Multi-Tone Carrier Technique for Signal Recovery from Collisions in UHF RFID with Multiple Acknowledgments in a Slot

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***Abstract*—In passive Radio Frequency IDentification (RFID) systems, tags do not have their own power source and they receive their operating energy from continuous modulated RF carrier transmitted by the reader. The tag while receiving this carrier randomly selects a slot and sends back its RN16 using backscatter modulation for purpose of its identification. The efficiency of the existing UHF RFID systems is limited, as only response from a single tag in a slot can be decoded successfully. If multiple tags select the same slot collision happens, information of physical layer is discarded and retransmission is executed. In this work, a multi-tone carrier wave is exploited to make the collided tag signals decodable. In addition, a novel method to acknowledge the multiple tag signals in a single slot is proposed. The system performance in terms of expected throughput is significantly improved with the use of both multi-tone carrier and the multiple acknowledgements technique at the same time.**

***Index Terms*—RFID, collision recovery, multiple acknowledgments, signal separation, tag identification.**

I. Introduction

Radio Frequency IDentification (RFID) is an advanced wireless technology in which the tagged objects are identified using radio waves. The RFID systems are operated in various frequency bands i.e. Low Frequency (LF) (125 KHz), High Frequency (HF) (13.56 MHz) and Ultra High Frequency (UHF) (860 MHz – 950 MHz). As the operating range and the data rates of UHF RFID systems are much higher than those of HF and LF, this work focuses on UHF RFID systems which follow EPC Class-1 Generation-2 standard and uses passive tags operate at UHF frequencies [1].

According to the defined standard, all the tags present in the reader range are scheduled on Medium Access Control (MAC) layer using Framed Slotted ALOHA (FSA) [2]. Thereby, response of single tag in a slot can be decoded successfully. If multiple tags select the same slot, collision occurs and the information is discarded [3]. Furthermore, the currently used protocol allows only single tag acknowledgment in a slot. Thus even if data of all the tags involved in the collision is correctly decoded, only one of them proceeds with the identification process.

Recently, different groups have started working on slots having multiple colliding responses from different tags. Khasgiwale et al. [4] exploited the physical layer information from tags collision and estimated the number of tag signals colliding in a single slot. They correctly decoded the data of tags involved in the collision as well. Shen et al. [5] analyzed the signal constellation of tag signals colliding in a single slot and successfully decoded four colliding tag signals; however, they focused on Low Frequency (LF) tags instead of UHF tags. Angerer et al. [2, 3] proposed the channel estimation for two tags colliding and successfully decoded the data of both the tags on the behalf of receivers using zero forcing and successive interference cancellation techniques with single antenna as well as multiple antennas. They achieved an increase in the theoretical throughput with physical layer collision recovery and showed that if the number of tags colliding in a single slot was less or equal to the number of receiving antennas then it was possible to recover each tag signal involved in the collision. In extension to this work, Kaitovic et al. [6] proposed the receivers to separate multiple colliding tag signals provided the number of tag signals colliding in a single slot was not greater than twice the number of receiving antennas. By acknowledging single tag per slot when there were eight tag signals colliding in a slot they achieved 2.6 times increase in throughput compared with that

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of the conventional RFID reader, by employing four receiving antennas. Furthermore, Kaitovic et al. [7] proposed channel estimation by modifying tag response, and the throughput was increased by 5.03 times that of the conventional reader by acknowledging two tags per slot. Benbaghdad et al. [8] used the transmitting antenna of the reader as a second receiving antenna in backscatter communication. Liu et al. [9] presented multi-carrier UHF RFID system for the range extension and later [10], they used this multi-carrier scheme for the improvement of performance. However, their criteria fulfilled the signal recovery of only one tag for acknowledgment in that slot.

In this paper, an algorithm is proposed for multiple acknowledgments in a slot in addition to the use of a multi-tone carrier for the recovery of collided signals in UHF RFID systems. The paper is organized as follows: The theoretical throughput increase of an FSA system with collision recovery and multiple acknowledgments in a slot is discussed in Section II. Section III presents a model of the signal in UHF RFID systems. With such a signal model, a collision recovery method using a multi-tone carrier is proposed in Section IV. Further, an algorithm for multiple acknowledgments in a slot is given in Section V. Finally, Section VI concludes the paper.

