Multi-slot and multi-user joint detection scheme for CRDSA in satellite network

Yali Feng, Guangliang Ren\textsuperscript{a)}, and Huining Zhang

State Key Laboratory of Integrated Service Networks, Xidian University, Xi’an, China
\textsuperscript{a} glren@mail.xidian.edu.cn

Abstract: A multi-slot and multi-user detection scheme is presented for the contention resolution diversity slotted ALOHA (CRDSA) in satellite networks. The scheme can effectively resolve the deadlock loop of the collided packets of $J$ users in $J$ slots, and can be applied to DVB-RCS2 directly with a little change on receiver. The simulation results show the throughput of the CRDSA with the proposed scheme can improve greatly when the PLR is at 0.001, and has less latency compared with the conventional CRDSA.

Keywords: CRDSA, satellite networks, dead loop, collided packets

Classification: Satellite Communications

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1 Introduction

Random access technique has attracted much more attentions in recent years, which can provide a large access capacity for the huge number of the machine to machine (M2M) communication terminals with low latencies [1]. Among the available RA
techniques, CRDSA [2] significantly enhances the throughput and the Packet Loss Ratio (PLR) with the iterative interference cancellation at the demodulator, and it has been employed in the DVB-RCS2 standards. However, in the CRDSA, the collisions resolution with the interference cancelling (IC) depends on the clean packets in the frame, and it performs well only for the long frame with hundreds of slots. The so-called “deadlock loop” increases as the channel load increases or the number of slots in the frame decreases, which greatly degrades the performance of the CRDSA. CRDSA++ and IRSA and other variants [3, 4] are proposed to mitigate the deadlock loop and further improve the throughput with the cost of more replicas or additional signalling overhead. However, the deadlock loops still exist, and the power consumption of the user terminal is also highly increasing.

By analysing the remained collided packet signals after the IC processing in the CRDSA at the access point, we model the collided packets of \( J \) users in the \( J \) slots, one of the deadlock loops, as a new multiple inputs and multiple outputs (MIMO) signal model, and propose a multi-slot and multi-user joint detection (MMJD) scheme to recover the packets of \( J \) users. It can improve the throughput of the CRDSA without any modification and increasing the power consumption at the user terminal, and is independence on the clean packets, and is also suitable for the short frame with several tens of slots, which can reduce the latency of the user data compared with the conventional CRDSA.

2 Proposed method

2.1 Signal model

A typical satellite random access system with the CRDSA is considered, and there are \( M \) terminals try to access the common channel in the frame with \( N_{\text{slot}} \) slots. By taking advantage of the broadcasting signal in the satellite network, the user terminal employs the time advance (TA) and frequency offset pre-compensation to synchronize in the uplink. Suppose the transmitted complex data of the packet of the \( u \)th user terminal in the slot is \( s^{(u)} = \text{diag}(s^{(u)}(1), s^{(u)}(2), \ldots, s^{(u)}(L)) \), where \( L \) is the number of the symbols. The \( u \)th user terminal randomly selects the slots to send the packets according the CRDSA protocol. If there are packets of \( K \) users which are sent on the \( j \)th slot, the discrete complex received signals can be described as

\[
y_j = \sum_{u=1}^{K} h^{(u)}_j s^{(u)} + w_j
\]

where \( y_j = [y_j(1), y_j(2), \ldots, y_j(L)]^T \), \( h^{(u)}_j = [h^{(u)}_j(1), h^{(u)}_j(2), \ldots, h^{(u)}_j(L)]^T \) is the complex channel vector between the \( u \)th user terminal and the access point during the \( j \) slot, \( w_j \) and is the zero mean and covariance matrix with \( E\{w_j w_j^H\} = \sigma_w^2 I_L \), and \( I_L \) is the identical matrix with \( L \) order.

