



Enhanced Contention Resolution Diversity Slotted ALOHA in Satellite-Based IoTs Using Sparse Code Multiple Access

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Abstract. As a efficient random access scheme, contention resolution diversity slotted ALOHA (CRDSA) improves the system throughput greatly, although deadlock problem limits the maximum throughput of system. To address this issue, in this paper, a non-orthogonal multiple access (NOMA) technique is proposed with random access (RA) scheme for supporting multiple terminals access in satellite IoT-oriented networks, by utilizing a code domain NOMA called Sparse Code Multiple Access (SCMA). In the proposed scheme, the throughput is mainly improved by physical (PHY) decoding and iterative decoding. Through mathematical analysis, the throughput lower bound of our scheme is shown and the simulated result proves the proposed scheme is efficient in enhancing RA throughput.

Keywords: SCMA · CRDSA · Random access · PHY decoding · Multiple terminals access

1 Introduction

As the number of Internet of things devices that can be expected to proliferate, existing random access methods need to be improved to better support multi-terminal simultaneous access. Recent research achievements called CRDSA-like random access protocols based on CRDSA [1] have shown great enhancement in the system throughput. CRDSA has been seen as a promising scheme for supporting massive machine type communication terminals(MTC) connectivity in future IoT-oriented satellite networks. Since the former research mainly focus on the MAC layer, theoretically, the throughput have a upper threshold of 1 packet/slot which can be reached only in the situation where no terminal collision occurs, such situation hardly exists in high traffic load communication

networks. When terminals heavily collide in CRDSA scheme, no more packets can be recovered and the deadlock appears (The deadlock is explained in Sect. 2). So shifting focus from MAC layer scheme to a Physical-MAC crossed layer scheme may work better. As a pioneering slotted ALOHA scheme with packets diversity, CRDSA allows multiple terminals to have access into satellite networks simultaneously tolerating channel collision in some extent. The most prominent contribution of CRDSA is the successive iterative interference cancellation (SIC) combined with packets diversity. In CRDSA, once a packet is decoded, its replica's slot location can be found according to the pointer information and thus, with SIC, replica packet can be canceled, enabling further more packets decoding in the replica's slot. However, there exists a deadlock problem in CRDSA which is caused by unrecoverable collision packets, resulting in the peak throughput about 0.55. CRDSA++ [2] is proposed as an enhanced version of CRDSA, which enhance the CRDSA through increasing the number of transmitted replicas, however, the enhancement of CRDSA++ only exists in low load region. Another enhanced CRDSA called irregular repetition slotted ALOHA (IRSA) is proposed in [3], the author describe the interference cancellation process with a bipartite graph model, giving a novel application of bipartite to SIC algorithm, and the throughput of IRSA is about 1.5 times of CRDSA in the same traffic load. The enhancements in [2, 3] are brought by different numbers of transmitted packets. Even the schemes mentioned above appear functional, the research are still confined to MAC protocol.

Researches in [4–6] shows power domain and code domain combined CRDSA have great improvement in throughput. The author in [4] devote his research direction in resolving the typical deadlock problem of CRDSA, by localizing all the replicas of a terminal utilizing a correlation based method, and then the replicas are combined to decode the packets. Since [4] is not a pure MAC scheme, assisted by power domain technique, the system can achieve a normalized throughput higher than 1.2. To better solve the deadlock problem, the author in [5] proposes an enhanced scheme based on [4], using shared information about time slots location on which terminals transmit their replicas. Research in [6] named coded slotted ALOHA (CSA) turns to a code domain scheme, relying on the combination of packet erasure correcting codes and SIC, this scheme depends on both packets repetition and coding.

NOMA has been proposed as a promising scheme for 5G mobile communication system, and researches about NOMA have increased greatly in the past several years. The research in [7] utilizes a NOMA technique called PDMA to enhance the CRDSA protocol, introducing a kind of multi-carrier scheme to CRDSA. As an efficient NOMA, the code domain NOMA sparse code multiple access (SCMA) proposed by HuaWei in [8] allows multiple terminals to occupy the same time-frequency resource (RE). The RE occupation and SCMA decoding have been described in [9–11].

In this paper, a SCMA based CRDSA scheme is proposed to solve the traditional deadlock problem in CRDSA and improve the system throughput performance. In the scheme, sporadic terminals randomly choose a codebook at

the transmitter, and the terminals will physically sent two copies of the same MAC packet like CRDSA. And at the receiver we mainly focus on PHY layer decoding and iterative decoding between MAC layer and PHY layer. Based on the decoding process, lower bound throughput of the proposed scheme is analyzed. We also show that our scheme improve the throughput greatly compared to traditional CRDSA.

