A Novel Feedback Method to Enhance the Graphical Slotted ALOHA in M2M Communications

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Abstract. The multiple access issue caused by the massive connections of devices is the key design aspect in the machine-to-machine communication system. As an uncoordinated access scheme, coded slotted ALOHA (CSA) is proposed and well studied to enable random access and high throughput simultaneously with no grant process. It shows efficient performance when the payloads are small. However, the CSA does suffer from the stopping set problem: the Successive Interference Cancellation (SIC) decoding process of CSA would come to a jam when normalized offered traffic is large. We propose an enhanced scheme based on CSA, that is, adding a novel physical layer feedback scheme on CSA to initiate the SIC decoding when there is no degree-1 slot. Considering the overhead of the feedback, simulations show that the proposed scheme can increase the number of successfully accessed devices in one frame.

Keywords: M2M · Coded slotted ALOHA · Feedback · Random access

1 Introduction

Machine-to-Machine(M2M) communications enable the trillions of devices communicate with each other with a mechanical automation. Many scenarios like intelligent transportation and home automation require the communications between the applications such as sensors, actuators, smartphones and so on. The number of M2M devices supported by the cellular networks in the future will be ten times more than now, it is the essential requirement in M2M communication. Many of devices have no/low mobility in M2M communications, what's more, the traffic involves a large number of short-lived sessions containing only few hundred bits, which is distinct from the human-to-human communications [1–3].

Solving severe congestions is the most critical challenge of M2M communications, so seeking a random access (RA) approach which can avoid the transmission collisions and reduce the access delay is the research priority. Several schemes are proposed to support M2M communications considering the signaling overhead and practical deployment [4,5]. Generally, two kinds of system-level

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designs can be adopted in M2M communication: (i) a one-stage design, where the data payload is communicated over a random access channel, and (ii) a conventional two-stage design, where the identity of devices is established over a random access channel and the payload is communicated during a scheduled stage [6].

In M2M communication, with smaller data packet, the ratio of signaling becomes larger. Theoretical research has proved that the one stage methods can achieve larger throughput. It's easy to understand this result since the signaling overhead is kind of fixed in each transmission. Thus as a result, the aforementioned one-stage technologies are varying promising in future M2M communication scenario.

As a typical one stage access technology, slotted ALOHA (SA) is a traditional random access scheme as an uncoordinated multiple access technique. In [7], a improvement of ALOHA is proposed, named contention resolution diversity slotted ALOHA (CRDSA), where users transmit their packets within two different slots randomly, and successive interference cancellation (SIC) is applied to reuse the collision slots. A more effective scheme irregular repetition slotted ALOHA (IRSA) is provided in [8,9], where each user sends multiple replicas instead of two within different slots randomly according to a predefined probability distribution function. [10] provides a further generalization, named coded slotted ALOHA(CSA). It encodes the packets via linear block code instead of the replicas, and combines the iterative SIC with decoding algorithm of linear block code to recover the packets. [11] provides a CSA scheme using rateless codes. It should be noted that, IRSA is a special case of CSA which uses repetition codes and has low complexity decoding algorithm and is easy to achieve without significant degradation of performance.

CSA draws interest for that it can provide high throughput. It has become one of the alternative offers for the RA in M2M. The common shortage of these methods is that the SIC only starts at the packet which does not have collision, resulting in low throughput under high traffic load when the collision problem is serious. In this paper, we proposed an enhanced scheme of CSA based on feedback design to overcome the problem.

The reminder of this paper is organized as follows. The description of the system model is given in Sect. 2. Section 3 provides the details of the proposed scheme and formulates the overhead. Then, numerical and simulation results are given in Sect. 4. Finally, Sect. 5 concludes the paper.

2 System Model

Consider a typical M2M communication system, where cell radius is r_0 and the base station is in the origin, while there are D devices distributed in the cell evenly. Devices connect with the base station (BS) by contention, and send the packet with a random access pattern without the assigned resource by the BS.