II. BENEFITS OF COLLISION RECOVERY AND MULTIPLE ACKNOWLEDGMENTS IN A SLOT IN FSA

In FSA, reader begins an inventory round by issuing a *Query* command with information of frame size F. While receiving this command, tag randomly selects a slot and reply with its RN16 (16 bit Random Number) in the corresponding slot using backscatter modulation. The reader acknowledges the tag with respective RN16 as a handshake mechanism and upon correct acknowledgment the tag returns its unique identifier completing the arbitration process.

It happens that certain slots are selected by only one tag (singleton slots), some slots are not selected by any tag (empty slots) and some are used by more than one tag (collision slots). The conventional system can only make use of singleton slots and achieves maximum average throughput of 0.368 successful read outs per slot only if the frame size F is set equal to the number of tags present in the reader range (F=N) [2]. The number of empty and collision slots is always a waste, which makes the system inefficient.

With z tags transmitting in a slot, the maximum average throughput is given by:

$$T = \sum_{z=1}^{M} \binom{N}{z} \left(\frac{1}{F}\right)^{z} \left(1-\frac{1}{F}\right)^{N-z}. \tag{1}$$

Here, value of z can be 0 (empty slot), 1 (singleton slot) or 2 and more (collision slot) and M is the number of tag signals the reader is capable to resolve in a single slot. The increase in expected throughput of the system with parameter M is shown in Fig. 1.

Equation (1) follows acknowledgment of only a single tag in a slot (A=1) even if it is able to recover from collision as defined by the standard, where A is the number of tags acknowledgment per slot.

The throughput can be increased further with multiple acknowledgments per slot and is given by [3]:

$$T = \sum_{z=1}^{A} \binom{N}{z} \left(\frac{1}{F}\right)^{z} \left(1-\frac{1}{F}\right)^{N-z} z + \sum_{z=A+1}^{M} \binom{N}{z} \left(\frac{1}{F}\right)^{z} \left(1-\frac{1}{F}\right)^{N-z} A. \tag{2}$$

The increase in expected throughput with two tags acknowledgment per slot (A=2) and parameter M is shown in Fig. 2.

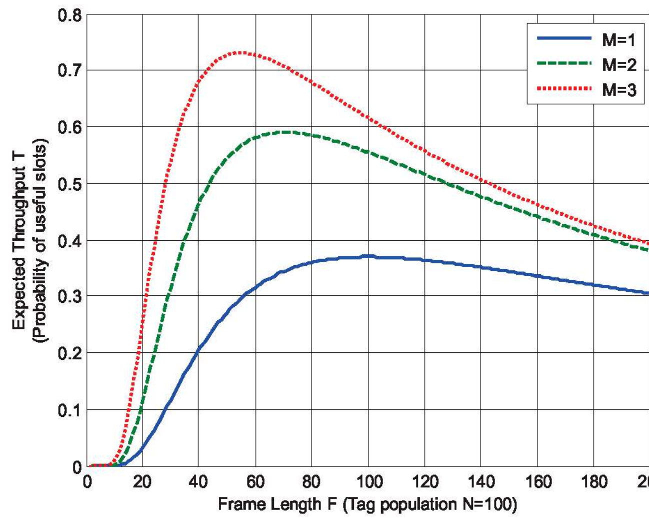

Fig. 1. Expected throughput T vs. collision recovery factor M

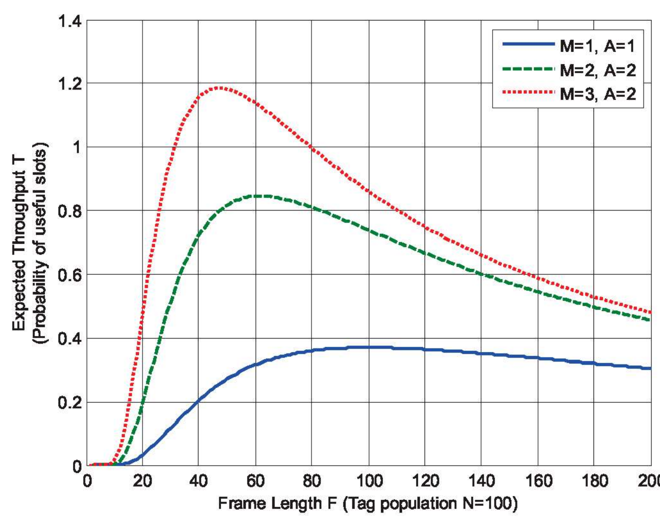

Fig. 2. Expected throughput T vs. collision recovery factor M for acknowledgments $A \leq 2$

TABLE I
Maximum theoretical throughput for collision recovery factor $M = (1, 2, 3)$ & acknowledgments $A \leq 2$

System	Maximum Expected Throughput T
M=1 A=1	0.368
M=2 A=1	0.587
M=3 A=1	0.726
M=2 A=2	0.841
M=3 A=2	1.184

The results are summarized in Table 1. Theoretical increase of the expected throughput with collision recovery and multiple tags acknowledgment in a slot is motivating the development of such a receiver.