The system model is introduced in Sect. 2. Details about our proposed packets decoding scheme are explained in Sect. 3, and complexity and throughput analysis are shown in Sect. 3 and simulation results are presented in Sect. 4.

2 System Model

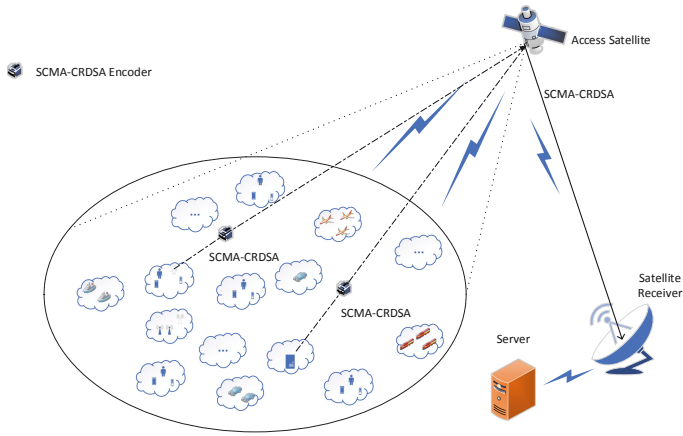


Fig. 1. Multi-type terminal random access model.

The physical communication model used in this paper is shown in Fig. 1. The ellipse enclosed by the light dotted line represents the satellite coverage area, the black dotted line represents the uplink access link, and the black solid line represents the downlink transmission link. The SCMA-CRDSA encoder in the figure is related to the algorithm proposed later in this paper. The satellite can provide access services for different types of wireless terminals in areas it can cover. Considering the energy consumption of the satellite itself, the data received at the satellite end will be forwarded to the ground satellite receiving station for processing. After that, the processed data will be sent to the server. We construct a RA communication scenario, in which N MTC terminals share the common uplink channel of the satellite, N is set to be a finite number in the model. Each RA frame is composed of M equal length slots (slot length is T_S while frame length is $T_F = M \cdot T_S$), and the terminal randomly choose two slots send their packets according to CRDSA. Deadlock in CRDSA is as shown

in Fig. 2, the only single packet in slot 5, denoted by PK3 (PK3 in the figure refers to packet from terminal 3), is recovered first. Then according to the SIC in CRDSA, PK2, PK1 and PK6 can be recovered in turn. At the end, only PK4 and PK5 can not be recovered and a deadlock comes into being.

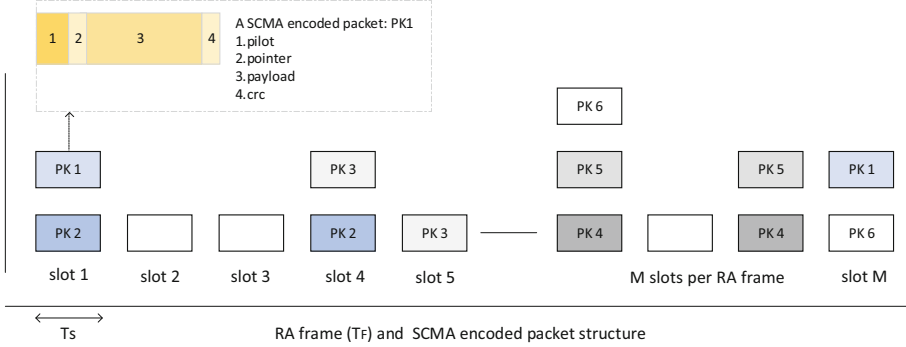


Fig. 2. RA frame and SCMA encoded packet structure.

In the proposed scheme, only MAC load is considered, the system load G is defined as N/M . Packets are synchronized across the time slots and frames, and no packet retransmission is considered. Each packet in the scenario contains k bits, which is denoted by

$$\mathbf{p}^{(u)} = [\mathbf{p}_{\text{poi}}^{(u)}, \mathbf{p}_{\text{payload}}^{(u)}, \mathbf{p}_{\text{crc}}^{(u)}] \quad (1)$$

where $\mathbf{p}_{\text{payload}}^{(u)}$ is the valid bit information carried by a packet from user u . The head of the packet $\mathbf{p}_{\text{poi}}^{(u)}$ contains the pointer bit information that indicates the location of the twins packet. $\mathbf{p}_{\text{crc}}^{(u)}$ in the packet is used to check the correctness of payload bits. In order to reduce the influence of noisy channel fading during data transmission, an effective Forward Error Correction(FEC) code is considered. The FEC encoded bits in packets can be denoted by

$$\mathbf{b}^{(u)} = [\mathbf{b}_{\text{poi}}^{(u)}, \mathbf{b}_{\text{payload}}^{(u)}, \mathbf{b}_{\text{crc}}^{(u)}] \quad (2)$$

The symbols $\mathbf{b}_{\text{poi}}^{(u)}, \mathbf{b}_{\text{payload}}^{(u)}, \mathbf{b}_{\text{crc}}^{(u)}$ represent the FEC encoded bits corresponding to $\mathbf{b}_{\text{poi}}^{(u)}, \mathbf{b}_{\text{payload}}^{(u)}, \mathbf{b}_{\text{crc}}^{(u)}$ respectively.