Frame structure is used in this system, and the duration of each frame is T_F. Each frame is divided into N_{SA} slots, resulting that the length of the slot can be presented as $T_{SA} = \frac{T_F}{N_{SA}}$. We assume only M devices represented by $\{u_1, u_2, \cdots, u_M\}$ are active in one frame, and each transmits one information package to the base station during the duration of one frame. Further define the normalized offered traffic as $G = M/N_{SA}$ representing the average number of packets loaded per slot and the normalized throughput as T representing the average number of packets can be accepted successfully per slot. Device u_i chooses the value of replicas r_i of its packet, which is named after degree of device, according to a predefined degree distribution, then selects r_i slots randomly to transmit its packet repeatedly. We can define Λ_r as the probability of the device transmitting the packet for r times. Then the degree distribution can be expressed by

$$\Lambda(x) = \Lambda_1 x + \Lambda_2 x^2 + \cdots + \Lambda_{N_{SA}} x_{SA}^N \tag{1}$$

we have $\sum_r \Lambda_r = 1$. And the average degree of devices is given by

$$\overline{r} = \Lambda^{'}(1) = \sum_r \Lambda_r r. \tag{2}$$

The received signal in slot s_i is given by

$$Y_i = \sum_{i=1}^{M} a_{i,j} X_i + N_j, 1 \leq j \leq M \tag{3}$$

where N_j is the additive gaussian white noise and $a_{i,j}$ represents the corresponding coefficient between the i-th device and the j-th slot, $a_{i,j} = 1$ means the i-th device transmits its packet in the j-th slot, otherwise it's 0. The process of the access can be represented by a bipartite graph $\mathcal{G} = (\mathcal{B}, \mathcal{S}, \mathcal{E})$ like Fig. 1. $\mathcal{B}$ represents the set of devices $U = \{u_1, u_2, \cdots, u_M\}$, $\mathcal{S}$ represents the set of slots in one frame, and $\mathcal{E}$ is the set of edges in which the edge connecting a device node and a slot node indicates that the device transmits its packet in corresponding slot. The number of the edge connected to one slot is defined as the degree of the slot. This results in a collision when more than one devices connect to the same slot, in traditional ALOHA protocol the collision packets will be abandoned, but in [9] the collision packets may be decoded with inter-slot SIC.

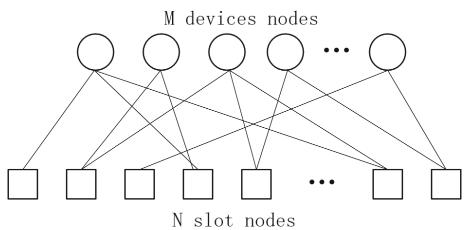

Fig. 1. System model of CSA

Firstly, the packets transmitted in degree-one slots can be recovered immediately, and edges connecting to the corresponding devices can be removed at the same time, since their carrying packets are decoded now. The degrees of the slots are updating as the process of the decoding. Repeat the above steps until that there is no evidence of the slot with degree one or all the packets are recovered.

Figure 2 shows an example about the process of SIC, where the frame consists of 4 slots and 3 devices, represented by circles and squares separately. The solid circles mean that the packets of these devices have been or can be already recovered in this step, and the hollow circles mean the packets still remain unrecovered.