III. Signal Model in UHF RFID Systems

The basic communication process of an RFID reader with group of tags is shown in Fig. 3. The wireless channel attenuation is neglected for the sake of simplicity. The signal is strong enough in downlink (from the reader to the tag) communication, therefore the noise is considered as Additive White Gaussian Noise (AWGN) only in the uplink (from the tag to the reader) communication.

The communication in UHF RFID systems is half duplex and during times the reader does not modulate any signal, it provides energy to the tags in the form of continuous carrier wave transmission.

$$s_{TX}(t) = \sin(w_c t). \quad (3)$$

This continuous carrier wave transmission also leaks into the receiving antenna of the reader and is given by:

$$s_{leak}(t) = A_l \sin(w_c t + \varphi_l). \quad (4)$$

Here, $w_c = 2\pi f_c$ and f_c is the carrier frequency of the carrier wave and is composed of a single frequency of UHF band. The phase shift φ_l is the propagation delay from transmit to receive antenna and the amplitude A_l is determined by decoupling of both antennas.

The tag transmits back its information to the reader by switching its antenna input impedance from the absorbing energy state to the reflecting energy state using backscatter modulation. This tag signal is received by the receiving antenna of the reader and is given by:

$$s_{tag}(t) = a_t(t) \sin(w_c t + \varphi_t). \quad (5)$$

Here, phase shift φ_t denotes the propagation delay between the receiving antenna of the reader and tag, whereas $a_t(t)$ is the amplitude of tag signal.

The tag signal adds up with the carrier leakage and noise $n(t)$ at the air interface. Hence, the final signal received at the reader can be written as:

$$s_R(t) = s_{leak}(t) + s_{tag}(t) + n(t). \quad (6)$$

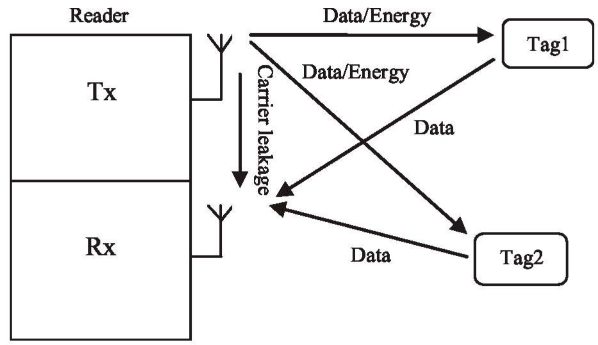

Fig. 3. Communication between an RFID reader and multiple tags

Consequently, the received signal is down converted by the reader to the baseband and as the carrier leakage is 90dB stronger than the backscattered signal, in case when the noise present remains below the certain limit, the receiver is capable of extracting the encoded data of the tags easily [2].

When multiple tags try to communicate with the reader at the same time, collision happens. Thus, the modulation sequences from these tags $s_i(t)$ add up and the resultant signal is given by:

$$s_{RX}(t) = \sum_{i=1}^{z} s_i(t) + s_{leak}(t) + n(t). \quad (7)$$

IV. Collision Solving Technique

All the signal components used in the model are modulated by the same carrier frequency originating from a single source i.e. transmitter of the reader, which makes the system feasible to use the same modulation frequency to jointly down convert all the signal components [3]. In this scenario, the technique proposed here is to use multi-tone carrier instead of single frequency carrier, which will eventually help in decoding the collided tag signals.

To meet the goal, it is required to make the modifications in the reader as well as in the tag. Thus, on the reader side the carrier wave is modified in such a way that it is composed of number of frequency components instead of a single frequency i.e. a multi-tone carrier in UHF band. The carrier wave transmitted by the reader is now given by:

$$s_{TX}(t) = \sum_{j=1}^{R} \sin(2\pi f_{cj} t). \quad (8)$$

Here, R is the total number of frequency components used by the carrier wave.

On the tag side, a band pass filter is added which allows only single frequency component of the multi-tone carrier to pass. The tag uses it for backscattering modulation same as defined by the standard.

