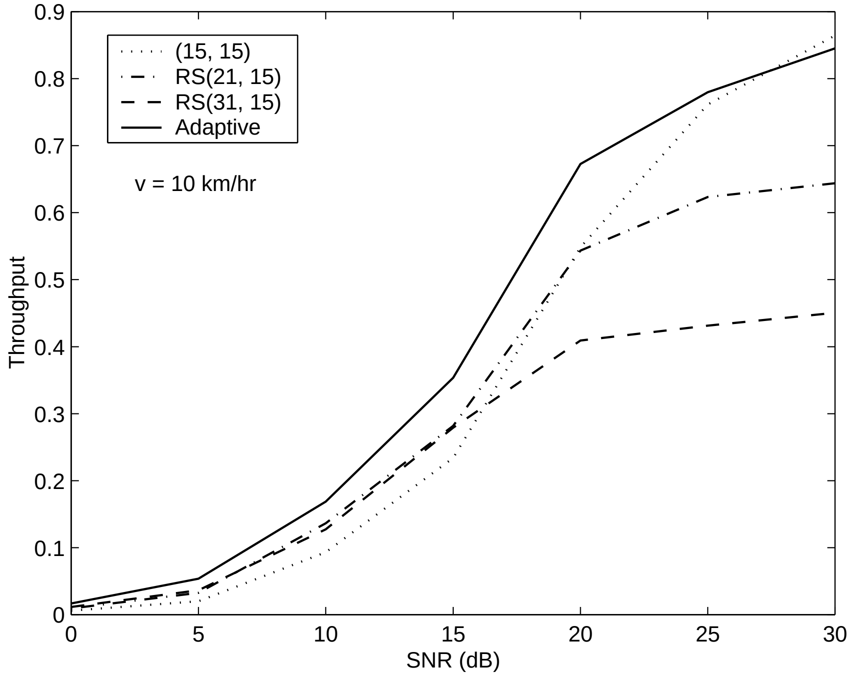

Figure 9. Throughput of the adaptive and nonadaptive ARQ schemes for mobile speed of 10 km/hr

unnecessary mode switching, the adaptive system has a slightly lower throughput than the conventional one at the very high SNR value. At the very low SNR value, noise is the main contributor to packet errors and adaptive system would most of the time be in mode H under such a very noisy condition. As a result, the adaptive system does not achieve throughput improvement for very low SNR value.

For the case with 50 km/hr, the adaptive system does not achieve the same kind of improvement as 10 km/hr and 1 km/hr cases due to its less tracking capability to time-varying channel with a faster fading rate. However, the adaptive system throughput still follows the trend it should. In other words, for the SNR region where the throughput of conventional scheme with mode L code is higher than the other two conventional cases, the throughput of adaptive system follows that of conventional scheme with mode L code. Similarly, it follows that of mode M code for the corresponding SNR region of mode M code.

In brief, the simulation study of the throughput performance in a time-varying mobile radio channel shows that the proposed adaptive ARQ system can adapt to the channel variations quite closely, especially for slow fading case, and hence achieve significant throughput

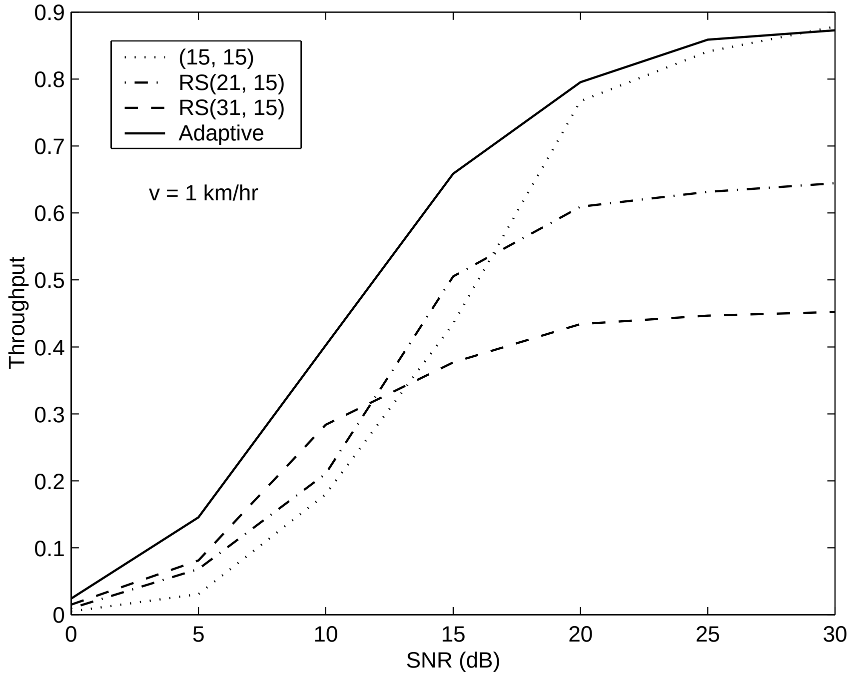

Figure 10. Throughput of the adaptive and nonadaptive ARQ schemes for mobile speed of 1 km/hr

improvement over nonadaptive schemes. Moreover, the results also confirm the applicability of the adaptive system parameters, so-obtained by analysis and optimization in stationary channel case, to the time-varying fading channel case.

7. Conclusion

In this paper, a simple and efficient stop-and-wait (SW) automatic repeat-request (ARQ) scheme with adaptive error control is investigated. In this scheme, the channel state information (CSI) is extracted by monitoring the contiguous positive acknowledgment (ACK) or negative acknowledgment (NAK) messages. Exploiting this CSI, we adapt the coding strategy to the changes in the channel condition, and thus improve the throughput efficiency.

In order to facilitate the throughput analysis and parameters optimization, we model the adaptive system by a Markov chain. Using this analytical model and assuming a static channel, an exact throughput expression for the adaptive ARQ protocol is derived and suboptimal adaptive system parameters are obtained. These design parameters are applied for the adaptive system in a typical time-varying mobile radio channel characterized by Rayleigh multipath fading on top of lognormal shadowing. The throughput performance of the proposed adaptive SW-ARQ scheme in such a time-varying fading channel is evaluated by computer simulation. For slow fading channels, the proposed adaptive system can track the channel variations very well, hence much throughput improvement is achieved over conventional nonadaptive SW-ARQ schemes for almost all SNR values considered. The simulation results also confirm the applicability of the adaptive system parameters so-obtained by the throughput analysis in static channel, to a time-varying mobile radio channel. It is noted that the analysis and optimization methods presented in this paper are applicable to a more general class of adaptive systems (e.g., modulation or packet length) which employ the proposed channel sensing algorithm for link adaptation. Similarly, the performance of an adaptive system with more than three operation modes can be evaluated using the methodology outlined in Section 3.

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