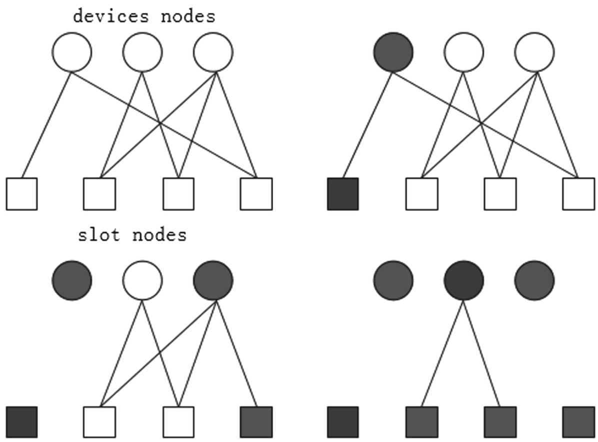

Fig. 2. Graph representation of the SIC procedure

3 Feedback Enhanced Design

In traditional CSA, high SNR is assumed, so we don't consider the effect of noise. BS will send ACK to the whole devices after SIC decoding when all the packets in this frame are recovered and then each device transmits a new packet in following frame. Otherwise, when the BS fails to recover some the packets in the decoding process, it will abandon the packets received now and start a new frame. The BS will send ACK to the devices whose packet is resolved to let them transmit their next packets and send NACK to the devices whose packet is unresolved to inform them to retransmit their packet in the next frame. In the feedback based model, it will not start a new frame but continue and add some additional slots to the current frame, and reuse the packets received and try to recover more packets by retransmitting parts of unrecovered packets. The number of retransmission packets and the additional slots are the same, and it is named retransmission number which is represented by N_{RE}. The retransmission procedure is detailed below.

When SIC procedure terminates with no evidence of degree-one slot, the BS sorts the devices with the updated degree in descending order, and informs the first N_{RE} devices to retransmit their packets sequentially. The number N_{RE} can be optimized by the simulation in Sect. 4. The packets of the devices with higher degree contain more information, and can be more useful in the SIC decoding algorithm comparing to these of the devices with lower degree. So, the BS chooses the more useful packets as the feedback information to recover the packets stored in the buffer.

As an example in Fig. 3. The SIC algorithm stops, remaining some packets unrecovered whose corresponding device nodes are represented by hollow circles in the final step. The BS finds N_{RE} devices with largest degree, informs them to retransmit their packets by sequence in the following N_{RE} slots and assigns specific slots for the retransmission packets individually. As an example, the set of devices $u_{i_1}, u_{i_2}, \cdots, u_{i_{N_{RE}}}$ are called to retransmit their packets, then u_{i_1} transmits its packet in the first additional slot, u_{i_2} transmits its packet in the next additional slot, and so on. The not involved devices wait for the next frame and don't transmit packets in the additional slots. The additional slots should be taken into account when calculating the normalized offered traffic, is given by $G = M/N$, where $N = N_{SA} + N_{RE}$, so as the normalized throughput. The BS continues the SIC algorithm after receiving the retransmitting packets, labels the packets recovered and removes the edges connecting to the corresponding devices. With the retransmitted packets, the performance of the system can be promoted and number of access devices can be increased to satisfy the system requirements.

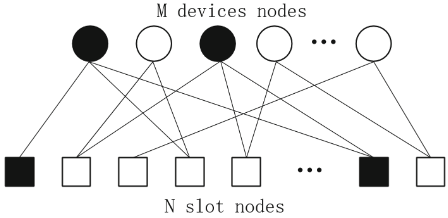

Fig. 3. Example of interrupting of SIC

3.1 Motivation of Feedback on CSA

Here we state the motivation of adding feedback in CSA transmission. When offered traffic load becomes close to 1, e.g. $G = 0.85 \sim 0.9 * N$, the collisions are significant. In this situation, applying SIC between slots will meet the stopping set problem [12], a term used in fountain coding, where no degree-one slot can be decoded due to circles between device nodes and slot nodes. If we just abandon the received slots, the system throughput would drop dramatically. To fully use the received signals, retransmissions of some transmitted packets with large degree will help to initiate the SIC decoding, and thus able the rebuilding of the previous received data packets. The retransmission order is announced by the receiver in dedicated feedback physical channel.

3.2 Overhead Analysis

When the SIC stops without recovering all the packets, the BS should send messages to all the devices to coordinate the transmission condition in the next N_{RE} slots. The chosen devices are required to retransmit their packets sequentially by the order received from the BS. There should be $\lfloor log(M) \rfloor * N_{RE}$ bits used for the instructions, where $\lfloor . \rfloor$ represents selecting the minimum integer larger than the value inside. Compared to the packets transmitted by the devices, the waste of the instructions is negligible, and the instructions can be transmitted in the traditional feedback channel.