The FEC encoded bits will go through a SCMA encoder before being transmitted. Through SCMA encoding, bit data can be allocated to carrier resource blocks in the form of SCMA codewords.

At the receiver, we assume that the receiver is able to recognize slots with a single packet or collision packets, and that the packets in slot can be recognized by adding pilot sequence. The structure of RA frame with SCMA encoded packets is shown in Fig. 2. Based on the RA frame and packet encoding structure,

receiver perform a series of decoding processing, decoded packets will be CRC checked and successfully decoded packets can be used to SIC.

3 Proposed PHY Layer Assisted MAC Layer Scheme

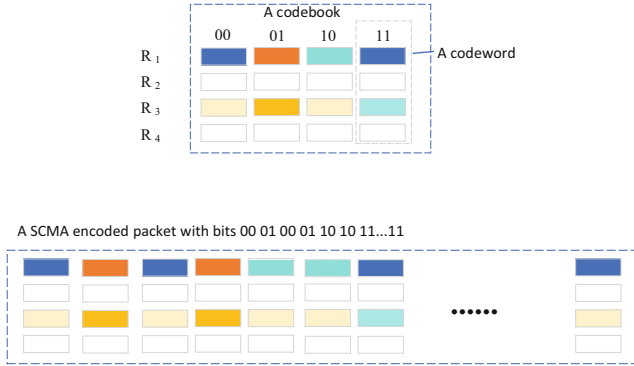


Fig. 3. A codebook and a SCMA encoded packet.

In this section, our proposed scheme and system performance evaluation are described detailedly. First, let us review the original SCMA [8]. In SCMA, the SCMA encoding of a packet is to map the bit information directly to complex number sequence through the selected codebook. The codebook is actually a sparse matrix, as shown in Fig. 3, each row of the sparse matrix represents a carrier. The non-zero row of the matrix represents that the terminal that chooses the codebook occupies the corresponding carrier, and the all-zero row represents that the carrier is not occupied by the terminal, while each column stands for a series of bits in the form of codeword (The codeword, as shown in Fig. 3, is a sparse complex vector). The correspondence between these bits and codewords depends on the modulation mode, taking QPSK modulation for example, the modulation order $O=4$, then every $\log_2(O) = 2$ bits is mapped to a codeword. So the codewords of the codebook in Fig. 3 stand for bits 00/01/10/11. R_1, R_2, R_3, R_4 stand for the carriers from 1 to 4 respectively. And after all the bits of a packet are encoded, the structure of a packet can be represented as the way shown in Fig. 3.

The proposed scheme, as a combination of SCMA and CRDSA, focus more on the PHY layer encoding and decoding. In the processing stage, the MAC and PHY layers gain each other. Details are as follows:

3.1 Encoder at the Transmitter

This section describe data processing before transmission. First, a terminal randomly choose the i -th codebook ζ_i from the codebook set $\mathbb{C} = [\zeta_1, \zeta_2, \dots, \zeta_i, \dots, \zeta_l]$,

l is the total codebook number in codebook set. Once a packet is generated, bit stream of the packet go through FEC encoder(e.g., Turbo encoder), the terminal's coded bits are then mapped to the SCMA codeword according to the selected codebook. The mapping rule follows that every $\log_2 O$ bits are mapped to a codeword. Bits of a packet from terminal u are represented by $\mathbf{b}^{(u)} = [\mathbf{b}_{\text{poi}}^{(u)}, \mathbf{b}_{\text{payload}}^{(u)}, \mathbf{b}_{\text{crc}}^{(u)}]$. Since we don't consider the detailed bits component when perform SCMA encoding, let $\mathbb{B}^{(u)} = \mathbf{b}^{(u)}$,

$$\mathbb{B}^{(u)} = [\mathbf{b}_{1.\log_2 O}^{(u)}, \mathbf{b}_{2.\log_2 O}^{(u)}, \dots, \mathbf{b}_{T.\log_2 O}^{(u)}] \tag{3}$$

where $\mathbf{b}_{T.\log_2 O}^{(u)}$ is a vector represents bits from T to $T + \log_2 O$. Now that ,according to the SCMA mapping rule, every $\log_2 O$ bits are mapped to a codeword, the output after SCMA can be represent by $\mathbb{C} = [\mathbf{c}_1, \mathbf{c}_2, \dots, \mathbf{c}_T]$, where \mathbf{c}_T stand for the result of $\mathbf{c}_{T.\log_2 O}^{(u)} \xrightarrow{\text{Mapping}} \mathbf{c}_T$. Each element in \mathbb{C} represents two bits of the packet in the form of a deterministic codeword. Hereto, all the encoder processing are completed, and the codeword sequences will be sent to the receiver according to corresponding carriers.