While receiving backscattered tag response, the reader demodulates it with traditional method by using the same transmitted multi-tone carrier as shown in Fig. 4. There is no overhead of the proposed solution if reader receives a single tag response.

If the reader is unable to read the data of the received tag signal by demodulating it with multi-tone carrier and finds a collision in the respective slot, it starts demodulating the received collided tag signal using each frequency component of the carrier separately and tries to read the data of each tag every time it demodulates the data.

If the tags involved in the collision used different carrier frequency components for their backscatter modulation, they are easily separable by demodulating them with their respective frequency as shown in Fig. 5.

The only case, the proposed solution does not work is when all the tags involved in the collision use same frequency component of the carrier for backscattering modulation, the reader fails to extract any of the tag signals and gets back the collided signal as shown in Fig. 6. The probability of the worst case depends upon the number of frequency components involved in the multi-tone carrier *R* and the number of tags designed to use certain frequency component of the carrier in the reader range. If each tag present in the reader range has equal probability to use certain frequency component of the carrier for modulation, the probability of collided slots that are un-decodable is only *1/R* of the probability of total collided slots.

The proposed solution is able to decode all of the tag signals involved in the collision if they have chosen different frequency components for their backscattering modulation.

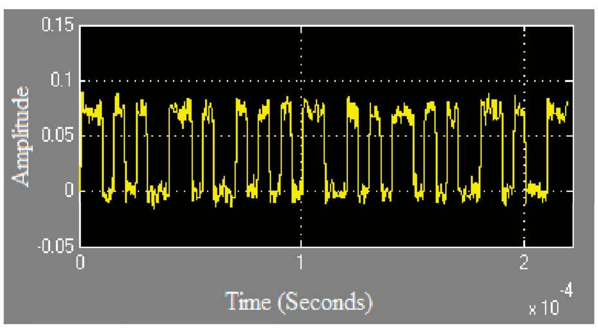

Fig. 4. Tag waveform with no collision

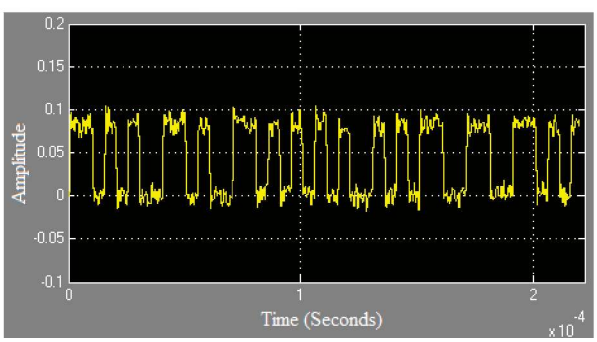

Fig.5. Tag waveform demodulated using respective carrier frequency (two tags collision)

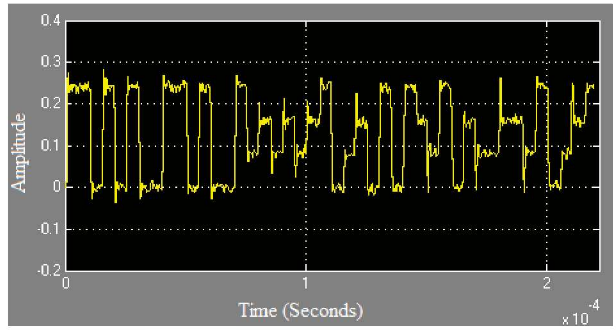

Fig. 6. Multiple tags using same carrier frequency (two tags collision)

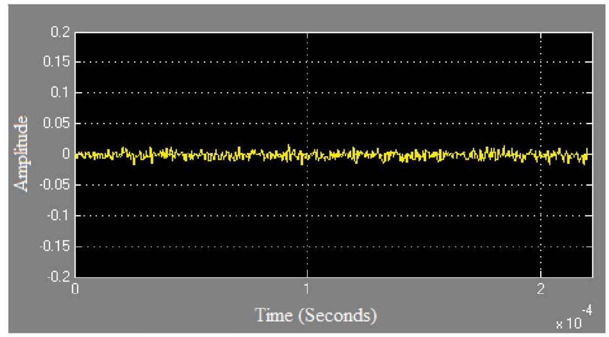

Fig. 7. Signal demodulated using carrier frequency not used by any of the tag

If in collision, a frequency component is not used by any of the tag, the reader gets no data when it uses the corresponding frequency for demodulation of the collided signal as shown in Fig. 7.