The proposed scheme always wastes some slots to retransmit the unrecovered packets. However, the waste of slots for retransmitting is considered in the calculation of the normalized offered traffic and the normalized throughput.

3.3 Analysis on the Optimal N_{RE} value

In the papers about ALOHA random access, the highest achievable throughput is always regarded as one important metric to show the advancement of one access method. So in this section, we make some qualitative analysis in the optimal N_{RE} value to achieve highest throughput.

As aforementioned, when the decoder meets problem resulting from the stopping set, a number of N_{RE} devices conduct retransmission sequentially. For one specific feedback slot, it will either unlock a stopping set, or happen to be a slot decoded by BS with the aid of previous feedback slots, except for the very first feedback slot. Thus the latter a slot is retransmitted, the more possible this slot is a waste of resource.

When N_{RE} slots are feed back to the BS, define function $f(\Lambda, N, G, N_{RE})$ as the average number of decodable slots when N_{RE} slots are retransmitted, which is affected by Λ, N, G. Then the optimization problem can be shown by:

$$\max_{N_{RE}} \frac{N * T(G) + f(\Lambda, N, G, N_{RE})}{N + N_{RE}} \tag{4}$$

where $T(G)$ is the normalized throughput achieved by SIC decoder. The main challenge remains in the calculation of function $f(\Lambda, N, G, N_{RE})$, which is highly correlated to the stopping set distribution. Paper [7] studies the stopping set with low G, however, when G grows, the situation is pretty complex and become hard to derivate the analytic expression. In the following part of the paper, Montel-Carlo simulation is made to analysis the suboptimal value of N_{RE}, while fixings Λ with a classical formulation.

4 Numerical Results

We perform the simulation to verify the performance of our scheme, the simulation results are shown in the following. We adopted the degree distribution function $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$, and set the maximum iteration as 100 and the frame size as $N_{SA} = 200$ slots. Select the retransmission number as $N_{RE} = 1, 5, 10, 15, 20$, plot the throughput vs. traffic load curves, and compare the performance with traditional CSA. The curves are presented in Fig. 4. It can be seen that when the retransmission number is 5 or 10, the performance outperforms others. The proposed scheme has performance gains compared to CSA for that the largest peak throughput reaches $T \approx 0.83$, while the CSA is $T \approx 0.77$. The N_{RE} must be chosen suitably, in avoiding the case where although the retransmission packets promote the SIC decoding procedure, the peak throughput point still decreases since the retransmission cost too much resources. On the other hand, when the N_{RE} value is too small, performance gains will be inapparent. Choosing the optimal N_{RE} by theoretical calculations is quite hard, we changed the N_{SA}, and found the functional relation between the suboptimal N_{RE} and N_{SA} by simulation.

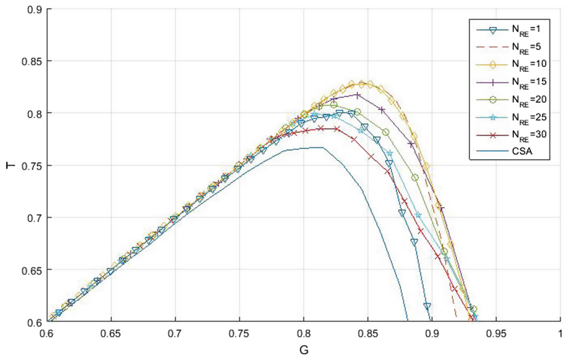

Fig. 4. Simulated throughput for $\Lambda(x) = 0.5x + 0.28x^2 + 0.22x^3$, $N_{SA} = 200$

As mentioned in Sect. 3, the higher-degree packets can be better able to promote the gain of throughput. As a comparison, we compare the situation where retransmitting the higher-degree packets to that randomly selecting the retransmitting packets, and prove that the scheme proposed in this paper is better than selecting the packets purposelessly. Comparison is shown in Fig. 6.

