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Cross-layer design of LT codes and LDPC codes for satellite multimedia broadcast/multicast services

Wang Zhenbang, Wang Zhenyong *, Gu Xuemai, Guo Qing

School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150001, China

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Abstract According to large coverage of satellites, there are various channel states in a satellite broadcasting network. In order to introduce an efficient rateless transmission method to satellite multimedia broadcasting/multicast services with finite-length packets, a cross-layer packet transmission method is proposed with Luby transform (LT) codes for efficiency in the network layer and low density parity check (LDPC) codes for reliability in the physical layer jointly. The codewords generated from an LT encoder are divided into finite-length packets, which are encoded by an LDPC encoder subsequently. Based on noise and fading effects of satellite channels, the LT packets received from an LDPC decoder either have no error or are marked as erased, which can be modeled as a binary erasure channels (BECs). By theoretical analysis on LT parameters and LDPC parameters, the relationships between LDPC code rates in the physical layer and LT codes word lengths in the network layer are investigated. With tradeoffs between the LT codes word lengths and the LDPC code rates, optimized cross-layer solutions are achieved with a binary search algorithm. Verified by simulations, the proposed solution for cross-layer parameters design can provide the best transmission mode according to satellite states, so as to improve throughput performance for satellite multimedia transmission.

1. Introduction

As an important part of next-generation Internet, satellite networks are expected to provide multimedia data transmission and high-speed Internet access services. Fountain codes are attractive for satellite multimedia broadcast and multicast services.[1–3] Fountain codes can produce limitless encoded packets for a decoder to recover source data until an acknowledgement is received from a receiver. Designed for binary erasure channels (BECs) with fixed and known erasure rates, Luby transform (LT) codes[4,5] and Raptor codes[6–8] are the two most widely used fountain codes. Raptor codes have been standardized as a forward error correction (FEC) solution to support file downloading services of multimedia broadcast/multicast services (MBMS) of third-generation partnership program (3GPP).[9–12]

For satellite MBMS transmission, channel coding is required to provide protection against fading and noise. Turbo codes in the physical layer and Raptor codes in the application

* Corresponding author. Tel.: +86 451 86413513x8123.
E-mail addresses: zhenbangw@gmail.com (Z. Wang), ZYWang@hit.edu.cn (Z. Wang).
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layer are included in MBMS.[13–15] In order to analyze multi-layer packet transmission theoretically, an analysis framework is proposed for coding and throughput optimization based on information theory,[16] where a fixed erasure probability in the physical layer is assumed. Without addressing the connection between the physical layer and the network layer, a multi-layered communication system is studied based on information theory for lossy packet networks in Ref.[17]. In Refs.[18,19], the decoding failure probability of LT codes in the network layer caused by the lack of degree-one packets is emphasized without consideration of quality of service (QoS) issues. For requirements of reliability and efficiency of MBMS, FEC coding in the network layer and the physical layer needs to be designed jointly according to time-varying satellite channels.

With various decoding failure probability, the number of encoded LT packets required to complete LT decoding is different. With header information and cyclic redundancy check (CRC), each LT packet constitutes a finite-length packet as the input of an LDPC encoder. In the physical layer, an LDPC encoder with different code rates R_c can generate various lengths of codewords. Obviously, LDPC codes with a lower code rate can provide more reliable transmission, but cause a lower system throughput. By considering both the decoding failure probability δ of LT codes in the network layer and the LDPC code rate R_c in the physical layer, cross-layer optimization needs to be investigated for trade-off between throughput and transmission reliability.

In this paper, a cross-layer packet transmission scheme is proposed with a combination of LT codes in the network layer and LDPC codes in the physical layer. Firstly, finite codeword length constraints in the network layer and the physical layer are studied for throughput optimization. Secondly, optimal parameters for LT codes and LDPC codes are investigated jointly. Finally, the relationships among these parameters are discussed to propose cross-layer optimization to achieve the best overall system throughput performance.

The rest of the paper is organized as follows. Section 2 presents the system model of cross-layer satellite multimedia broadcasting. In Section 3, the cross-layer scheme is proposed with joint design of LT codes in the network layer and LDPC codes in the physical layer for throughput optimization. Simulation and result analysis are discussed with throughput performances in Section 4. Section 5 presents conclusions and future works.

