Resolving Collision in EPCglobal Class-1 Gen-2 System by Utilizing the Preamble

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***Abstract*—The collision resolution mechanism is a key factor for successful communication in dense Radio-Frequency Identification (RFID) systems. One of such collision resolution mechanisms is the ALOHA protocol used in the EPCglobal Class-1 Gen-2 standard (EPCglobal). The success of the ALOHA-based protocols in RFID systems depends on the estimation of the number of tags in the electromagnetic field of an interrogator. The majority of the proposed optimization methods of the ALOHA-based protocols focus mainly on the estimation of the number of tags based on past slot results. Only few of the proposed methods try to determine the exact number of tags that involve an analysis of the received signal. One such method is the Radar Cross Section (RCS) method. We will show that RCS is not appropriate for RFID systems that include channel filtering as in the case of the EPCglobal standard. As a replacement for the RCS method, we propose a new anti-collision method to improve the anti-collision mechanism based on the utilization of the frequency analysis of the preamble. We will demonstrate that the method improves the existing anti-collision algorithm used in the EPCglobal and enhances the capture effect capability.**

***Index Terms*—ALOHA, anti-collision, backscattering, EPCglobal, interrogator, media access control, Miller coding, RFID.**

I. Introduction

MEDIA ACCESS CONTROL (MAC) is a mechanism for resolving one of the most critical moments in communication. In RFID systems [1], the MAC mechanism defines the procedure of establishing the communication link between the tags and the interrogator. This part of the communication process is especially critical for high-density RFID systems where several hundred tags are placed in the electromagnetic field of an interrogator at the same time. Examples of such RFID systems can be found in warehouses.

The main goal of a MAC mechanism in such systems is to minimize the collision occurrences due to mutual transmissions of two or more tags at the same time, which represents a loss in a communication channel. A prolonged communication between an interrogator and a tag due to the loss in the communication channel will result in a decreased life time of a battery-powered tag or in an unidentified tag if the tag leaves the electromagnetic field of the interrogator before it is identified.

In RFID systems the MAC manages communication links by enabling the frequency and time range inside which a tag and an interrogator may transmit to minimize the number of collisions. For this purpose, the EPCglobal standard utilizes the Dynamic Frame Slotted ALOHA (DFSA) based protocol.

The main problem of the DFSA protocol in RFID systems is to determine the number of tags in the field of an interrogator. This information is needed to set the optimal frame size [2] and to achieve the maximum throughput of the protocol.

A number of solutions have been proposed on how to adjust the frame size. The majority of these solutions are focused on the observation of the success of each time window (slot) in a frame [3]. Only a few of the proposed methods focus on signal analysis to determine the exact number of tags in the collision windows such as RCS-based methods [4]. In this paper, we will show that the proposed RCS methods will fail when embedded in the EPCglobal RFID system. In addition to the aforementioned methods, the capture effect methods will be presented. As it will be explained later in this paper, these methods are not suitable as standalone solutions where no other methods are needed, since they require a good distribution of communication over time. This means that the underlying algorithm to distribute the tag transmissions over frame is still needed.

The paper will present a new method that improves MAC in the case of the EPCglobal standard. The main advantage of the proposed method is that it can be implanted in the EPCglobal standard and is superior to the existing methods that are in scope of the EPCglobal standard. We will also show that the presented method improves the capture capability of the additionally employed methods based on capture effect.

The paper is organized as follows: Sections II and III explain the most important basics of the EPCglobal standard, the existing methods and the problems associated with these methods. A new algorithm for the improved anti-collision scheme and data decoding is proposed in Section IV. In Sections V and VI, measurement results are shown that prove the concept and an evaluation of the proposed scheme is performed.

II. Collision Avoidance in EPCglobal

To establish a communication channel between a tag and an interrogator, a tag must be identified by an interrogator. After the identification of a tag, an interrogator can start the data exchange.