We simulated the following four scenarios where $N_{SA} = 200, 500, 1000, 2000$ respectively, and the degree distribution function remained unchanged as before. The simulation results of $N_{SA} = 200, 500$ are shown in Figs. 4 and 5. When $N_{SA} = 200$, the performance gain is obvious for about 10%. There is also a performance gain for more than 5% in the scenario where $N_{SA} = 2000$. As a summary, plot the variation of the peak throughput with different values of

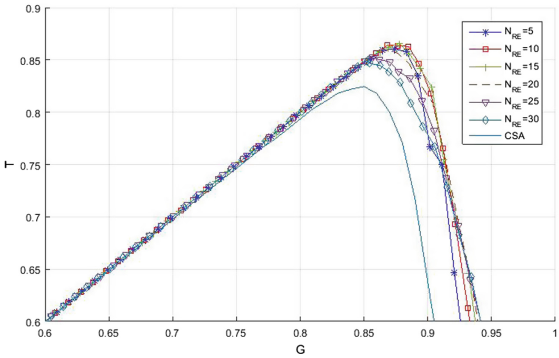

Fig. 5. Simulated throughput for $\Lambda(x) = 0.5x + 0.28x^2 + 0.22x^3$, $N_{SA} = 1000$

retransmission number N_{RE} in the four scenarios in Fig. 7. The peak throughput is increasing quickly when N_{RE} is quite small and the growth rate becomes slow as the increase of N_{RE}. There is an suboptimal value of N_{RE} promoting the throughput reaching the largest peak that when the N_{RE} is higher than it, the peak throughput will descend. Find the suboptimal values of N_{RE} in different scenarios. It's clear that the relation of suboptimal N_{RE} and N_{SA} is not linear. When the N_{SA} is really high, the suboptimal N_{RE} nearly remains unchanged. The performance is really similar when the N_{RE} ranging around 10, so we can choose the suboptimal N_{RE} as 10.

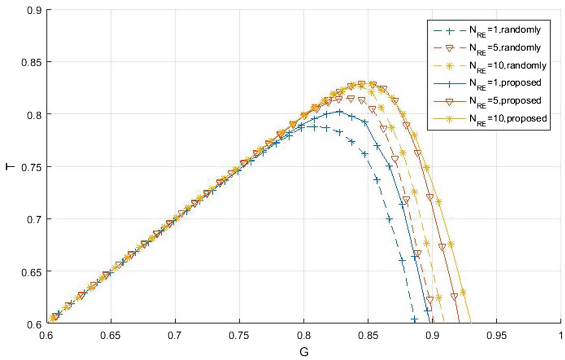

Fig. 6. Comparison of retransmitting the higher-degree packets to randomly selecting the retransmitting packets

Intuitively thinking, when a degree-8 user's packet is retransmitted, more packets is expected to be decoded, since this user may form a number of different stopping sets far more than 2 or 3. Once the degree-8 users are all retransmitted, with the growing of N_{RE}, the normalized throughput is expected to experience a