2. System model

The cross-layer satellite multimedia broadcasting is modeled as a single transmitter attempting to deliver a message to single or multiple users. The message symbols are divided into data frames. The packet and frame structures are depicted in Fig. 1.

Each data frame contains total K source symbols $S = \{s_1, s_2, \ldots, s_K\}$, which are encoded by an LT encoder to generate a packet with L_c encoded symbols. A packet header information (P_h symbols) and CRC (P_{CRC} symbols) are added to each of these L_c encoded symbols to form a packet of length L_s, and $L_s = L_c + P_h + P_{CRC}$. Then, each packet is encoded by an LDPC encoder with a code rate R_c, so that a linear block codeword C of length N_t is obtained, where $N_t = L_s/R_c$. After that, the codeword C is modulated for transmission over satellite channels.

The system diagram is illustrated in Fig. 2. For each frame, the transmitter keeps sending packets until either the acknowledgements from all the intended receivers are received or the allowed maximum number of packets is reached. Then, the transmitter starts to send the next frame. For receivers, the LDPC codewords are decoded firstly. If a received codeword over $GF(2)$ does not meet the requirements of LDPC decoding, it is assumed to be invalid and dropped as an erasure. Furthermore, CRC is introduced to successfully decoded LDPC packets for undetected errors. If CRC fails, the entire packet would be dropped. Then, the correctly decoded packet is delivered to the LT decoder to retrieve the original source symbols. Once the receiver decodes the frame successfully, an acknowledgement is sent back to the transmitter.

In this paper, satellite multimedia broadcasting is modeled with some assumptions as below. Firstly, the satellite channel is a block fading model. The fading coefficient h in one packet remains constant and varies independently between successive packets. Secondly, all the satellite channels are spatially independent with no interference. Thirdly, CRC error detection is perfect to make sure that there are no undetected errors. Finally, as the introduced redundancy is negligible compared with the number of payload symbols, the header information

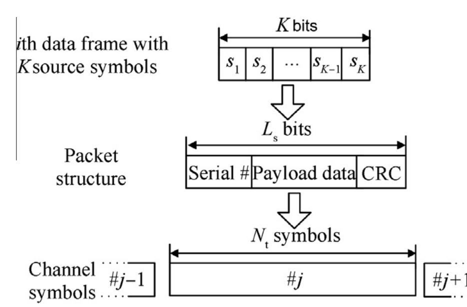


Fig. 1 Structure of packet and frame.

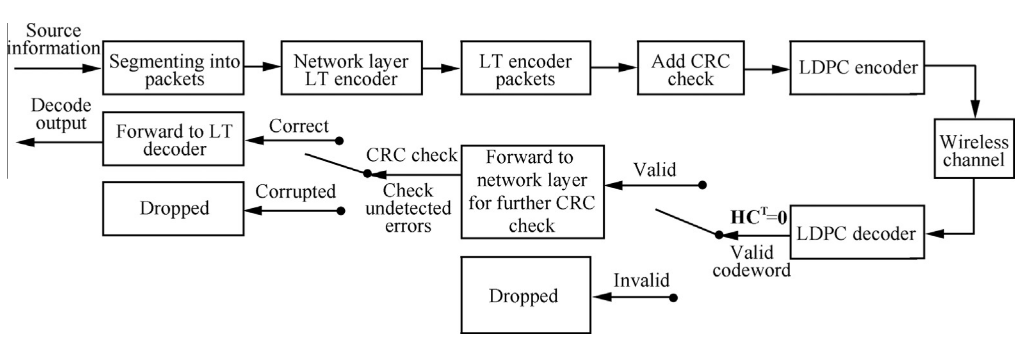


Fig. 2 System model of cross-layer transmission.

and CRC parity symbols in each packet are not included in the throughput calculation.

The system throughput is defined in term of the average number of message symbols transmitted per channel symbol. Therefore, the system throughput can be calculated as

$$T_{\mathrm{s}} = \frac{K}{N_{\mathrm{t}}} \times R_{\mathrm{LDPC}} \times R_{\mathrm{LT}} \tag{1}$$

where R_{LDPC} is the ratio of the correctly decoded packets by the LDPC decoder and R_{LT} is the ratio of the successfully recovered messages from the LT decoder. It is attractive to investigate key parameters in the network layer and the physical layer, which influence the system throughput dramatically.