3.2 Decoder at the Receiver

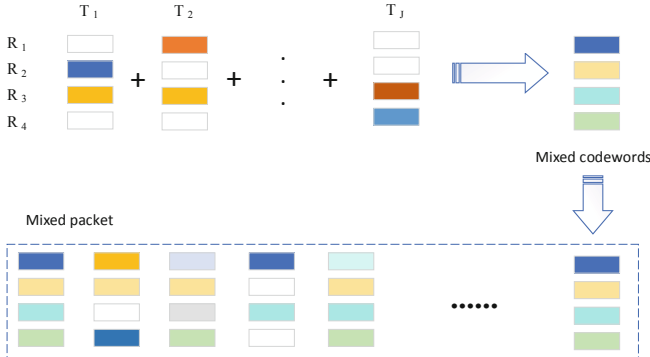


Fig. 4. Superposed signals of a mixed packet.

Physical Decoding. In SCMA-encoded communication systems, since different terminals reuse the same resource (that is, the carrier), the signal received by the receiver is the superposition signal consists of each terminal's codeword. We focus on a certain slot where the received superposition codewords are from J terminals, as shown in Fig. 4, can be written as: $\mathbf{R} = [\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_i, \dots, \mathbf{r}_l]$ (l is the total mixed codewords number in a slot). Where the i -th superposed codeword \mathbf{r}_i is represented by

$$\mathbf{r}_i = \sum_{j=1}^J \text{diag}(\mathbf{h}_j) \mathbf{x}_j + \mathbf{n} \quad (4)$$

The signals received by the receiver may be a mixture of hundreds or thousands of codewords from multi-terminal.

The Eq. (4) represents received mixed codeword that have went through different channel and noise. Among the equation, $\mathbf{x}_j = [x_{1j}, x_{2j}, x_{3j}, x_{4j}]^T$ ($j = 1, 2, \dots, J$) is the sparse codeword selected from the corresponding codebook, $x_{mj} = 0$ ($m = 1, 2, 3, 4$) if the m -th carrier doesn't be occupied by terminal j . And $\mathbf{h}_j = [h_{1j}, h_{2j}, h_{3j}, h_{4j}]^T$ represents the channel condition vector between terminal j and receiver, h_{mj} ($m = 1, 2, 3, 4$) is the channel coefficient on carrier m . The vector $\mathbf{n} = [n_1, n_2, n_3, n_4]^T$ is Gaussian noise with variance σ^2 .

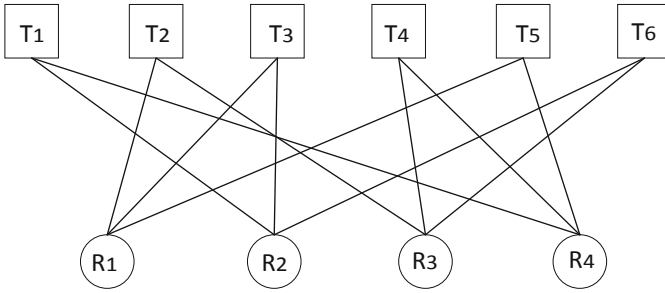


Fig. 5. Factor graph.

Typically, there are 6 terminals (T_1 to T_6) contend for the 4 carriers (R_1 to R_4). Based on the reception model, the relationship between terminals and carriers can be represented by factor graph like Fig. 5. The terminal nodes and carrier nodes are so-called variation nodes (VN) and function nodes (FN). During decoding processing, the mixed packet in a slot is divided into multiple superposed codewords as shown in Fig. 4. Now that decoding of the packet is conducted in parallel, we only need to analyze a specific mixed codeword at the receiver. So the following decoding analysis in section *a* refers to a mixed codeword.