In any RFID system, the most critical moment due to the possible occurrence of collision is a tag identification. Tag

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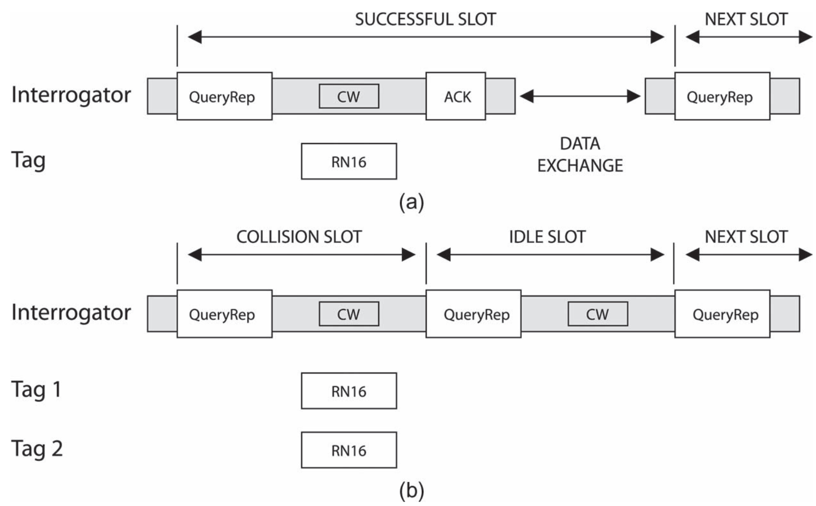

Fig. 1. EPCglobal anti-collision protocol.

identification is a part of the anti-collision process where the tag transmits its unique identification number (UID) to the interrogator. The identification is successful if the interrogator successfully receives the UID and transmits it back to the tag as confirmation of the established communication link. Once the tag has been successfully identified by the interrogator, the protocol employed in the RFID ensures that other tags will not transmit for the duration of the communication between the interrogator and the identified tag.

The mechanism employed for resolving media access during the identification of the tags in the EPCglobal is the DFSA. The DFSA divides communication time into frames, where each frame consists of several slots. The number of slots in each frame is set by the interrogator at the beginning of the frame. A tag is allowed to transmit only once in a randomly selected slot per frame.

Communication in the DFSA is initialized when the interrogator transmits a query command by which it defines the initial size of the frame. Each tag randomly selects one of the slots in the frame and transmits a 16-bit random number (RN16) that represents the UID of a tag during the anti-collision phase as shown in Fig. 1.

An interrogator confirms the received RN16 with returned acknowledgement (ACK) that includes the received RN16. After that point, the interrogator and the tag can continue with data exchange (Fig. 1(a)). In cases where the signal is corrupted due to data collision caused by mutual transmission from several tags in the same slot or in the case of an idle slot where none of the tags have transmitted (Fig. 1(b)), the interrogator will omit ACK response and continue the frame with the next slot by sending a new QueryRep command.

By changing the size of the frame, the interrogator changes the distribution of the tags over the slots in a frame. If the frame size is too small in comparison to the number of tags, the probability of a collision increases, which will end in a slow anti-collision process. If the frame is too large, the same problem is observed since the number of empty slots will increase, which also represents a loss in throughput during the identification of all tags.

The maximum throughput of the anti-collision process is achieved when the frame size is the same as the number of tags that are trying to transmit their own UID. The probability equation defining the relation between the number of slots in a frame and tags in the interrogators field in relation to the maximum channel throughput is equal to

$$E\{\varkappa_R\} = K\binom{N}{R}\left(\frac{1}{K}\right)^R\left(1-\frac{1}{K}\right)^{N-R} \tag{1}$$

where $E\{\varkappa_R\}$ denotes the expected value of the random variable $\varkappa_R$ that indicates the number of slots with precisely R tag responses, N is the number of tags in the interrogators range, K is the frame size, and R is the number of tags transmitting in the same slot. The maximum throughput of the DFSA protocol is when [2]:

$$K = N, \ \frac{E(\varkappa_1)}{K} = 0.368. \tag{2}$$

According to (2), the maximum average expected number of slots with single transmission is 36.8% if the frame size is set to the optimal value. Since the number of tags is unknown in advance, the interrogator selects a frame size that is defined as an initial frame size by the application. The frame size is then adapted during the communication.

For adapting the frame size, the EPCglobal standard proposes the Q-algorithm shown in Fig. 2. During the anti-collision phase, the Q-algorithm updates the value Q_{fp} based on the success of the slot. In the case of an empty slot, the value Q_{fp} is decreased, while in the case of a collision slot, the value Q_{fp} is increased. The successful slot has no effect on the value Q_{fp}.