2.1. LT codes design in the network layer

For the network layer, the robust Soliton degree (RSD) distribution is introduced in LT codes design. Hence, the number of source symbols involved in generating a coded symbol is determined by a predetermined check node degree d from RSD, where the degree distribution can be expressed as

$$d(x) = \sum_{j=1}^{d_{\max}} \rho_j x^j \tag{2}$$

where $d_{\max}$ is the maximum degree obtained from the RSD distribution and ρ_j denotes the fraction of check nodes.

$$\sum_{j=1}^{d_{\max}} \rho_j = 1 \quad \rho_j \in (0, 1) \tag{3}$$

As d source symbols are uniformly chosen from $s_1, s_2, \ldots, s_K$ (as shown in Fig. 1) to form an encoded symbol of an LT encoded codeword, the variable node degrees $s(x)$ follow a Poisson distribution:

$$s(x) \approx \sum_{i=1}^{s_{\max}} s_i x^i \tag{4}$$

where $s_{\max}$ is the maximum variable node degree and s_i is the fraction of variable nodes of degree i, which is given by

$$s_i = \frac{\mathrm{e}^{-\lambda}}{i!} \tag{5}$$

To ensure the decoding can run to completion, with a probability of at least $1-\delta$, the number of encoded packets L_{c} has to be $L_{\mathrm{c}} = K \times Z$, where $Z = \sum_d \rho(d) + \tau(d)$. $\rho(d)$ and $\tau(d)$ are given by

$$\begin{cases} \rho(1) = 1/K \\ \rho(d) = 1/d(d-1) \quad d = 2, 3, \cdots K \end{cases} \tag{6}$$

$$\tau(d) = \begin{cases} (S/K) \times (1/d) & d = 1, 2, \cdots, K/S \\ (S/K) \times \ln(S/\delta) & d = K/S \\ 0 & d > K/S \end{cases} \tag{7}$$

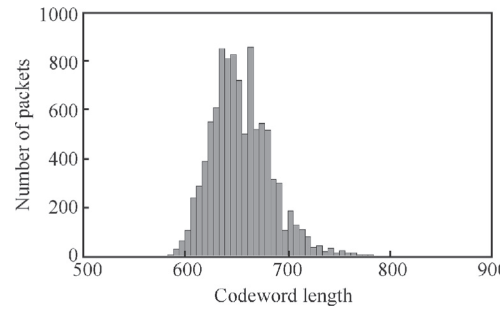
$$S \equiv c\sqrt{K}\ln(K/\delta) \tag{8}$$

where c is a constant of order 1, which can be viewed as a free parameter $c \in (0, 1)$.

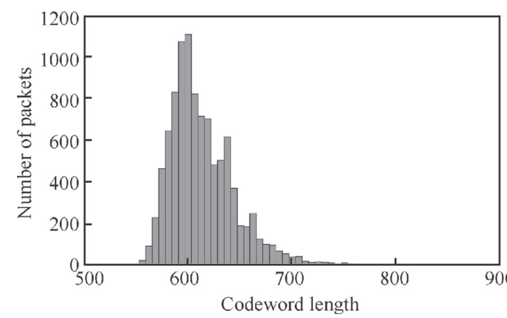
Fig. 3 shows the histograms of the actual numbers of packets required for a couple of settings of the parameter δ. The length of the encoded codeword can be expressed as

$$L_{\mathrm{c}} = K + 2S\ln(S/\delta) \tag{9}$$

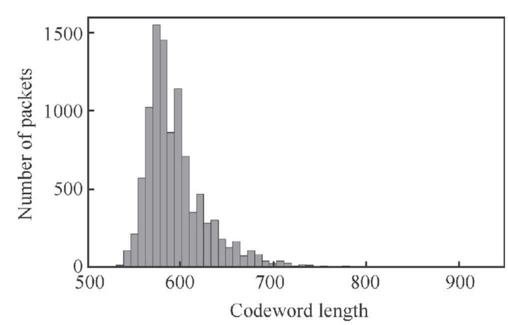
After that, CRC and header information are added to form a codeword of length L_{s}. The encoded symbols of length L_{s} are the input symbols of an LDPC encoder. The two-step coding scheme is defined as a composition of linear mappings as $K \xrightarrow{\mathrm{LT}} L_{\mathrm{c}} \xrightarrow{\mathrm{CRC}} L_{\mathrm{s}} \xrightarrow{\mathrm{LDPC}} C.$



