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Performance Analysis and Comparison of HARQ Protocols Based on Outage Probability in Wireless Communication Networks

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Abstract

Hybrid Automatic Retransmission reQuest (HARQ) protocol can effectively compensate the signal transmission error caused by complex time-varying channels and multi-path effects of wireless communication networks. This paper analyzes and compares the principle and system performance of three HARQ protocols from the perspective of system outage probability, and the expressions of system throughput and energy efficiency are derived by establishing a one-dimensional Discrete Time Markov Chain (DTMC) and calculating the steady-state distribution. MATLAB numerical simulations are applied to evaluate and compare the performance superiority among three HARQ Protocols.

Keywords: HARQ; Outage probability; DTMC; Throughput; Energy efficiency

1. Introduction

Various factors such as noise interference, multi-path effects, shadow effects and complex time-varying channels cause the instability of wireless communication, inducing the phenomenon of communication interrupt when the channel is in a deep fading state, which seriously affects the system performance and Quality of Service (QoS) of the

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network. Therefore, effective and reliable error control technology is one of the important means to improve system performance. In the wireless communication network, two of the most popular error control technologies are Automatic Retransmission reQuest (ARQ) protocol and Forward Error Correction (FEC), the former aims at recovering error data frames through performing the feedback responses and data retransmissions between the sender and receiver, and the latter is mainly focused on comparing the redundancy code between the two ends to detect the accuracy of received data. Much works demonstrated their superiority in error control[1]. However, ARQ protocol and FEC technology show their respective limitations when the wireless channel is under long-term deep fading[2]. At this point, Hybrid ARQ (HARQ) protocol, which combines these two technologies, emerges in order to improve the bad effect of high Frame Error Rate (FER) on the system performance. It can provide both higher decoding reliability than the single FEC and higher throughput than the single ARQ.

As a hybrid error control scheme, HARQ protocol is studied extensively[3,4,5]. [3] discussed the average number of retransmission and system throughput performance of HARQ-Type I and HARQ with Chase Combining (HARQ-CC) protocols using Distributed Space-Time Codings(DSTCs), a closed expression of throughput was derived in [4] by analyzing the packet loss probability of HARQ protocols on a Rayleigh block fading channel, and [5] investigated the throughput of a HARQ scheme based on a DTMC model, but the assumption of infinite retransmission times will result in unacceptable delay for the system. It is obvious that most works mainly focused on the analysis and evaluation of the throughput performance in HARQ protocols, which is not sufficient in some communication scenarios, such as the time delay in real-time interactive communication networks or the energy efficiency in energy-limited communication networks. The impact of HARQ protocols on throughput and energy efficiency was studied in [6] from the perspective of cross-layer analysis, which indicated that HARQ protocols can achieve better performance improvement by reducing the number of competing nodes. [7] studied the system performance of HARQ with Incremental Redundancy (HARQ-IR) protocol in Wireless Sensor Networks(WSNs) by establishing an energy efficiency analysis model, and the Monte Carlo simulation was adopted to prove its effectiveness and superiority. But none of above works has ever analyzed and compared all three kinds of HARQ protocols, i.e. HARQ-Type I, HARQ-CC and HARQ-IR, in terms of both throughput and energy efficiency.

On the other hand, most of the above works only discussed the system performance under the infinite retransmission times, and did not consider the truth of the limited number of retransmission in reality. Although [8] proposed improvement in analyzing the system throughput efficiency under limited retransmission times based on Packet Error Rate(PER), it just restricted the retransmission number only once, which lacks generality.

Therefore, this paper analyzes and compares the throughput and energy efficiency of the three kinds of HARQ protocols from the perspective of system outage probability. firstly, the outage probability expressions of them are analyzed and calculated, respectively. Secondly, the system throughput and energy efficiency performance with arbitrary maximum number of retransmission are derived by establishing a one-dimensional DTMC model and solving its steady-state distribution. Finally, the performance evaluation and comparison are executed through MATLAB numerical simulation.

The rest of the paper is organized as follows: the system description and outage probability analysis of HARQ protocols are introduced in Section 2. The establishment of a one-dimensional DTMC model and the derivation of its steady-state distribution are discussed in Section 3. The section 4 is the computation and evaluation of system performance. Simulations are performed in section 5. Finally, the conclusions follow in Section 6.

