Performance of Dual-Branch Diversity Receiver based SR-ARQ in Rayleigh Fading Channel

Ghaida A. AL-Suhail[†], *Tharaka A. Lamahewa*[$\star$] *and Rodney A. Kennedy*[$\star$]

[†]Computer Engineering Dept., University of Basrah, Basrah, Iraq
and [$\star$]College of Engineering and Computer Science, The Australian National University, Canberra, Australia.
`ghaida_alsuhail@yahoo.com, {tharaka.lamahewa, rodney.kennedy}@anu.edu.au`

***Abstract*— Automatic repeat request (ARQ) schemes are quite effective for improving the throughput of system diversity in time-varying channel environments. In this paper, a dual-branch selection diversity receiver based selective repeat-ARQ scheme is investigated to evaluate the optimal throughput performance in terms of the average bit error rate in Rayleigh fading channels. Both uncorrelated and correlated antenna branches are considered. The numerical results shows the effect of optimal switching threshold on the throughput performance in case of switched diversity as well as the mobility effect of the selection combining diversity receiver when correlated antenna branches are present. A significant improvement in the system throughput of selection diversity outperforms that of switched diversity.**

I. INTRODUCTION

Automatic repeat request (ARQ) error control schemes achieve high reliability especially in the time-varying wireless systems when the data transmitted blocks are equipped with error detection strategies such as a cyclic redundancy check (CRC). ARQ protocols in general employ an error detection code and a feedback channel so that the receiver can request retransmission of the erroneous packets, or it can use the feedback channel to acknowledge the correctly received packets [1–3]. There are three basic ARQ protocols: stop-and-wait (SW), go-back-N (GBN), and selective-repeat (SR). Among all ARQ schemes, SR is reported to show the best throughput performance [4] and thus it is interesting to analyze and investigate its behavior in order to have an upper limit on the throughput performance that any ARQ protocol can achieve in practice.

If the ARQ scheme has to be used over a mobile radio channel, the time-varying multipath fading characteristics introduce a certain amount of correlation between different ARQ packet (re)transmissions; that is, channel errors cannot be assumed to be independent from packet to packet. Therefore, many recent researches [3–7] have dealt with such ARQ schemes in different approaches in order to increase and enhance the system throughput (quality of service) either by applying adaptive modulation format and coding (AMC) [8], and/or by varying the packet size [5], or by controlling, for example, the throughput efficiency over multipath block fading channels when having a perfect knowledge of the complex path gains [2].

On the other hand, diversity technique is a powerful tool that has long been used in wireless communication systems to mitigate fading effects [9]. The depth of the fades and/or the fade duration is reduced by supplying the receiver with multiple replicas of transmitted signal that have passed over independently fading channels [10, 11]. The simplest form of diversity combining is the selection diversity (SC). The conventional selection diversity scheme selects, among the L diversity branches, the branch providing the largest signal-to-noise ratio (SNR) (or largest fading amplitude). This system is so-called SNR-based SC and is considered feasible only for TDMA (Time Division Multiple Access) systems, but not for continuous transmission systems [12]. However, its performance is evaluated under the assumption of continuous branch selection. Thereby, many schemes [9, 11, 13, 14] have been proposed to provide significant power gains over existing selection diversity schemes in Rayleigh fading channels. [15], for example, has introduced that in very slow fading channels, the dual-branch switched diversity scheme at the transmitter also can improve the throughput efficiency of the ARQ protocol significantly. More specifically, the diversity benefit obtained from this scheme can reduce the delay in transmitting the data packet and this will be an attractive goal in many applications such as audio, image and real-time video streaming.