That We adopt the non-orthogonal technique of SCMA in the physical layer will introduce extra overhead to decoding, so a low-complexity multiple terminal decoding algorithm is required. Here we choose the Message Passing Algorithm (MPA). The MPA algorithm is essentially an iterative update of external information between carrier nodes and terminal nodes just as [12]:

- Information passed from FN nodes to VN node.

$$I_{k \rightarrow j}^t(\mathbf{x}) \propto \sum_{\tilde{\mathbf{x}}_j: \tilde{\mathbf{x}}_j = \mathbf{x}} \left\{ M_k(\tilde{\mathbf{x}}) \prod_{\tilde{j} \in \xi_k \setminus j} I_{\tilde{j} \rightarrow k}^{t-1}(\tilde{\mathbf{x}}_{\tilde{j}}) \right\} \quad (5)$$

In the equation, $I_{k \rightarrow j}^t(\mathbf{x})$ represents external information from FN node k to VN node j , where t stands for current iteration number, $\tilde{\mathbf{x}}_j$ is the codeword might sent by terminal j . ξ_k is the set of terminals carried by FN j and the symbol \setminus stands for ‘exclude’.

- Information passed from VN nodes to FN node.

$$I_{j \rightarrow k}^t(\mathbf{x}) = \prod_{\tilde{k} \in \zeta_j \setminus k} I_{\tilde{k} \rightarrow j}^t(\mathbf{x}_j) \quad (6)$$

In the equation, ζ_j stands for the carriers occupied by terminal j .

- The combination function(CF) $M_k(\tilde{\mathbf{x}})$.

$$M_k(\tilde{\mathbf{x}}) = \exp \left\{ -\frac{1}{\sigma^2} \left\| y_k - \sum_{j \in \xi_k} h_{k,j} x_{k,j} \right\|^2 \right\} \quad (7)$$

The CF is actually the conditional probability for given codeword combination.

As shown in equations above, the realization process of MPA algorithm is divided into two steps, the first is to update the information of VN node through the factor graph, and the second is to update the information of FN node. When the maximum iteration number is reached, the MPA algorithm will converges. And the output codeword can be judged as:

$$\hat{\mathbf{x}} = \max_{\mathbf{x}} \prod_{\tilde{k} \in \zeta_j} I_{\tilde{k} \rightarrow j}^{t_{max}}(\mathbf{x}) \quad (8)$$

The $\hat{\mathbf{x}}$ represents the codeword may sent by terminal j , once the output codeword is obtained, the corresponding bit information can be recovered. Since a terminal’s packet contains many codewords, when all the codewords are retrieved, bits in the packet can be recovered. The CRC check is then performed to determine whether the packet has been decoded completely. If the packet passes the CRC check, it can be considered as a collision-free packet and then be used for MAC layer SIC.

As shown in Fig. 6, The MPA algorithm performs much worse than MPA algorithm combined with Turbo coding in BER. So in our scheme the FEC encoding(e.g., Turbo encoding) is indispensable. Channel coding can largely eliminate

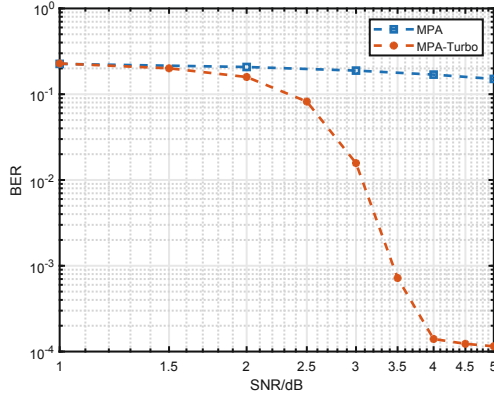


Fig. 6. BER of MPA and MPA-Turbo under low SNR.

the influence of MPA decoding error, which makes it easier to analyze the positive effect brought by introducing SCMA scheme. At low SNR, supposing that there is a lower bound δ of BER in MPA-Turbo scheme, which is achieved when the SNR reaches a certain value. The δ in the MPA-Turbo scheme is approximately equal to 10^{-4} when SNR = 5 dB.

MAC Decoding. In fact, this section is about the interference cancellation algorithm. In order to perform an iterative decoding process, the receiver will store all the signals, sampled from each frame, in the memory. Just as traditional CRDSA scheme, the SIC decoder's iteration number i_1 is set to 1, the SIC decoding process will cease when the maximum iteration number I_1 is reached.

At the beginning, because a slot's packets have been tried to be decoded by the physical layer, the packets in this slot may have been completely recovered or may be misunderstood due to codebook collision. If the BER value is far beyond the predefined threshold δ in a slot, the slot is assumed to be bad (It is often caused by terminals' codebook collision), otherwise, this slot is assumed to be good (that is, no collision occurs and more powerful FEC coding can be used to enhance BER performance and the BER can be low enough to ignore), packets in the good slot can be recovered as possible. For easier analysis, here we assume that the packets in slots with codebook collision are unrecoverable. Then, packets successfully recovered in each slot will be applied to SIC according to the pointer information contained in packet.