2. System model and outage probability analysis

2.1. System model

This paper assumes that both the sender S and the destination D in the network are equipped with a single antenna and cannot send and receive at the same time. The perfect channel state information (CSI) and ideal feedback channels are also assumed in this paper. The channel model in this paper is quasi static Rayleigh fading channel and the noise is Additive White Gaussian Noise. The Signal Noise Ratio (SNR) between S and D can be expressed:

$$\gamma_{SD} = \frac{P_t |h_{SD}|^2}{N_0}$$

where P_t is the transmitting power of S, h_{SD} is the channel gain coefficient and N_0 is the variance of the noise. $E\left(|h_{SD}|^2\right) = \lambda_{SD} \propto d_{SD}^{-n}$, d_{SD} is the distance between S-D link and n is the path loss factor.

Outage probability analysis

The outage behaviors of three kinds of HARQ protocols are discussed in this section. We set $B = 1$, so the channel capacity of the S-D link in the *l*-th ARQ round is:

$$C_l = B\log_2\left(1+\gamma_{SD}\right) = \log_2\left(1+SNR|h_{SD}|^2\right) \tag{1}$$

where $SNR = P_t / N_0$. According to Shannon's information theory, the outage event occurs when the channel capacity is less than the signal transmission rate (bits/slot/Hz). Then, the outage probability of the S-D link in the *l*-th ARQ round is:

$$\Pr\left(SD_{out,l}\right) = \Pr\left\{C_l < r\right\} = \Pr\left\{\log_2\left(1+SNR|h_{SD}|^2\right) < r\right\}$$

and $\Pr\left(SD_{out.l}^{\text{joint}}\right)$ denotes the joint outage probability of the S-D link after *l* rounds, it can be expressed as:

$$\begin{aligned}\Pr\left(SD_{out,l}^{\text{joint}}\right) &= \Pr\left\{C_1 < r\right\} \times \Pr\left\{C_2 < r \mid C_1 < r\right\} \times \cdots \times \Pr\left\{C_l < r \mid C_{l-1} < r\right\} \\ &= \Pr\left\{C_1 < r, \cdots, C_l < r\right\}\end{aligned}$$

2.2. HARQ-Type I

HARQ-Type I is a kind of simple combination of ARQ and FEC. For simplicity, we denote SN and RN represent the data frame sending (receiving) serial number at S (D), respectively. IN is the serial number of incremental redundancy frames transmitted by S. The rules are: S sends a new frame with $SN = i$, if D can receive and decode this frame correctly, the ACK frame containing $RN = i+1$ is fed back to S, indicating that the transmission is successful, and S will transmit the next new frame with $SN = i+1$ at the next time slot, otherwise D will directly discard this frame that is received but not decoded correctly at D and the NACK with $RN = i$ is sent, requesting S to retransmit data frame $SN = i$. D will discard the frame whose serial number is $SN = i$ if it can not decode the frame correctly until the maximum number of retransmission L is reached. The flow chart is shown in Fig. 1(a) and the channel capacity is equation (1), then the joint outage probability of S-D link is:

$$\Pr\left(SD_{out,l}^{\text{joint}}\right) = \Pr^l\left\{\log_2\left(1+SNR|h_{SD}|^2\right) < r\right\} = \Pr^l\left\{|h_{SD}|^2 < \frac{2^r - 1}{SNR}\right\} \tag{2}$$

2.3. *HARQ*-CC

Different from Type I, D in HARQ-CC will buffer these data frames that cannot be decoded correctly, and decode them by combining with the data frame received later. Each data frame retransmitted by S is exactly same with the original frame. The flow chart is Fig. 1(b) and the channel capacity of HARQ-CC is:

$$C_l = \log_2\left(1 + l \cdot SNR\left|h_{SD}\right|^2\right) \tag{3}$$

for $C_1 \leq \cdots \leq C_{l-1} \leq C_l$, the joint outage probability of S-D link is:

$$\Pr\left(SD_{out,l}^{\text{joint}}\right) = \Pr\left\{\log_2\left(1 + l \cdot SNR\left|h_{SD}\right|^2\right) < r\right\} = \Pr\left\{\left|h_{SD}\right|^2 < \frac{2^r - 1}{l \cdot SNR}\right\} \tag{4}$$

2.4. HARQ-*IR*

Different from CC, a data frame with incremental redundancy information is transmitted by S when the data frame is not received correctly by D. At D, the data frame and the incremental redundancy frame are jointly decoded to improve system performance. The flow chart is Fig. 1(c) and the channel capacity of HARQ-IR is:

$$C_l = l \cdot \log_2\left(1 + SNR\left|h_{SD}\right|^2\right) \tag{5}$$

then the joint outage probability of S-D link is:

$$\Pr\left(SD_{out,l}^{\text{joint}}\right) = \Pr\left\{l \cdot \log_2\left(1 + SNR\left|h_{SD}\right|^2\right) < r\right\} = \Pr\left\{\left|h_{SD}\right|^2 < \frac{2^{\frac{r}{l}} - 1}{SNR}\right\} \tag{6}$$