The relation between the value Q_{fp} and the frame size (K) is given by

$$K = 2^{Q_{fp}}. \tag{3}$$

The frame size is adjusted at the end of the frame. The increase rate of the frame size depends on the constant C. The EPCglobal proposes the value of C in range of 0.1–0.5.

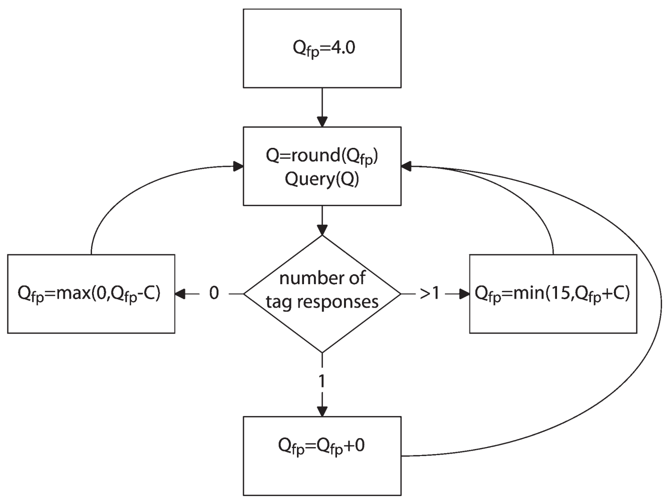

Fig. 2. EPCglobal Q-algorithm [5].

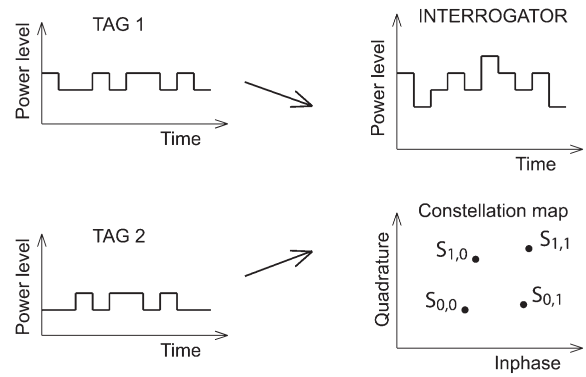

Fig. 3. Superposition of power levels.

III. The Existing Q Algorithm Optimizations

The optimization of the EPCglobal protocol throughput can be divided in two groups: the first group includes methods that improve the convergence to the optimal size of the frame by estimating the number of tags in the interrogator's field. Such methods are based on the statistics of past slots and RCS methods. For the RCS method, we will explain and show why it cannot be applied to the RFID system employing EPCglobal standard.

In the second group are methods that improve the throughput during the anti-collision phase by decoding the UID also from the slots were collision occurred. These methods are based on the capture effect.

A. Methods Based on Observations of the Frames

The first group of optimizations comprises methods where a new frame is calculated on the basis of the results from the past slots. A part of this group is also the Q-algorithm. Since the calculation of the number of tags is based on probability, the optimal frame size can only be estimated. These methods are evaluated by comparing the convergence rate against the optimal frame size, which is then reflected in increased throughput.

The basic problem of the Q-algorithm that the new methods are trying to resolve is that the Q-algorithm does not differentiate between frames based on the ratio between collision, empty and successful slots. This can be seen from the fact that the C value is a constant. To improve the Q-algorithm, the new methods propose an adaptation of the C value during the anti-collision phase. An exhaustive overview of DFSA optimizations for RFID systems can be found in [6].

B. Methods Utilizing RCS

The methods based on RCS are focused on the analysis of the received signal to solve the problem of the unknown number of tags in the collision slots in the last frame. The basic principle of the RCS method is based on the observation of the received signal and identification of the number of RCS vectors. The methods based on RCS for solving the data collision process in EPCglobal RFID systems are proposed in [2], [7]–[9].

Tags performing in accordance with the EPCglobal standard utilize the backscattering principle [4] to communicate with the interrogator. When backscattering is employed, the tag switches between two input resistances during the transmission. In this way, it modulates the backscattered signal, which can be seen as an amplitude modulation. The backscattered data is then demodulated on the interrogator's side by employing an I/Q demodulator.