2.2 Multi-slot and multi-user joint detection scheme

At the access point in the satellite network, the received packets signal of the frame is firstly processed as that in the CRDSA, which searches the clean packets, and recovers the corrupted packets with the interference cancellation (IC) processing. After the IC processing, there are still remained many corrupted packets on the slots when the channel load is high. This is because the collided packets of the different
users are in the formation of the deadlock loops. By analysing packets of the deadlock loops, we find that the probability of the packets of $J$ users colliding on the $J$ slots is high, where $J$ is less than the slot number of the frame. To resolve the loop and recover the packets of $J$ users, we firstly model the received signals of the $J$ slots, and then present the data recovery method.

In the deadlock loop of the packets of $J$ users colliding on $J$ slots, the indexes of the slots and users are written as $j_1, j_2, \ldots, j_J$ and $u_1, u_2, \ldots, u_J$ respectively. By Eq. (1), the received signals of $J$ slots can be given as

$$
\begin{bmatrix}
y_{j_1} \\
y_{j_2} \\
\vdots \\
y_{j_J}
\end{bmatrix} =
\begin{bmatrix}
h_{j_1}^{(u_1)} & h_{j_1}^{(u_2)} & \ldots & h_{j_1}^{(u_J)} \\
h_{j_2}^{(u_1)} & h_{j_2}^{(u_2)} & \ldots & h_{j_2}^{(u_J)} \\
\vdots & \vdots & \ddots & \vdots \\
h_{j_J}^{(u_1)} & h_{j_J}^{(u_2)} & \ldots & h_{j_J}^{(u_J)}
\end{bmatrix}
\begin{bmatrix}
s^{(u_1)} \\
s^{(u_2)} \\
\vdots \\
s^{(u_J)}
\end{bmatrix}
+ \begin{bmatrix}
w_{j_1} \\
w_{j_2} \\
\vdots \\
w_{j_J}
\end{bmatrix}
$$

(2)

where the $\{h_{j_i}^{(u_1)}, h_{j_i}^{(u_2)}, \ldots, h_{j_i}^{(u_J)}\}^T$ in the channel matrix is the channel vector between the $u_i^{th}$ user terminal and the access point on the different slots, and the elements are zero except the channel elements on the selected slots that the $u_i^{th}$ user terminal transmitted the packets. It is also noted that the nonzero channel elements in the channel matrix can be estimated by the preambles of the packets, and the channel matrix is a sparse matrix. For the received vector in the $J$ slots, the $k_{th}$ received symbol vector is

$$
Y_{J,k} = [y_{j_1}(k), \ldots, y_{j_J}(k), \ldots, y_{j_J}(k)]^T = H_{J,k}S_{J,k} + W_{J,k}
$$

(3)

From the Eq. (3), it is seen that the received signal model during the $k_{th}$ symbol period is a MIMO signal model. The model can be dubbed the multi-slot and multi-user joint MIMO signal model. Therefore, many MIMO detection algorithms can be used to recover the data of the $J$ symbols of the $J$ users.

To recover the packets of $J$ users effectively, we employ a soft MIMO detection algorithm to give the soft information of the coded bits in the symbols, and the soft decoders are employed to decode the bits of the $J$ users. The multi-slot and multi-user joint detection (MMJD) scheme is shown in Fig. 1. The received signals of the $J$ slots are input to the MMJD detector. If the complex symbol in Eq. (3) contains $Q$ coded bits, which can be described as $c_{k}^{(u_i)} = [c_{k,1}^{(u_i)}, \ldots, c_{k,q}^{(u_i)}]$, the log-likelihood ratio (LLR) in Fig. 1 can be represented as

$$
LLR(c_{k,q}^{(u_i)}) = \ln \frac{p(c_{k,q}^{(u_i)} = 1|Y_{J,k})}{p(c_{k,q}^{(u_i)} = 0|Y_{J,k})}
$$

(4)

By using Eq. (4), the MMJD detector output the soft information of the coded bits of the $J$ packets, which are input to the corresponding de-interleavers and soft-
decoders. The soft-decoders output the bits of the $J$ users. The transmitted data of the $J$ users can be recovered from the collided packet signals in the $J$ slots.