V. Multiple Acknowledgments in a Slot

As stated earlier, present protocol does not allow multiple acknowledgments in a slot. So even if the data of multiple tags is decoded successfully from a collision slot, only one of these RN proceeds with the identification process. To acknowledge all of these tags, a novel algorithm is proposed.

Figure 8 shows an example of acknowledging two tags per slot after recovering from collision. When there is a collision of two tag signals in a slot and the reader correctly decodes data of the both tags involved in the collision, instead of transmitting one of the successfully decoded RN16 for acknowledgment, it transmits both the RN16s in a queue format as a 32 bit data with an *ACK* command. Tags with their slot counter zero while receiving these 32 bits, only read the first 16 bits in the beginning. If it's transmitted RN16 matches the start bits, the tag reply back its EPC (Electronic Product Code) immediately and discards the remaining bits. If the transmitted RN16 of a tag does not match first 16 bits, it reads next stream of bits and if its RN16 matches the remaining bits, it reply back its EPC with a defined delay in the same slot.

The reader after transmitting 32 bits *ACK* waits for the first tag reply and after a defined delay expects the reply of second tag. The algorithm requires tags data from collision in the same slot prior to acknowledge multiple tags in a slot.

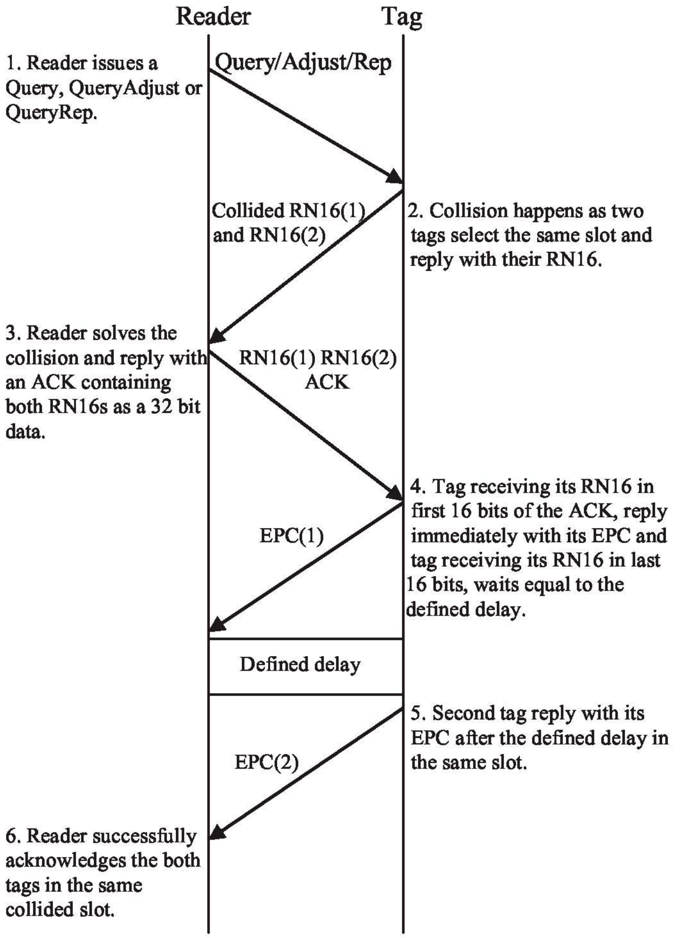

Fig. 8. An example of acknowledging two tags per slot

The proposed algorithm of acknowledging multiple tags in a slot can be extended for more than two tags in a slot as well. It breaks through the limit of expected throughput and maximizes it up to more than one.

VI. Conclusion

In this paper, we have presented the way of increasing the theoretical throughput with physical layer collision recovery and multiple acknowledgments in a slot of FSA RFID systems. There is no overhead of the proposed solution when there is no collision. The probability of collisions, not able to be recovered, is reduced by number of frequency components used by the multi-tone carrier. Moreover, we have proposed an algorithm for multiple acknowledgments in a slot which requires tags data from collision in the same slot prior to its operation. The methods proposed in this paper would require little modifications in the existing RFID standard. The simulations of the proposed system clearly show that the theoretical throughput for a reader, capable of acknowledging two tags per slot with three tags colliding, is increased by 3.2 times that of a conventional reader. It is also worth-mentioning that the proposed solution does not limit the throughput; the higher the number of frequency components involved in the carrier as well as the time duration of multiple acknowledging slots, the higher the throughput will increase.

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