The binary backscattered signal from a tag can be observed on the interrogator's antenna as two different power scalar values of the returned signal (the non-modulated and the modulated value). The reflected power from a tag also depends on the modulation phase of the backscattered signal due to which an interrogator needs an I/Q demodulator. A scalar value and a phase of the reflected power are combined to obtain an RCS vector.

Fig. 3 shows the reflected power levels on the interrogator's side during the scattering of the electromagnetic field from two tags. The scattering of the electromagnetic field from the tags is superpositioned. For this reason, four different power levels can be observed on the interrogator's side representing four combinations, which means that we get four different RCS vectors. The observed four power levels can also be presented on a constellation map that can be created by using the outputs of the I/Q demodulator.

An I/Q demodulator has an inphase and quadrature output. If both outputs are used for plotting an I/Q constellation map, the same result is obtained as in the case of RCS identification.

To identify the number of collided tags in a slot, the clusters in the constellation map need to be counted. Such a method can be developed based on the Independent Component Analysis (ICA) as shown in [9]. The relationship between the number of tags (N_S) that transmit in the same slot and the number of different observable RCS vectors (S) is $S = 2^{N_S}$.

The problem of the RCS method arises when we try to implement the method on an RFID system based on the EPCglobal standard. The standard specifies the communication where the interrogator may choose the channel of communication (channel hopping). This means that additional filtering of the input

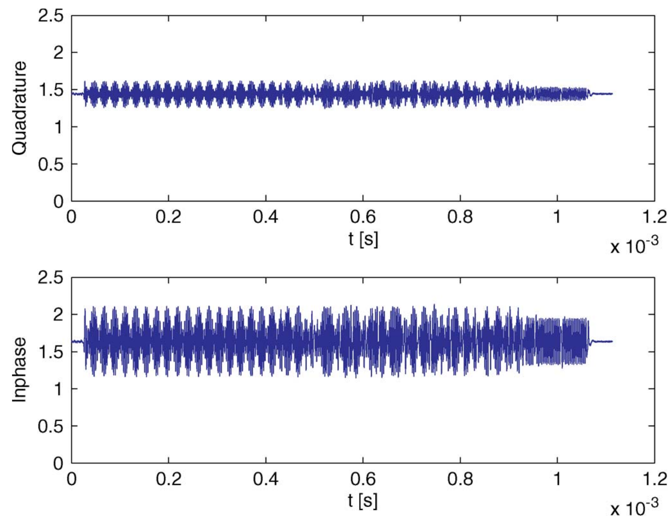

Fig. 4. Collision of 2 tags on output of a real I/Q demodulator.

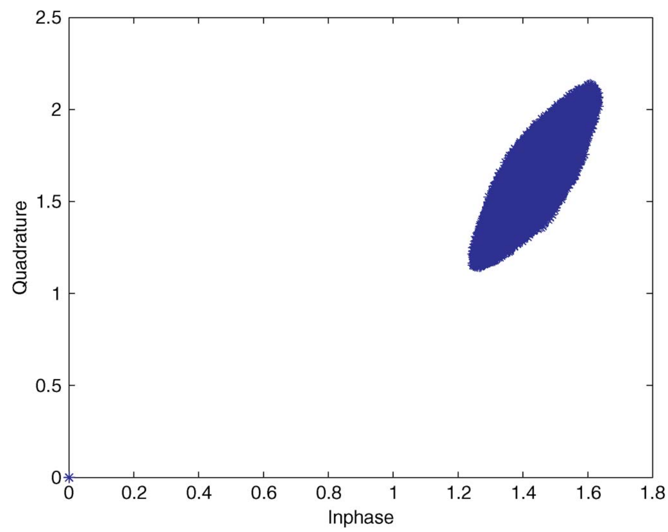

Fig. 5. I/Q constellation plot of 2 colliding tags.

signal on the interrogator's side must be applied to filter the neighbor channels. An example of a signal on the output of a real I/Q demodulator that also includes the band pass filter [11] is shown in Fig. 4.