In this paper, we present the throughput performance of an SR-ARQ scheme associated with two types of receiver diversity over time-varying Rayleigh fading channels as follows: (i) a classical dual-branch selection receiver which is so-called non-switched diversity (NSD), and (ii) a dual-branch switched receiver antenna diversity; that is so-called switched-and-stay combiner (SSC). The SSC diversity is an attempt to simplify the complexity of selection diversity system rather than continually connecting the diversity path with the best quality. The receiver selects a particular diversity path until its quality drops below a predetermined threshold. When this happens, the receiver switches to another diversity path [16]. In both schemes, we have investigated the optimum throughput and the channel gain expected under different conditions. The simulation results introduces the effect of optimal switching threshold on the performance in case of switched diversity as well as the mobility effect of the selection combiner diversity receiver (SC-NSD scheme) when Rayleigh fading is considered in the antenna branches.

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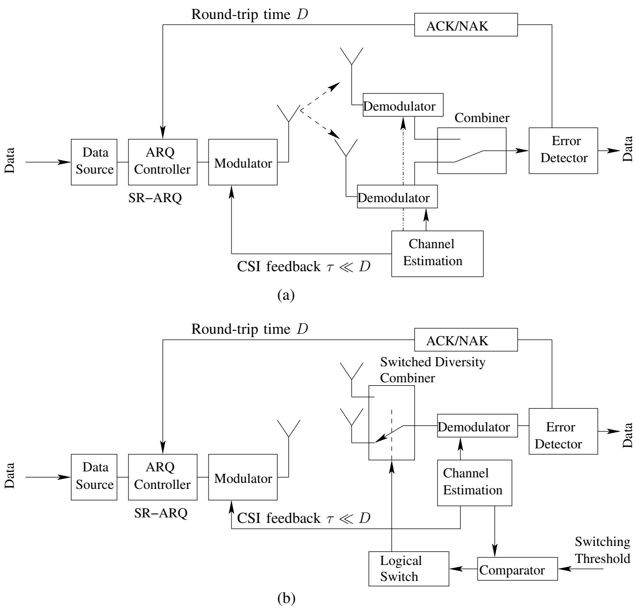
II. SYSTEM MODEL

Let us assume a wireless communication system consisting of one transmit antenna and two receiver antennas. We assume that perfect channel state information (CSI) is available at the receiver and the channel is time-varying and frequency flat fading. CSI and feedback antenna information are sent back to the transmitter by using an error free feedback CSI channel, with a CSI sensing delay $\tau < D$ (round-trip delay of ARQ feedback); whereas the sensing delay can be artificially reduced by using prediction filters [17]. In Fig. 1, we present an ARQ scheme associated with two types of dual-branch receiver diversity: (i) a classical selection combiner (SC-NSD), and (ii) a switch-and-stay combiner (SSC) [16]. For both receivers, an error free feedback channel is assumed over which positive (ACK) or negative (NACK) acknowledgements can be sent at the radio-data link layer. The ideal selective-repeat SR-ARQ strategy, assuming negligible round-trip delay, is considered. This ARQ scheme forms the basis of the SC based ARQ as follows.



(a)

(b)

Fig. 1. Block diagrams of the two dual selection diversity systems (a) SC-NSD-ARQ post-reception scheme, (b) SSC-ARQ pre-detection scheme.

A. *SC-NSD-ARQ Diversity Scheme*

We consider post-selection combining, i.e., two receivers using the usual basic SR ARQ scheme (Fig. 1(a)) complete with individual antennas receive identical transmission from a transmitter. Here, individual receivers are associated with each antenna. The decision process after the receivers (demodulators) considers a reception as correct using the usual cyclic redundancy check (CRC) bits, if it is correctly received over any of the diversity branches. A correct packet hence is chosen to the output.

B. *SSC-ARQ Diversity Scheme*

In this scheme, the receiver may has L antenna (Fig. 1b), only one of which is used at a time. Here, we will consider the case of $L = 2$ for all the space diversity reception systems. In the same way as in [15], if a packet is received incorrectly, it is concluded that the current path has encountered a deep fade, and the receiver needs to select the other branch of SSC receiver. Note that this scheme is equivalent when having L transmit antennas as where the difference is that the transmitter switches between the antennas after gathering information in the return CSI feedback channel. However, for both combiners described in Fig. 1, the wireless link implements the Selective Repeat (SR) protocol for retransmission of erroneous packets with perfect code detection and suitably large buffers at the transmitter and the receiver. Furthermore, the receiver selection here is done after reception of a block, in contrast to the SSC scheme, where the receiver with the highest SNR (or power level) is chosen before reception of a block (packet) as shown in Fig. 1(b). Nevertheless, the throughput of this SC-NSD scheme is always higher than that scheme of the basic SR-ARQ of only one transmitter-receiver pair. In general, if a packet of the basic SR-ARQ scheme is received incorrectly, it is discarded and a retransmission is requested.