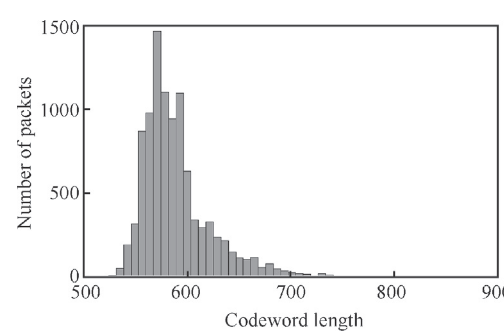
(a) $c = 0.05, \delta = 0.01$ $(Z = 1.27524, L_{\mathrm{c}} = 638)$



(b) $c = 0.05, \delta = 0.1$ $(Z = 1.17320, L_{\mathrm{c}} = 587)$



(c) $c = 0.05, \delta = 0.5$ $(Z = 1.11556, L_{\mathrm{c}} = 558)$



(d) $c = 0.05, \delta = 0.9$ $(Z = 1.09742, L_{\mathrm{c}} = 549)$

Fig. 3 Number of packets L_{c} required to recover a file of $K = 500$ packets.

At the receiver side, inverse operations are applied. Without considering congestion and packet loss due to memory overflow, there are two factors to determine the overall system throughput. Firstly, due to the transmission error in the physical layer, the transmitted codes words are erased with certain probability. Secondly, the received packet may not be able to be decoded due to the absence of a degree-one encoded symbol, which is recovered at any stage of LT decoding.

2.2. LDPC codes design in the physical layer

In this section, the selection of LDPC code rate R_c is studied to maximize the throughput of encoded packets from the LT encoder. In this paper, R_c is adapted between $R_c \in [0.5, 0.897]$. $R_c = 0.5$ is selected as the lower value due to LDPC's superior performance. A 1/2 LDPC code with a packet length $n = 504$ can reach a bit error ratio (BER) of 10^{-6} at 3 dB under the AWGN channel.[20] The reason to take $R_c = 0.897$ as the upper value will be explained in the following sections. To accommodate various ratios for LDPC codes, array codes are involved for efficient linear encoding and good performances.[21] Defined on rings, array codes have an algebraic structure with the framework to deterministic constructions. Array codes can be viewed as binary codes when their parity-check matrices exhibit sparseness, which can be decoded as LDPC codes using the sum product algorithm (SPA).

The parity-check matrix $\boldsymbol{H}$ of an array code is specified by three parameters: prime number p and two integers k and j (j, $k \leqslant p$). k and j are specified as row weights and column weights of matrix $\boldsymbol{H}$, which has dimensions of $jp \times jk$.

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{I} & \dots & \boldsymbol{I} \\ \boldsymbol{I} & \boldsymbol{\alpha} & \boldsymbol{\alpha}^2 & \dots & \boldsymbol{\alpha}^{k-1} \\ \boldsymbol{I} & \boldsymbol{\alpha}^2 & \boldsymbol{\alpha}^4 & \dots & \boldsymbol{\alpha}^{2(k-1)} \\ \vdots & \vdots & \vdots & & \vdots \\ \boldsymbol{I} & \boldsymbol{\alpha}^{j-1} & \boldsymbol{\alpha}^{2(j-1)} & \dots & \boldsymbol{\alpha}^{(j-1)(k-1)} \end{bmatrix} \tag{10}$$

where $\boldsymbol{I}$ is the $p \times p$ identity matrix and $\boldsymbol{\alpha}$ is a $p \times p$ permutation matrix representing a single left or right cycle shift. Based on the introduced parameters, the length of an encoded LDPC codeword and the message part of the codeword are given by $N_t = k \times p$ and $K_{\mathrm{LDPC}} = (k - j) \times p$, respectively. The code rate is calculated as $R_c = K_{\mathrm{LDPC}}/N_t$. Therefore, the length of a finally formed codeword at the physical layer can be generally expressed as

$$N_t = \frac{K + 2S\ln(S/\delta) + P_{\mathrm{CRC}} + P_h}{R_c} \tag{11}$$

3. Cross-layer design and optimization

From Eq. (11), N_t is determined by δ and R_c. Parameter δ decides the length of an LT codeword in the network layer, which will be encoded by an LDPC encoder in the physical layer. Parameter R_c determines the length of message symbols inside a codeword once the size of the transmitted packet is determined. Different R_c affect performance of LDPC codes, resulting in affecting the overall system performances. Thus, there must be trade-offs between layers by adjusting parameters to achieve optimal performances.