When performing filtering on a signal that is binary modulated—square, the harmonics of the signal that are outside of the channel bandwidth are lost [10]. This kind of filtering poses a problem when implementing the presented method. To be able to apply the methods like ICA on the I/Q constellation map, the distribution of the signal states must be Gaussian [9]. Due to the applied channel filtering, the signal is sinus-shaped and the signal states cannot be identified.

When a signal from a real I/Q demodulator is used to create an I/Q constellation plot, we obtain the result as shown in Fig. 5. As it can be seen from the constellation map, a sinus-shaped signal states have non-Gaussian distribution. For this reason, an RCS method cannot be used in the RFID system employing the EPCglobal standard.

C. Methods Utilizing the Capture Effect

The last group of applicable solutions to improve the throughput during the anti-collision phase comprises the methods based on capture effect [12], [19]. These methods propose a solution in terms of detecting the strongest signal. When the signal strength from various sources is different enough, the receiver is able to decode the signal with the highest received power. Such methods can be applied on collision slots. The advantage of the successfully recovered data from the collision slots is an increased throughput since the number of unsuccessful slots is reduced.

The basic approach proposed for capture effect is based on creating the conditions where one of the received data streams has the strongest signal, as described in [19]. To increase the capture effect capability, various methods propose approaches that would enable the recovery of the collided slot even when the difference between the received signal strengths is small.

The method described in [12] proposed a special bit coding that improves the capture effect capability. It also assumes that tags that collided did not transmit at the same time, which is true in the case of pure ALOHA protocols. The proposed design solutions enable the decoding of a signal that is stronger compared to the others between 1–3 dB or as little as 0.17 dB.

The problem with the existing capture effect methods is that when more than two tags transmit with a similar signal strength at the same time the efficiency of these methods is decreased significantly. For this reason, the capture effect methods should be used as a throughput enhancement for the two previously mentioned methods, where algorithms such as the Q-algorithm or the one that we will propose provide for a good distribution of tags over time. The capture effect methods are presented in this paper only to explain the effect of the proposed method on the capture effect capability itself.

IV. Improved Collision Resolution Algorithm

In this section we will present a new method that enables fast convergence to optimal frame size and improve the throughput of the anti-collision protocol. The approach is built on observing the properties of the RFID system that performs according to the EPCglobal and can also be used in other similar RFID systems. We will also explain why this approach impacts the performance of the applied capture effect methods.

A. The Analysis of the Signal During the Anti-Collision

Each data packet transmitted by a tag during the anti-collision phase in the RFID system that operates according to the EPCglobal standard is comprised of a preamble and data. The length of the preamble depends on the parameter (TRext) defined by the interrogator at the beginning of each frame. An interrogator can also choose between a FM0 and Miller 2, 4 and 8 types of the data encoding and different backscattered link frequencies. Fig. 6 shows an example of Miller 2 encoded preamble which can be divided into leading zeros (pilot tone) and bit sequence (010111) indicating start of data frame.

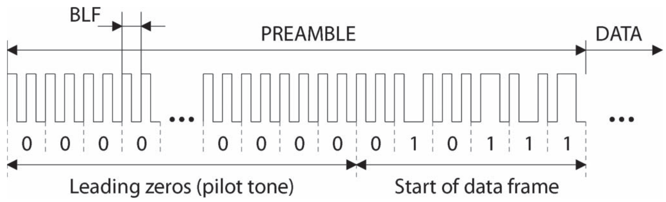

Fig. 6. Miller 2 encoded preamble.

When transmitting data, the tag modulates the carrier wave, where the carrier is the electromagnetic field of the interrogator. The frequency at which the tag modulates the carrier is called Backscatter Link Frequency (BLF) and is generated by the internal oscillator of the tag. The BLF can be directly observed as frequency of the pilot tone that consists of the Miller coded zeros in the preamble as shown in Fig. 6.

When the tag backscatters the signal to the interrogator, a signal s_t is observed on the interrogator's antenna defined as

$$s_t(t) = x_d(t) \cdot \cos(2\pi f_c t + \Theta_{td}) \tag{4}$$

where x_d, f_c, and Θ_{td} are backscattered binary data, frequency of the carrier and tag to interrogator phase delay [14], respectively.