III. ARQ PERFORMANCE ANALYSIS

A. *Throughput Efficiency*

A protocol performance is usually characterized by many important parameters which are defined by the communication system requirements. These parameters are the probability of receiving a packet without errors and the protocol throughput efficiency. There are several definitions of the protocol throughput efficiency. Most frequently it is defined as the ratio of the mean number of information bits successfully accepted by the receiver to the number of bits that could have been transmitted during the same time interval [4]. To derive an expression for the throughput efficiency of the ARQ protocol, the assumption of an "optimal" ARQ protocol can be assumed in that only packets containing errors are retransmitted. The throughput efficiency of ARQ scheme that uses packets having N bits is determined by [1]

$$\eta_s = \left(\frac{K}{N}\right)\frac{1}{\overline{R}}, \tag{1}$$

where the first term K/N represents the ratio of information bit to the total bits in a packet and $C = N - K$ is being the CRC bits, and consequently can express the channel code rate. $\overline{R}$ represents the average number of transmission attempts per packet. Assuming that the ARQ scheme retransmits a packet until the ACK of a successful reception, the average number of attempts $\overline{R}$ required to successfully transmit one packet is given by,

$$\overline{R} = (1-p) + 2p(1-p) + 3p^2(1-p) + \cdots = \frac{1}{1-p}, \tag{2}$$

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where p is the block or packet error rate (PER). Then, for a given p, the throughput efficiency of ARQ is given by,

$$\eta_s = \left(\frac{K}{N}\right)(1-p). \tag{3}$$

When a perfect retransmission algorithm is employed that can happen only when retransmit packets are in error and can continuously transmit new packets as long as no errors occur. Thus for a selective repeat (SR-ARQ) scheme, throughput is given by the well-known formula [4]

$$\eta_{SR} = \left(\frac{K}{N}\right)(1-p_b(\gamma_b))^N, \tag{4}$$

where N is the packet size in bits including the number of over-head bits (e.g., CRC); and $p_b(\gamma_b)$ is being the channel bit error rate (BER) as a function of the channel SNR per bit γ_b.

B. *Choosing Optimal Packet Size*

For a perfect retransmission algorithm, the optimal packet size to be used by the data-link layer can be expressed as an analytical solution by assuming K has continuous values. By differentiating (4) with respect to K and setting it to zero, the optimal K can be expressed as [18]

$$K^*(\gamma_b) = \frac{C}{2} + \frac{1}{2}\sqrt{C^2 - \frac{4C}{\ln(1-p_b(\gamma_b))}}, \tag{5}$$

where C denotes the CRC bit for error detection and ignoring the effects of control and framing bits at data-link layer. Using (5), it is noticed that a much smaller packet size is efficient under a much higher channel BER especially in real-time applications because a small packet has low packet error rate. On the contrary, a much larger packet size makes efficient use of the channel when the channel BER is much lower.