3.1. Throughput optimization in the network layer

First, the throughput influenced by δ of LT codes is investigated with a fixed R_c for all channels. From the analysis of the parameters in the network layer, $L_c = K + 2S\ln(S/\delta)$ and S is a monotonically decreasing function of δ. As K is the given size of source message symbols, L_c is also a monotonically decreasing function of δ:

$$L_c = K + 2\ln(K/\delta)\sqrt{K}\ln\frac{\ln(K/\delta)\sqrt{K}}{\delta} \tag{12}$$

which is denoted by a function of δ as $L_c = f_1(\delta)$. The overall system throughput T_s is determined by K, N_t, R_{LT}, and R_{LDPC}, in which $N_t = L_c/R_c$ with neglecting of the effects of P_h and P_{CRC}, while R_{LT} and R_{LDPC} are the recovered information ratio in each layer. Based on the simulation results shown in Fig. 4, the relationship between R_{LT} and δ can be matched as an exponential function $R_{\mathrm{LT}} = a^{\delta}$ with a basis $a \in (0, 1)$.

In addition, the performance of LDPC codes in the physical layer depends on the length of the formed codeword N_t. For example, it was shown that a half-rate code having a block length of 10^7 exhibited a performance within 0.004 dB of the Shannon limit at a BER of 10^{-6}.[22] In this paper, a range of δ generates various L_c and different N_t are subsequently obtained. Since there is no significant difference for the length of N_t, the throughput R_{LDPC} over the fading channel has quite similar performances.

Table 1 shows throughput performances of LDPC codes based on various δ under the condition of SNR = 4 dB over Rayleigh fading channels.

When the factor of R_{LDPC} is ignored, the system throughput can be simplified as

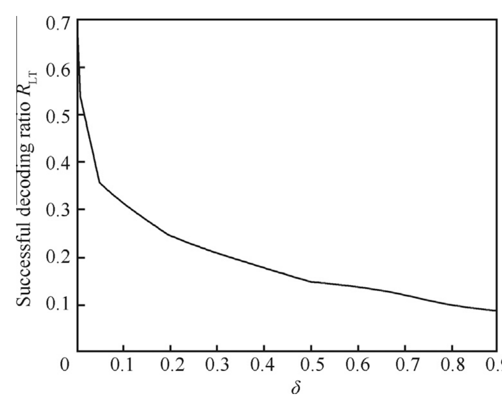


Fig. 4 Successful decoding ratio R_{LT} influenced by δ.

Table 1 Throughput performances of LDPC codes based on various δ.

δ	L_c	N_t	R_{LDPC}
0.001	700	1400	0.9779
0.010	638	1276	0.9650
0.100	587	1174	0.9620
0.500	557	1114	0.9580
0.900	549	1098	0.9530

$$T_s \approx \frac{KR_c}{L_c} \times a^{\delta} \tag{13}$$

which can be denoted by $T_s(\delta) = f_2(L_c, \delta, a^{\delta})$. Therefore, the optimization problem is formulated as

$$\begin{cases} \text{maximize} \quad T_s(\delta) = f_2(L_c, \delta, a^{\delta}) \\ \text{subject to} \quad \delta > 0 \end{cases} \tag{14}$$

Eq. (14) represents that, in order to achieve the maximum value of T_s, the parameter δ is the only optimization variable. Choosing a smaller δ results in a smaller ratio of K/L_c and a bigger value of a^{δ} as R_{LT}, so the best value for $\delta = 0.001$ is found by using the binary search algorithm.[23]

3.2. Throughput optimization in the physical layer

In this section, the code rate R_c is taken as the optimization variable in the physical layer, which can be simplified as

$$R_c = \frac{K_{LDPC}}{N_t} = \frac{(k-j) \times p}{k \times p} = 1 - \frac{j}{k} \tag{15}$$

From Eq. (15), R_c is decided by j and k. For a given array code, if k is fixed, a range of R_c can be obtained by adjusting j. For LDPC codes, with increasing of SNR on wireless channels, the lower code rate, the better BER performance can be achieved and the better throughput can be obtained. Increasing j leads to a smaller R_c with a better throughput performance R_{LDPC}, which can be denoted by a monotonically increasing function of j as $R_{LDPC} = f_3(j)$.