The proposed MAC layer decoding scheme relies on interaction between MAC layer and PHY layer essentially, this kind of interaction is reflected as iteration between SCMA decoding and MAC layer SIC processing. At each iteration, the superposed packets are recovered through PHY decoding and then used to SIC. More packets may be recovered through SIC, which makes it possible that codebook collision disappears in some slot, as a result of collided packets being eliminated by SIC. Once the codebook collision is eliminated, the deadlock will

be solved, and then the next iteration processing begins. The iteration number can be represented by i_2 , while the maximum iteration number is I_2 .

Based analysis above we proposed a SCMA-CRDSA algorithm in Algorithm 1.

Algorithm 1. SCMA-CRDSA ALGORITHM

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1: Initialization:
2: received mixed in slot:  $\mathbf{R} = [\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_i, \dots, \mathbf{r}_l]$ 
3:  $I_1$ : maximum number of iterations in CRDSA.
4:  $t_{max}$ : maximum number of iterations in MPA.
5:  $I_2$ : maximum number of iterations in SCMA-CRDSA.
6: Output: successfully recovered packets
7: for  $i_2$  from 1 to  $I_2$  do
8:   for eachslot from 1 to  $L$  do
9:     perform message passing algorithm, iteration  $t \leq t_{max}$ , analyze BER in the
       slot after MPA.
10:    if The BER is tolerable compared to  $\delta$  then
11:      This slot is good. Packets in this slot can be recovered to perform SIC.
12:    end if
13:  end for
14:  perform SIC processing using the packets have just recovered by MPA.
15:  for eachslot from 1 to  $L$  do
16:    search for clean slots
17:    perform SIC processing using the packets have just discovered in clean slots.
       Iteration number is no more than  $I_1$ 
18:  end for
19: end for

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3.3 Complexity Analysis

The complexity of traditional CRDSA protocol is mainly related to the SIC iteration number I_1 , however, the proposed scheme enhance the system throughput at the cost of introducing extra complexity. The extra complexity comes from MPA decoding at the receiver, which is to the order of M_{d_f} , the modulation order M here is 4, and d_f is the maximum degree of a function node. Complexity of updating a variable node based on the function node is analyzed through the iteration Eq. (2), which needs $M \cdot (d_r + 1) \cdot M^{(d_r - 1)}$ addition terms, $M \cdot (d_r + 2) \cdot M^{d_r - 1}$ multiplication terms and $M \cdot M^{d_r - 1}$ exponential terms. While updating a function node based on the variation node needs $M \cdot (d_c - 2)$, where d_c is the resource number occupied by a terminal. So, among a iteration, the total complexity is $I_2 \cdot (I_1 + O(M^{d_r} \cdot K \cdot d_r \cdot t_{max}))$, where K is the non-zero row numbers in a codebook.

3.4 Throughput Analysis

The throughput T under MAC load G at the iteration i can be derived, like [1], as $T(i|G) = G \cdot P_{pd}(i|G)$, where $P_{pd}(i|G) = P \{ \text{packet successfully decoded at iteration } i | \text{MAC load} = G \}$.

The probability P_{pd} can be derived as:

$$\begin{aligned} P_{pd}(i|G) &= 1 - [(1 - P_{pd}^A(i|G)) \cdot (1 - P_{pd}^B(i|G))] \\ &= 1 - [(1 - (P_{pd}^A(i|G)))^2] \end{aligned} \quad (9)$$

where P_{pd}^A and P_{pd}^B correspond respectively to the probability that the twins A and B of the same packet are successfully decoded. In terms of throughput, what the difference in our proposed scheme with CRDSA is that a twins packet may be recovered by SCMA or CRDSA. Here we give a lower bound throughput of the proposed scheme, the lower bound can be achieved after the first iteration.

$$P_{pd}^A(i|G) \geq P_{SCMA} + P_{CRDSA} \quad (10)$$

where P_{SCMA} stands for probability that there is no codebook collision in the slot contains twins A, so P_{SCMA} is computed, as Eq. (13), in the situation that there is no more than $J - 1$ packets collide with A and the $J - 1$ packets also have no codebook collision. J is the total codebook number in the system. The probability that no more than $J - 1$ packets collided with A is represented by P_{col}

$$P_{col} = \sum_{n=1}^{J-1} \binom{N}{n} \cdot p_c^n \cdot (1 - p_c)^{N-n} \quad (11)$$

where $p_c = 1/M$, which stands for the probability that a packet is sent in the slot. The probability that no collision occurs between the V packets in a slot is represented by P_{nocol}

$$P_{nocol} = \frac{J \cdot (J - 1) \cdots (J - V + 1)}{J^V} \quad (12)$$

$$P_{SCMA} = \sum_{n=1}^{J-1} \binom{N}{n} \cdot p_c^n \cdot (1 - p_c)^{N-n} \cdot \frac{(J - 1) \cdots (J - n)}{J^n} \quad (13)$$

while P_{CRDSA} is the probability that twins A is recovered by CRDSA which means twins A suffers from codebook collision.

$$P_{CRDSA} \geq (1 - P_{SCMA}) \cdot P_{SCMA}^a \quad (14)$$

The letter a in Eq. (14) represents the packet number that collide with twins A. The Eq. (14) is interpreted as that twins of the packets collide with twins A are all recovered through SCMA decoding.