IV. THE CHANNEL PERFORMANCE

In practice, the signals in the diversity branches may not show completely independent fading. The envelope cross correlation ρ between these signals is a measure of their independence. Therefore,

$$\rho = \frac{E\left\{(r_1-\overline{r_1})(r_2-\overline{r_2})\right\}}{\sqrt{E\left\{|r_1-\overline{r_1}|^2\right\}E\left\{|r_2-\overline{r_2}|^2\right\}}}, \tag{6}$$

where r_1 and r_2 represent the instantaneous envelope levels for the normalized signals at the two receivers; and $\overline{r_1}$ and $\overline{r_2}$ are their respective means. More specifically, if a cross correlation (correlation coefficient ρ) of 0.7 between signal envelopes is available this will be sufficient to provide a reasonable degree of diversity gain [12]. Depending on the type of diversity employed, these diversity channels must be sufficiently *separated* along the appropriate diversity dimension. For spatial diversity, the antenna should be separated by more than the *coherence distance* to ensure a cross correlation of less than 0.7. Likewise in frequency diversity, the frequency separation must be larger than the *coherence bandwidth*, and in time diversity the separation between channel reuse in time should be longer than the *coherence time*. There coherence factors in turn depend on the channel characteristics. The coherence distance, coherence bandwidth, and **coherence time** vary inversely as the angle spread, delay spread, and **Doppler spread**, respectively.

The statistical properties of fading signals depend on the field component used by the antenna, the vehicular speed, and the carrier frequency. Specifically, for idealized case of a mobile surrounded by scatters in all directions, the covariance function, i.e., autocorrelation function of the received signal $x(t)$ (not the envelope $r(t)$), can be shown as

$$\rho = J_0(2\pi f_D T_s), \tag{7}$$

where $J(\cdot)$ is the Bessel function of the zero-th order first kind, T_s denotes the symbol time which is less than the coherence time T_c of fading period, i.e., correlation between two symbols over channel in case of slow fading, and the Doppler spread f_D of the signal represents a function of the mobile speed v and the carrier frequency $(1/\lambda)$. Note that the correlation properties of the fading process depend only[1] on $f_D T_s$. When $f_D T_s$ is small (e.g., $f_D T_s < 0.1$), the process is much correlated ("slow fading"); on the other hand, for large values of $f_D T_s$ (e.g., $f_D T_s > 0.1$), successive samples of the channel are almost independent ("fast fading"). For high data rates (i.e., small T_s), the fading process can typically be considered as slowly varying, at least for the usual values of the carrier frequency ($900 - 1800$ MHz) or (2 GHz) and for typical mobile speeds.

If the coherent BPSK modulation is used in particular in a dual SC-NSD-ARQ diversity scheme, the average bit error probability of correlated Rayleigh fading channel with the average SNR equal to $\overline{\gamma}$ can be expressed in closed form as [16, Eq. 9.268],

$$\begin{aligned} P_{b,SC} =& \frac{1}{1+\rho}\left[\frac{1+\rho}{2} - \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}} + \right. \\ & \left. \frac{1-\rho}{2}\sqrt{\frac{(1-\rho)\overline{\gamma}}{2+(1-\rho)\overline{\gamma}}}\right] \end{aligned} \tag{8}$$

where $\overline{\gamma}$ represents the average SNR of the first branch for equal average branch SNRs ($\overline{\gamma}_1 = \overline{\gamma}_2$), and ρ is the power correlation coefficient between the estimated and actual fading expressed in (7).

On the other hand, the average bit error rate of coherent BPSK over Rayleigh fading can also be expressed in a closed form in terms of the Gaussian Q-function in the case of a dual SSC-ARQ diversity scheme as follows [16, Eq. 9.306],

$$\begin{aligned} P_{b,SSC} =& \frac{1}{2}\left(1-\exp\left(-\frac{\gamma_T}{\gamma}\right)\right)\left(1-\sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}\right) \\ & + \exp\left(-\frac{\gamma_T}{\gamma}\right)Q\left(\sqrt{2\gamma_T}\right) \\ & - \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}Q\left(\sqrt{2\gamma_T\frac{(1+\overline{\gamma})}{\overline{\gamma}}}\right), \end{aligned} \tag{9}$$

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[1] Ignoring the effect of spatial correlation due to antenna spacing.