For a codeword C of length N_t, as R_c becomes smaller by increasing degree j, the length of the information message K_{LDPC} within the codeword C gets longer, which can be denoted by a monotonically decreasing function of j as $K_{LDPC} = f_4(j)$.

Tables 2–4 shows LDPC codes throughput performance under conditions of SNR = 8 dB, SNR = 9 dB, and SNR = 10 dB over Rayleigh fading channels based on array codes with parameters of $p = 29$ and j varying from 3 to 8.

From Table 2, it can be found that under the condition of $p = 29$ and $j = 3$, the highest ratio of LDPC codes used in this paper is $R_c = 0.897$.

As discussed above, K_{LDPC} is decreasing when j increases. Therefore, the successfully recovered information ratio in the network layer R_{LT} is also a monotonically decreasing function of j, which is denoted by $R_{LT} = f_5(j)$. Simulation results shown in Table 5 confirm the conclusion.

Thus, the overall throughput optimization problem in the physical layer scenario becomes

$$\begin{cases} \text{maximize} \quad T_s(j) = f_6(K, R_{LT}, R_{LDPC}) \\ \text{subject to} \quad j \geqslant 2 \end{cases} \tag{16}$$

The degree j is an important parameter for system performances of cross-layer satellite multimedia transmission. On one hand, degree j determines the performance of LDPC codes over fading channels in the physical layer. On the other hand, degree j controls the ratio R_{LT} as the successfully retrieved information in the network layer. The proposed cross-layer optimization process is seeking the value of j, which can achieve optimal throughput by balancing these two effects in both layers. In general, the optimization problem is hard, as R_{LT} within the function $f_6(\cdot)$ is a decreasing function of j; at the same time, R_{LDPC} in the function $f_3(\cdot)$ is an increasing function of j. To find the best solution, an exhaustive search method is introduced by listing all the values of R_{LT} and R_{LDPC} based on various j to find the best one suited for designated objectives.

Table 2 LDPC codes throughput over Rayleigh fading channels (SNR = 8 dB).

p	j	k	N_t	R_c	K_{LDPC}	R_{LDPC}
29	3	29	841	0.897	754	0.003
29	4	29	841	0.862	725	0.068
29	5	29	841	0.828	696	0.199
29	6	29	841	0.793	667	0.313
29	7	29	841	0.759	638	0.378
29	8	29	841	0.724	609	0.406

Table 3 LDPC codes throughput over Rayleigh fading channels (SNR = 9 dB).

p	j	k	N_t	R_c	K_{LDPC}	R_{LDPC}
29	3	29	841	0.897	754	0.540
29	4	29	841	0.862	725	0.890
29	5	29	841	0.828	696	0.962
29	6	29	841	0.793	667	0.978
29	7	29	841	0.759	638	0.982
29	8	29	841	0.724	609	0.984

Table 4 LDPC codes throughput over Rayleigh fading channels (SNR = 10 dB).

p	j	k	N_t	R_c	K_{LDPC}	R_{LDPC}
29	3	29	841	0.897	754	0.1129
29	4	29	841	0.862	725	0.4768
29	5	29	841	0.828	696	0.7170
29	6	29	841	0.793	667	0.8136
29	7	29	841	0.759	638	0.8526
29	8	29	841	0.724	609	0.8648

Table 5 Impact of j on R_{LT} for a range of δ.

δ	R_{LT}					
	$j = 3$	$j = 4$	$j = 5$	$j = 6$	$j = 7$	$j = 8$
0.01	0.999	0.993	0.983	0.933	0.706	0.292
0.05	0.997	0.991	0.982	0.953	0.859	0.583
0.20	0.998	0.996	0.984	0.979	0.932	0.828
0.50	0.998	0.996	0.984	0.970	0.932	0.853
0.90	0.998	0.996	0.984	0.970	0.932	0.853

4. Simulations and results analysis

Simulation methods are applied to study the throughput performance of the proposed cross-layer design scheme for satellite multimedia transmission. The solutions of cross-layer optimization problems are verified by results obtained with optimal parameters as discussed above. In simulations, each data frame consists of 500 source message symbols. The throughput performances are shown in Figs. 5 and 6 with fixed R_c and variable R_c, respectively.