4 Numerical Results

In this section, numerical results are presented to evaluate the proposed decoding scheme. First, we simulate our proposed scheme with the performance parameter throughput (measured in useful packets received per slot) vs. load (measured in useful packets transmitted per slot). As other parameters set in [1], each packet's length is 400 bits, and a frame contains 100 slots. The FEC coding we adopted is Turbo with coding rate $1/3$.

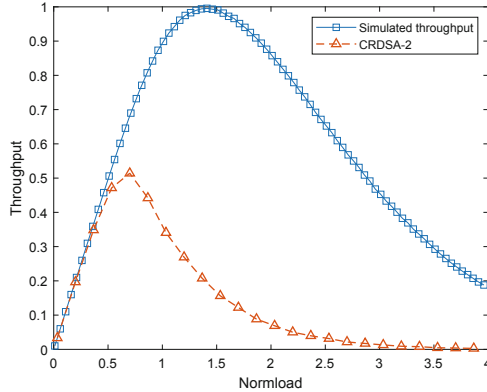


Fig. 7. Simulated result for the SCMA-CRDSA lower bound throughput. $I_1 = 1$, $t_{max} = 5$, $I_2 = 1$, codebook number $J = 6$, SNR = 5 dB.

In Fig. 7, the lower bound performance of SCMA-CRDSA scheme is shown by Monte Carlo simulation result, which proves that the proposed scheme is efficient. Before the load reaches about 0.7 packets/slot, it can be seen that the throughput of the system keeps increasing linearly as the load value increases. After the load value exceeds 0.7 packets/slot, the throughput growth rate of the system slows down. When the load value reaches about 1.4 packets/slot, the throughput of the system begins to decline. It's when the load reaches about 1.4 packets/slot, the maximum throughput about 1.0 packets/slot is achieved. So the throughput in this proposed scheme is about 2 times of throughput in CRDSA.

The throughput in Fig. 7 is actually the lower bound of our proposed scheme and is the result after the first iteration, so we would like to show the better performance after more iteration processing in Fig. 8. It's obvious that the throughput is enhanced a lot with the increased iteration number. However, when the number of iterations increases to a certain value, the system throughput no longer increases, which is caused by codebook collision and CRDSA deadlocks. In fact, the number of iterations need not be set to a large number, because even if the number of iterations increases later, the throughput performance will not improve significantly, but will lead to higher decoding complexity.

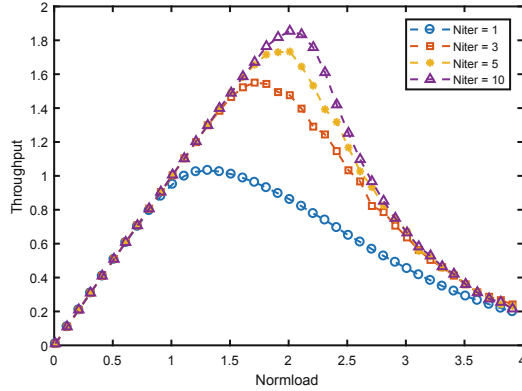


Fig. 8. Throughput of SCMA-CRDSA with iteration number = 1,3,5,10.

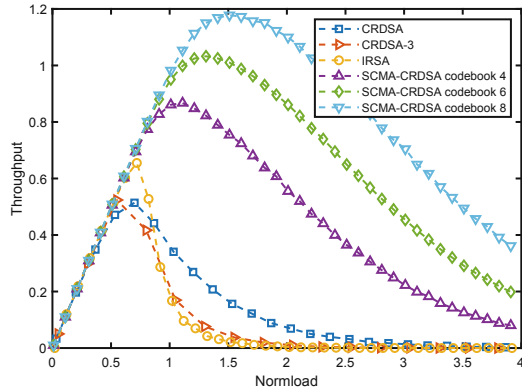


Fig. 9. Throughput of SCMA-CRDSA for codebook number = 4,6,8.

As shown in Fig. 9, with the number of codebooks increasing, throughput performance of the system is greatly improved. The reason for this is that the collision probability of the selected codebook is reduced due to the increase of the codebook number. Although the increasing in the number of codebooks can achieve positive effects, in real communication systems, the number of codebooks cannot be infinite, because the increasing in the number of codebooks also brings more complex decoding problems to the receiver.