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where γ_T denotes the SNR switching threshold which leads to derive the optimal threshold value to minimize the average error rate of (9). Since the average BER is a continuous function of γ_T, there exists an optimal value of γ_T for which the average BER is minimal. This optimal value γ_T^* is a solution of the equation,

$$\left.\frac{dP_{b,SSC}}{d\gamma_T}\right|_{\gamma_T=\gamma_T^*}=0 \tag{10}$$

hence, we can express the optimum threshold for BPSK over Rayleigh fading as [16]

$$\gamma_T^* =\frac{1}{2}\left[Q^{-1}\left(\frac{1}{2}\left(1-\sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}\right)\right)\right]^2. \tag{11}$$

The closed-form expression of (11) will allow us to compute only the optimum switching threshold γ_T^* (in the minimum error rate sense) for identical fading statistics.

In non-fading or slowly fading channels where the fade duration is longer than the packet period, the system output and its optimization can also be achieved. In this case, the packet error in burst-error condition cannot easily be modeled by a single equation. The reason is that the distribution of error-bits is not uniform. To simplify the estimation of BER performance, a BPSK scheme over AWGN channel can be applied for upload/download transmission [13]. In this case, the bit error probability in an AWGN channel with the SNR equal to E_b/N_0 is given by [10]

$$P_b =Q\left(\sqrt{2R_c\frac{E_b}{N_0}}\right), \tag{12}$$

where R_c denotes the channel code rate, (K/N).

Nevertheless, according to the proposed system models in Fig. 1, since bit error is random in an AWGN channel, the packet loss (error) is also random. Thus the SSC scheme does not provide a significant improvement over the simple basic SR-ARQ scheme in AWGN channels. In contrary, the throughput performance will be affected by the features of Rayheigh fading channels, and this can be explained in details through the numerical results. However, the switching threshold γ_T^* (in the minimum error rate sense) for identical fading statistics will then has a significant impact on the overall throughput performance. In the SC-NSD-ARQ post-reception scheme, the probability of successfully receiving a packet is that of a successful reception over either of the diversity branches, and this can be expressed as by

$$P_1 =1-(1-(1-P_{b,SC})^N)^2, \tag{13}$$

$P_{b,SC}$ is defined in (8), and consequently the effective throughput can be computed as,

$$\eta_{SC-NSD}=\left(\frac{N-C}{N}\right)P_1. \tag{14}$$

V. NUMERICAL RESULTS

A. System Settings

The channel model used in the simulations of the throughput performance is a flat Rayleigh fading channel. As a reference, we conducted the numerical results using a typical set of parameters as: the width of the Doppler spectrum, which is determined by the carrier frequency 2GHz and the vehicular speed v, the number of the CRC parity bits is 16 at the data-link layer, and the (raw) or reference bit rate at the physical layer is 9.6kbit/s-57.6 kbit/s as in $(3-35$km) GSM GPRS standards. We set the maximum packet size K_{max} to be no greater than 1080 bits, and packet error is assumed independent for the BPSK coherent demodulation scheme.

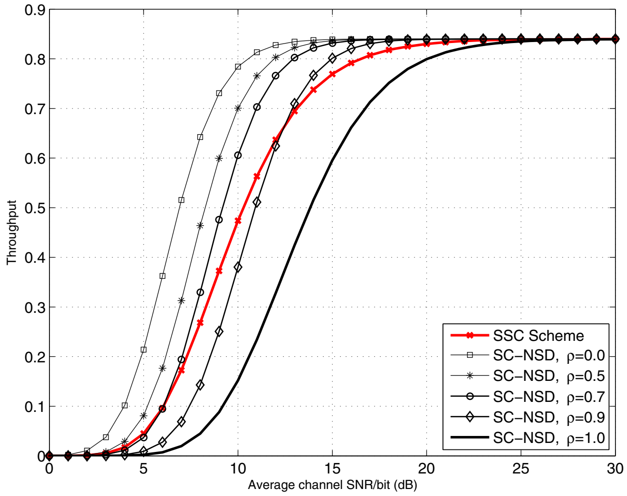

Fig. 2. Throughput performance vs. average channel SNR/bit over Rayleigh fading channel for various values of correlation coefficient ρ. Assume $N = 100$ bits and $K = 84$ bits.