For throughput optimization with fixed R_c, a (3,6)-regular LDPC code with code rate $R_{LDPC} = 0.5$ is used to accommodate the various sizes of the LT encoded codewords. As shown in Fig. 5, for $K = 500$ information symbols, decreasing the value of δ leads to the increasing of redundancy and helps to recover the codeword successfully in the network layer. Trade-offs between LDPC codes in the physical layer and LT codes in the network layer result in improvement of the overall system throughput. The dashed curve of $\delta = 0.001$ shows the best throughput performance.

For throughput optimization with variable R_c, the relationship between R_c and j is given by Eq. (8). As shown in Fig. 6, due to high BERs of satellite channels, there is no information received successfully with high-ratio LDPC codes at a low SNR. Along with the SNR becoming larger, the throughput increases. The throughput is related to degree j of array codes. When SNR = 7 dB, the throughput performance of degree $j = 8$ outperforms that of degree $j = 4$. However, when SNR = 10 dB, the throughput performance of degree $j = 4$ is better than that of degree $j = 8$. Thus the degree should be selected with caution to balance system performances within the whole SNR setting. As shown in Fig. 6, array codes with degree $j = 6$ corresponding to $R_c = 0.793$ is the best solution to maximize the throughput performance.

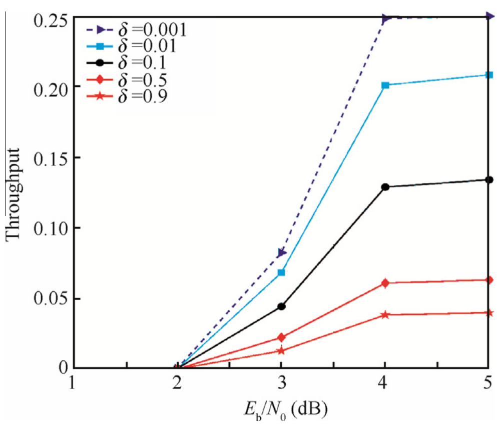


Fig. 5 Throughput influenced by δ with fixed R_c for $K = 500$ information symbols.

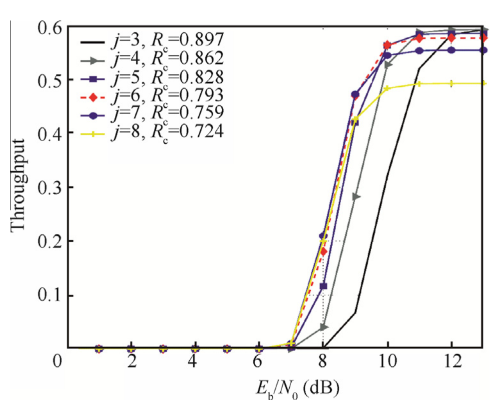


Fig. 6 Throughput influenced by δ with variable R_c for $K = 500$ information symbols.

5. Conclusions

(1) The proposed cross-layer scheme combines flexibility of rateless transmission with LT codes and reliability of channel coding with LDPC codes to maximize system throughput of satellite multimedia transmission.
(2) By analyzing parameters of LT codes in the network layer and LDPC codes in the physical layer, relationships among various parameters are derived. Modeled with optimization problems for maximum throughput, the LDPC code rate R_c and the decoding failure probability δ of LT codes with a finite codeword length constraint are found.
(3) Verified by simulation results, the proposed solution for cross-layer parameters design can improve throughput performance for satellite multimedia transmission.

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Wang Zhenbang is a Ph.D. student in the School of Electronics and Information Engineering at Harbin Institute of Technology. He received his M.S. degree from Harbin Institute of Technology in 2008. His area of research includes rateless codes, cognitive radio, and wireless cognitive network.

Wang Zhenyong received his B.S. and M.S. degrees in communication and information system from Harbin Institute of Technology in 2000 and 2002, respectively, and then became an instructor there. His main research interests are cross-layer design, satellite communication, wireless multimedia transmission, and wireless heterogeneous network.