Considering that the CRDSA scheme itself will increase the system overhead by sending data packets in multiples, we have adopted a transmission mode where only some of the data packets are repeated. In other words, the user at the transmitter randomly chooses whether to send two identical data packets. During the simulation process, We assume that the packet repetition probability is 0.6, 0.7, 0.8. The SCMA-CRDSA system throughput in these cases is shown in Fig. 10. Overall, the system throughput has better resistance to high load after

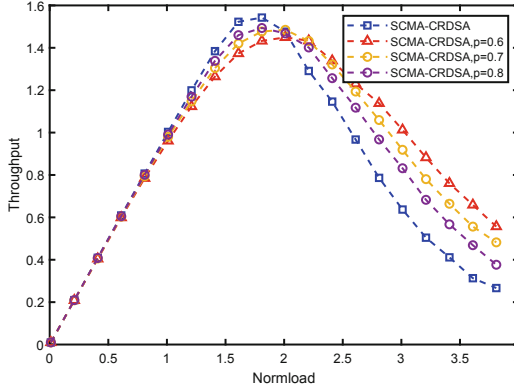


Fig. 10. Throughput of SCMA-CRDSA by sending two packets with different probabilities 0.6, 0.7, 0.8. Codebook number is 6, and $I_1 = 6$, $I_2 = 3$

controlling the probability. When the probability equals to 0.8, the system's peak throughput is not much different from the normal SCMA-CRDSA scheme, but the normal SCMA-CRDSA scheme's throughput performance is significantly worse under high load. It can be seen that in the SCMA-CRDSA scheme, not only the overhead of sending the number of data packets is reduced, but to a certain extent reducing the number of copies has greatly improved the throughput under high load.

5 Conclusion

In this paper, We propose a SCMA based CRDSA scheme and analyze the decoding process at the receiver. By utilizing SCMA, deadlock is more easier to be solved and then throughput of the system is greatly increased compared to traditional CRDSA scheme. And a lower bound of the proposed scheme is derived. The Monte Carlo simulation result proves that our scheme is efficient, enabling to better support multiple terminals access. In fact, we use a more general algorithm in the decoding process, the proposed scheme introduces a relatively high complexity, and the related complexity can be reduced by existing and updated research.

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References

1. Casini, E., De Gaudenzi, R., Del Rio Herrero, O.: Contention resolution diversity slotted ALOHA (CRDSA): an enhanced random access scheme for satellite access packet networks. *IEEE Trans. Wirel. Commun.* **6**(4), 1408–1419, April 2007

2. Del Rio Herrero, O., De Gaudenzi, R.: A high-performance mac protocol for consumer broadband satellite systems. In: 27th IET and AIAA International Communications Satellite Systems Conference (ICSSC 2009) (2009)
3. Liva, Gianluigi: Graph-based analysis and optimization of contention resolution diversity slotted ALOHA. *IEEE Trans. Commun.* **59**(2011–02), 477–487 (2011)
4. Bui, H.C., Zidane, K., Lacan, J., Boucheret, M.L.: A multi-replica decoding technique for contention resolution diversity slotted ALOHA. In: 2015 IEEE 82nd Vehicular Technology Conference (VTC Fall) (2015)
5. Zamoum, S., Lacan, J., Boucheret, M., Dupe, J., Gineste, M.: Shared position technique for interfered random transmissions in satellite communications. In: 2018 9th Advanced Satellite Multimedia Systems Conference and the 15th Signal Processing for Space Communications Workshop (ASMS/SPSC), pp. 1–8, September 2018
6. Paolini, E., Liva, M., Chiani, M.: Coded slotted aloha: A graph-based method for uncoordinated multiple access. *IEEE Trans. Inf. Theory* **61**(12), 6815–6832
7. Zhao, B., Ren, G., Zhang, H.: Random pattern multiplexing for random access in IoT-oriented satellite networks. *IEEE Syst. J.* 1–12 (2019)
8. Nikopour, H., Baligh, H.: Sparse code multiple access. In: 2013 IEEE 24th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC) (2013)
9. Jin, L., Zhou, S., Zhang, X., Wang, Y.: Low complexity decoding method for SCMA in uplink random access (2017)
10. Wang, C., Wu, Y., Chen, Yan., Bayesteh, A.: Sparse code multiple access for 5G radio transmission. In: 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall) (2018)
11. Yang, Y., Zhao, Y., Li, D.: SCMA uplink decoding with codebook collision. In: 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall) (2017)
12. Hoshyar, R., Wathan, F.P., Tafazolli, R.: Novel low-density signature for synchronous CDMA systems over AWGN channel. *IEEE Trans. Sig. Process.* **56**(4), 1616–1626