B. Performance Evaluation

In this study, throughput is the basic performance measure used in the two diversity schemes described in Section II. The results are obtained using Matlab programming to verify the system performance. We first consider a fixed small packet size of 100 bits including 16 CRC bits. Fig. 2 explains the throughput versus the average channel SNR in (dB) for both schemes. It is clearly noticed that SC-NSD scheme of the various values of power correlation coefficient factor ρ (fading conditions) and with equal average branch SNRs $(\overline{\gamma}_1=\overline{\gamma}_2)$, outperforms the SSC scheme of optimal switching SNR threshold, in particular for values of $\rho \leq 0.5$. Meanwhile, the power correlation coefficient will effectively degrade the system efficiency as far as this coefficient tends to be close to 1. For example, when $\rho = 0.7$ the SC-NSD performance will be more efficient than that of SSC scheme, and channel gain can be attained but only for the values of SNR greater than 7dB. However, values of $\rho > 0.7$ will also reveal a considerable deterioration in the performance especially in case of $\rho = 0.9$ or $\rho = 1.0$. That means, in general, higher

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values of ρ, i.e., lower values of $f_D T_s$ and lower diversity gain [16, pg. 415], introduce a limited gain improvement in the expected SNR channel performance as compared to lower values of ρ. Thus, a higher throughput performance can be clearly achieved in case of correlated or uncorrelated channel but when ρ is being small or close to zero especially in the low values of SNRs.

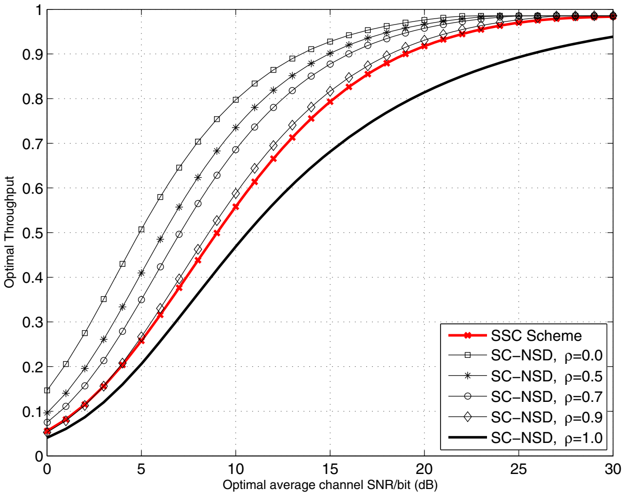

Fig. 3. Optimal system performance over Rayleigh fading channel for various values of correlation coefficient ρ. Assume $K_{max} = 1080$ bits and 16 CRC bits.

To provide highest performance, the optimal throughput versus the corresponding optimal average SNR is illustrated in Fig. 3. Achieving $K^*(\gamma_b)$ in (5) and setting the upper bound of packet length to 1080 bits in the region of higher values of SNRs, the optimal performance in terms of the corresponding bit error rate can be simply evaluated. It is found that there exists a significant channel gain which leads to the maximum upper throughput in case of SSC and SC-NSD in particular when correlation factor of the later scheme tends to be 0.9 or less. The SC-NSD outcomes nearly $10\% - 20\%$ channel gain for the higher values of SNR (greater than 10 dB).

Moreover, it is found that there is a clear attainable gain in the performance for the both schemes to the corresponding optimal packet length at low values of SNR operating range. For example, throughput achieves 50% at channel SNR of 5 dB when uncorrelated channels are considered in case of SC-NSD; and in contrary a high value of ρ will lead to degrade the throughput to be no more than 20% in case of $\rho = 1$ and comparing to throughput of 25% when using SSC scheme over flat fading channel.