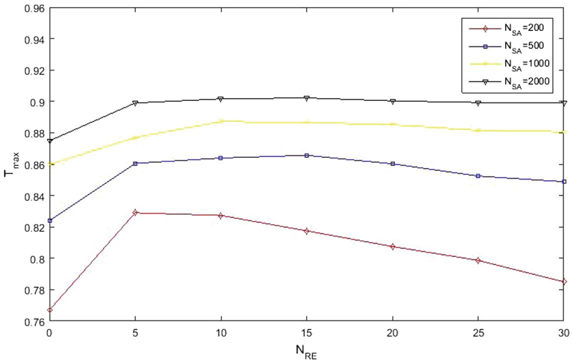

Fig. 7. Peak throughput as a function of N_{RE} in four scenarios

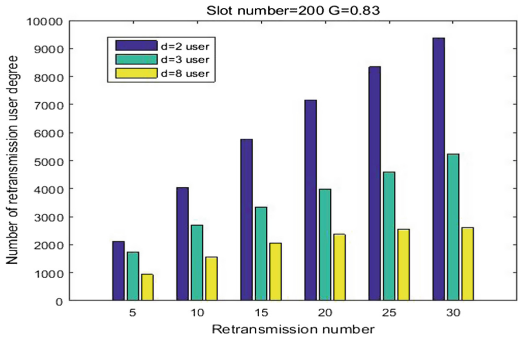

Fig. 8. Comparison of retransmitting the higher-degree packets to randomly selecting the retransmitting packets

dramatic decline. To this end, simulation is made considering number of different degree users out of retransmission users, as shown in Fig. 8. In the simulation result shown above, we observe that

1. When N_{RE} becomes larger, more degree-8 user is retransmitted, the system performance tends to grow. However, when N_{RE} is pretty large (i.e. larger than 15), more degree-2 or 3 users are retransmitted, meanwhile, the normalized throughput decreases.

2. Compare the situation $N_{RE} = 10$ with $N_{RE} = 15$, although the latter situation retransmitted more degree-8 users, which leads to decoding of more packets, it does cost more resources (almost 2%). Thus the best N_{RE} is chosen to be the tradeoff between the retransmission resource and decoded packets by retransmission, which happen to be 10 in the proposed scenario.

5 Conclusion

In this paper, we proposed an enhancement of the CSA to improve the throughput of the system meeting the demand of M2M communications. This is achieved by feedback scheme which make use of the abandoned packets of the traditional CSA. We calculated the overhead of the feedback and optimized the retransmission scheme. The simulations show the performance improvement of the proposed scheme compared to CSA.

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References

1. M2M Whie Paper: The Interoperability Enabler for the Entire M2M and IoT Ecosystem, April 2016. http://www.onem2m.org
2. Cellular Networks for Massive IoT, April 2016. https://www.ericsson.com
3. LTE-M - Optimizing LTE for the Internet of Things: White Paper, April 2016. https://networks.nokia.com
4. Chang, C.H., Chang, R.Y.: Design and analysis of multichannel slotted ALOHA for machine-to-machine communication. In: IEEE Global Communications Conference (GLOBECOM), San Diego, CA, pp. 1–6 (2015)
5. Yuan, J.: Coded slotted Aloha (CSA) schemes for machine-to-machine communications. In: 2015 9th International Conference on Signal Processing and Communication Systems (ICSPCS), Cairns, QLD, pp. 1–2 (2015)
6. Dhillon, H., Huang, H., Viswanathan, H., Valenzuela, R.: Fundamentals of throughput maximization with random arrivals for M2M communications. IEEE Trans. Commun. **62**(11), 4094–4109 (2014)
7. Cassini, E., Gaudenzi, R.D., 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 (2007)
8. Liva, G.: Graph-based analysis and optimization of contention resolution diversity slotted ALOHA. IEEE Trans. Commun. **59**(2), 477–487 (2011)
9. Ghanbarinejad, M., Schlegel, C.: Irregular repetition slotted ALOHA with multiuser detection. In: 2013 10th Annual Conference on Wireless On-demand Network Systems and Services (WONS), 18–20 March 2013, pp. 201–205 (2013)
10. Paolini, E., Liva, G., Chiani, M.: High throughput random access via codes on graphs: coded slotted ALOHA. In: Proceedings of IEEE International Conference on Communications, Kyoto, Japan, pp. 1–6, January 2011
11. Stefanovic, C., Popovski, P.: ALOHA random access that operates as a rateless code. IEEE Trans. Commun. **61**(11), 4653–4662 (2013)
12. Ivanov, M., Brannstrom, F., Amat, A.G., Popvski, P.: Error floor analysis of coded slotted ALOHA over packet erasure channels. IEEE Commun. Lett. **19**(3), 419–422 (2015)