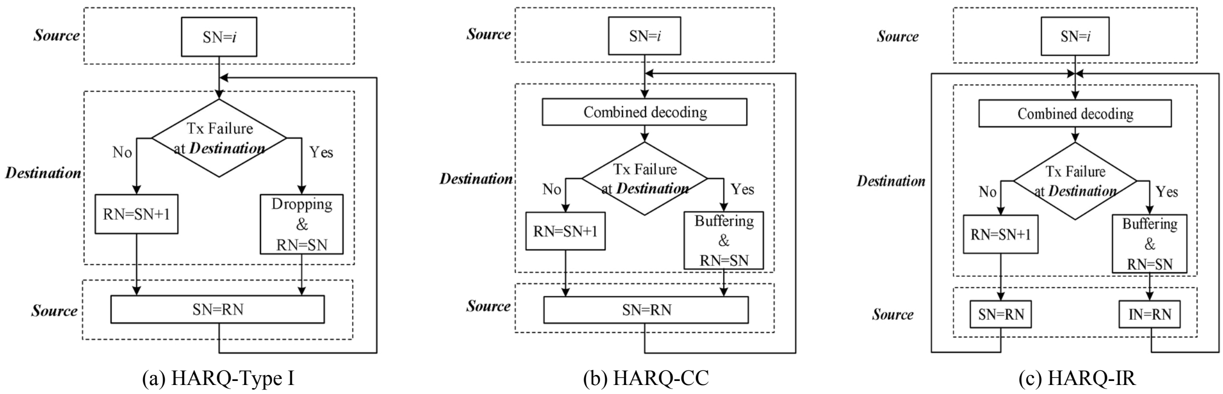

Fig. 1. The transmission flow chart of HARQ protocols.

3. Establishment and Analysis of System Model

This section analyzes and establishes a one-dimensional DTMC to describe HARQ protocols at any maximum number of retransmission L. State E_i represents that D fails to decode the data frame in the *i*-th ARQ round, state S represents that D decodes the received data frame without error and state F represents that D cannot decode the data frame successfully until L is reached. The state transition diagram is Fig.2 and there are totally $L+1$ states.

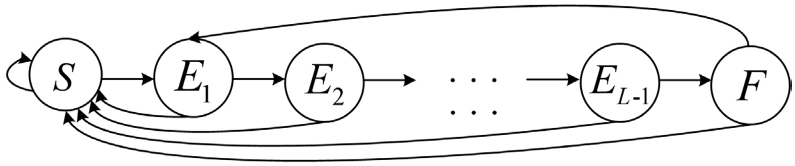

Fig. 2. The DTMC model.

from Fig.2, the one-step transition probabilities easily yield as: $\Pr_{E_i S} = 1 - \Pr\left(SD_{out,i+1} \mid SD_{out,i}^{joint}\right), 1 \le i \le L-1$, $\Pr_{SS} = \Pr_{FS} = 1 - \Pr\left(SD_{out,1}\right)$, $\Pr_{SE_1} = \Pr_{FE_1} = \Pr\left(SD_{out,1}\right)$, $\Pr_{E_i E_{i+1}} = \Pr\left(SD_{out,i+1} \mid SD_{out,i}^{joint}\right), 1 \le i \le L-1$, $\Pr_{E_{L-1}F} = \Pr\left(SD_{out,L} \mid SD_{out,L-1}^{joint}\right)$, other state transition probabilities are 0 and the steady-state distribution is $\vec{\pi} = \{\pi_S, \pi_1, \pi_2, \cdots, \pi_F\}$, which can be obtained by the equilibrium equation $\vec{\pi} P = \vec{\pi}$ and $\sum \vec{\pi} = 1$, P is the transition probability matrix of the DTMC.