In Fig.4 the impact of the client mobility at the diversity receiver of the SC-NSD scheme for various values of average SNR values is also investigated. It is found that the speed of the mobile (1km/h-180km/h) will affect the performance of SC scheme when the correlation coefficient achieves a value equal or nearly close to 1 where $f_D T_s$ tends to be small enough less than 0.1, i.e., "slow fading" (Fig. 5). That refers to the fact which states low values of f_D corresponds to highly correlated channels; and high values of f_D corresponds to a less correlated channel "fast fading", in which significant variations of the fading coefficients over short time periods occur [4]. As a result, the expected optimal throughput gradually increases through the diversity gain obtained when $f_D T_s$ increases slightly that is provided a perfect CSI is available at the receiver. In addition, the optimal channel gain will consequently achieve highest upper bound once the high SNR are present at the dual-branch antenna receiver. Finally, we can conclude that high values of SNRs will guarantee a higher throughput performance once a mobile speed arises but not beyond 200km/h in practice at normalized Doppler shift not

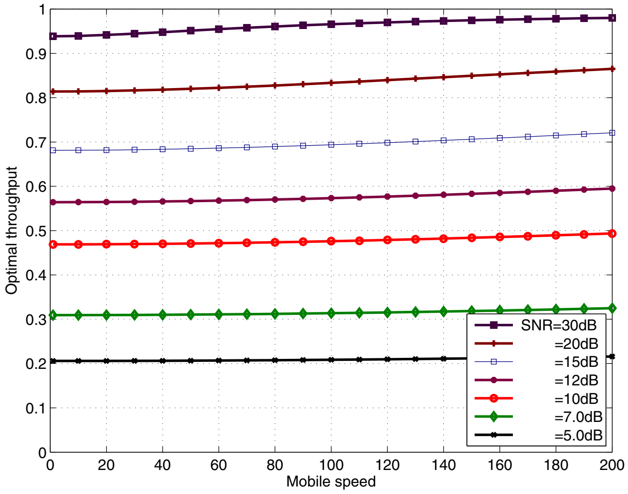

Fig. 4. Optimal throughput of SC-NSD scheme vs. mobile speed over Rayleigh fading channel for various values of average SNR per receiver antenna. Assume $K_{max} = 1080$ bits and 16 CRC bits.

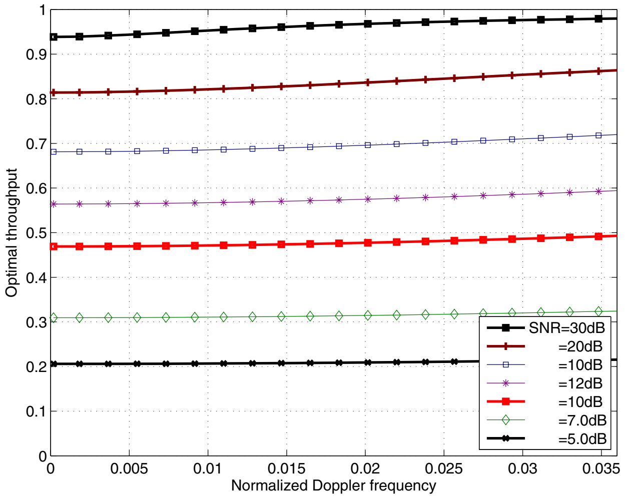

Fig. 5. Optimal throughput of SC-NSD scheme vs. normalized Doppler spread over Rayleigh fading channel for various values of average SNR per receiver antenna. Assume $K_{max} = 1080$ bits and 16 CRC bits.

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greater than 0.035 (f_D must not exceed 370Hz), in Fig. 5.

VI. CONCLUSION

In this paper, we have dealt with two dual-branch selection diversity receivers; SSC and SC-NSD schemes based selective repeat-ARQ over the time-varying channels. The optimal throughput performance in both uncorrelated and correlated antenna branches has been evaluated. A significant improvement (channel gain) in the system throughput of SC-ARQ-NSD outperforms that of SSC scheme. The simulation results introduces the effect of optimal switching threshold on the performance in case of switched diversity as well as the mobility effect of the selection diversity receiver when Rayleigh fading is considered in the antenna branches. Further work can also be extended to involve channel-adaptation techniques in order to provide more improvement in the throughput performance of the dual-branch diversity receivers.

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