2.3 Algorithm for CRDSA with MMJD

The MMJD scheme can effectively resolve the collided packets of $J$ users on the $J$ slots, one of the deadlock loops in the CRDSA. Its algorithm to process the received signals is described as follow.

Algorithm for CRDSA with MMJD:

Initialization:
Set the number of the clean packets, the number of loop, the initial number of users in the loop and the number of all the slots in the frame, as $N_{\text{clean}} = 0$, $N_{\text{loop}} = 0$, $J = 2$, and $N_{\text{slot}}$ respectively. Initialize the clean packet index set $P_{\text{index}}$ and the loop index set $P_{\text{loop}}$ to the empty sets.

START:
1) Scan and search the clean packets in all the slots in the frame, and set $N_{\text{clean}} =$ the number of clean packets, and $P_{\text{index}} =$ {indexes of clean packets}.
2) If $N_{\text{clean}} \neq 0$, get the indexes of the clean packets from the set $P_{\text{index}}$, demodulate the clean packets; else go to 4).
3) Using the demodulated data of the clean packets, reconstruct the signals of their replicas, and cancel them from the collided packets signals, go to 1).
4) Scan and search the loop of the packets of the $J$ users in the $J$ slots in the remained signals, set $N_{\text{loop}} =$ the number of loops, and $P_{\text{loop}} =$ {indexes of the loops}.
5) If $N_{\text{loop}} \neq 0$, get the indexes of the loops from the set $P_{\text{loop}}$, use the MMJD scheme to demodulate the packets of $J$ users.
6) Increase $J$, if $J < N_{\text{slot}} + 1$, go to 4), else, go to 7).
7) End.

3 Simulation results

In the simulation, the SC-FDMA packet with preamble and pilots in [5] and the 3GPP turbo code are employed at the user terminal; the channel model is ITU-R M.1225, and the perfect power control is assumed. The frame size of 100 slots is used. The traffic of user terminal is modeled as Poisson traffic sources and transmits fixed copies of packets (2 or 3) at random selected slots during a frame according to the CRDSA. An open loop transmission scheme is assumed, that is, there is no re-transmission or congestion control in simulation.
Fig. 2 shows the packet error rate (PER) curves of two detection methods. It can be found that the PLR of the MMJD is better than that of the detection of the clean packets because the user packet and its replicas are all used in the MMJD, and only one packet of the user is employed in the detection of the clean packets.

![Fig. 2. Packet error rate of two detection methods](image)

Fig. 3(a) shows the throughput of the CRDSA with and without MMJD versus channel load. It is seen that the throughput peak of CRDSA-2 with MMJD is higher 6% than the CRDSA-2, and the CRDSA-3 with MMJD is higher 23.2% than the CRDSA-3.

Fig. 3(b) shows PLR of the CRDSA with and without MMJD versus channel load. It is seen that the PLR of the CRDSA with MMJD is lower than that of the CRDSA. At the $PLR = 10^{-3}$, the channel loads of the CRDSA-2 without and with MMJD are 0.055 and 0.35 respectively, and those of the CRDSA-3 without and with MMJD are 0.55 and 0.8 respectively. So, the MMJD scheme can improve the channel load 6.4 and 1.5 times for the CRDSA-2 and CRDSA-3 respectively.

![Fig. 3. (a) Throughput of the CRDSA with and without MMJD. (b) PLR of the CRDSA with and without MMJD](image)

3.1 Conclusion
By using proposed multi-slot and multi-user detection algorithm, some of the deadlock loops in the collided packets can be solved effectively. The proposed scheme can be applied to DVB-RCS2 directly with a little change on receiver,
improve the throughput and reduce the latency of the return link by using short frame size effectively.

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