4. System performance analysis

The throughput in this paper is defined as the average number of data frames decoded successfully by the D in one time slot, which can be calculated as the average number of time slot that the DTMC spends in state S, i.e., the steady state distribution π_S. When $L=2$ and $L=3$, the throughput is as follows:

$$\pi_S = \left(1 - \Pr_{SE_1} \Pr_{E_1 F}\right) \Big/ \left(2 - \Pr_{SS}\right), \quad L=2$$

$$\pi_S = \left(1 - \Pr_{SE_1} \Pr_{E_1 E_2} \Pr_{E_2 F}\right) \Big/ \left(1 + \Pr_{SE_1} + \Pr_{SE_1} \Pr_{E_1 E_2}\right), \quad L=3$$

The energy consumption considered in this paper is mainly the power consumption of amplifiers P_A and circuit blocks P_C. $P_A = (1+\beta) P_t$, where β is a parameter relating to network parameters such as modulation schemes, etc. $P_C = P_{ct} + P_{cr}$, where P_{ct} and P_{cr} are the power consumption of circuit blocks relating to sending end and receiving end, respectively. The total power consumption of each transmission is:

$$P = P_A + P_{ct} + P_{cr}$$

and the average power consumption for one data frame is:

$$\overline{P} = \sum_{i=1}^{L} \Pr(i) \cdot \mathrm{P}(i) \tag{7}$$

where $\Pr(i)$ is the probability that the HARQ process for one data frame is completed in the *i*-th ARQ round and $P(i)$ is its corresponding power consumption value.

$$\Pr(i)=\begin{cases}1-\Pr\left(SD_{out,1}\right), & i=1\\ \Pr\left(SD_{out,i-1}^{\text{joint}}\right)\left[1-\Pr\left(SD_{out,i}\,|\,SD_{out,i-1}^{\text{joint}}\right)\right], & 2\le i\le L-1\\ \Pr\left(SD_{out,L-1}^{\text{joint}}\right), & i=L\end{cases} \tag{8}$$

and

$$P(i)=i\left(P_A+P_{ct}+P_{cr}\right),\qquad 1\le i\le L \tag{9}$$

Finally, the energy efficiency is defined as the average number of data frames transmitted correctly per energy consumption, which can be expressed as:

$$\eta=\frac{1-FER}{\bar{E}}=\frac{R\cdot(1-FER)}{\bar{P}} \tag{10}$$

where FER is the frame error rate and $FER=\Pr\left(SD_{out,L}^{\text{joint}}\right)$. $R=\frac{R_b}{m}$, where R_b is the bit rate, m is the frame length in bits.

5. System performance simulation and evaluation

The numerical simulation and performance evaluation of throughput and energy efficiency in HARQ protocols under $L=2$ and $L=3$ are performed in this section. We consider that d_{SD} varies from 100 to 1000m and $N_0=10^{-13.5}W$, $n=4$, $\beta=0.3$, $P_t=10^{-3}W$, $P_{ct}=10^{-4}W$ and $P_{cr}=5\times10^{-5}W$.

Fig.3 and 4 depict the system performance versus d_{SD}, respectively. From the figures, we can see that as the quality of the channel deteriorates, i.e., the increase of d_{SD} or L, both performances of three HARQ protocols show a decreasing tendency. Secondly, the system performance of Type I, whether throughput or energy efficiency, will gradually be worse than that of the other two, while IR performs better than CC. It is mainly because that the different redundant versions of frames is sent in IR, which can effectively improve the decoding accuracy at the receiver under poor channel conditions, proving that HARQ-IR protocol is the most effective mechanism against severe channel conditions among the three methods.

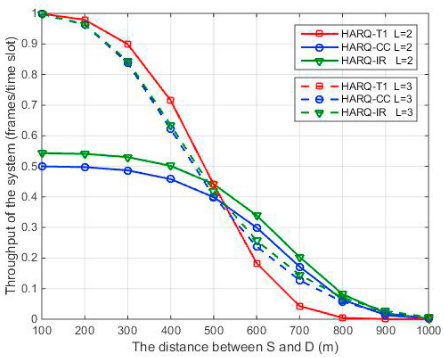

Fig. 3. Throughput of HARQ protocols.

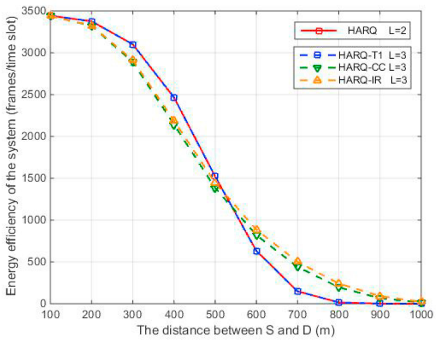

Fig. 4. Energy efficiency of HARQ protocols.

6. Conclusions

This paper makes theoretical analysis and performance evaluation of three HARQ retransmission mechanisms in wireless communication networks. It can be seen from the results that the retransmission mechanism of Type I has better performance under good channel conditions but CC and IR are more recommended to be used when the channel conditions are not very good, and the HARQ-IR protocol is the most effective one among them.

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