In the case when two tags backscatter the data at the same time, the backscattered signals are superpositioned. The quadrature output on the I/Q demodulator when tag A $(s_{t,A})$ and B $(s_{t,B})$ are transmitting in the same slot is

$$z_Q(t) = [(s_{t,A}(t) + s_{t,B}(t)] \cdot \sin(2\pi f_c t) \tag{5}$$

$$\begin{aligned} z_Q(t) &= (x_{d,A}(t) \cdot \cos(2\pi f_c t + \Theta_{td,A}) + x_{d,B}(t) \\ &\quad \cdot \cos(2\pi f_c t + \Theta_{td,B})) \cdot \sin(2\pi f_c t) \\ &= x_{d,A}(t) \cdot \frac{1}{2}(\sin(\Theta_{td,A}) - \sin(4\pi f_c t)) \\ &\quad + x_{d,B}(t) \cdot \frac{1}{2}(\sin(\Theta_{td,B}) - \sin(4\pi f_c t)) \end{aligned} \tag{6}$$

$$\begin{aligned} z_{LPF,Q}(t) &= LPF[z_{i,Q}(t)] \\ &= x_{df,A}(t) \cdot \frac{1}{2} \cdot \sin(\Theta_{td,A}) + x_{df,B}(t) \cdot \frac{1}{2} \cdot \sin(\Theta_{td,B}) \end{aligned} \tag{7}$$

Equation (7) represents a quadrature signal $z_{LPF,Q}$ on the output of the low pass filter (LPF). Low pass filtering is applied due to carrier rejection. Since the EPCglobal also requires operation on different channels (channel hopping), an additional band pass filtering (BPF) is applied to the signal $z_{LPF,Q}$

$$z_{BPF,Q}(t) = BPF[z_{LPF,Q}(t)]. \tag{8}$$

The effect of the band pass filtering of the binary coded data is that all the higher harmonics of the square binary signal (x_{df}) that are outside the band pass are also part of the filtering rejection. Since the I/Q demodulator in the interrogator usually also comprises filters, the I/Q demodulator will be referred to as a demodulator that includes the necessary band pass filter.

The presented results show that the shape of the signal on the I/Q demodulator output depends on the channel bandwidth. The EPCglobal defines 500 kHz and 600 kHz channel bandwidths, where the channel bandwidth depends on the regularity region [5]. The square signal is defined as

$$x_{square}(t) = \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\sin(2\pi(2k-1) \cdot f \cdot t)}{2k-1}. \tag{9}$$

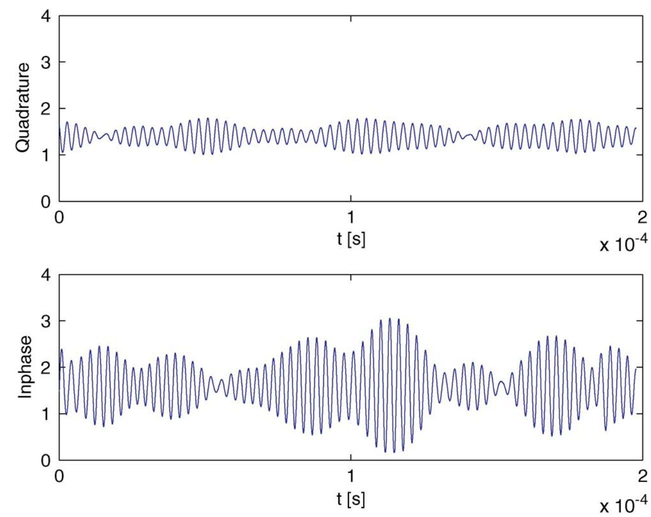

Fig. 7. Pilot tone in case of collision of 4 tags.

To preserve the second harmonic in the case of 600 kHz bandwidth, the BLF frequency should be $f_{BLF} \cdot 2 \leq 300$ kHz. This means that for any BLF that is higher than 150 kHz, the second harmonic of square backscattered signal will be part of filtering rejection. For this reason, any backscattered data transmitted at BLF higher than 150 kHz observed on the I/Q demodulator will be sinus-shaped, since only the first harmonic is within the band pass of the filter.

The signal in Fig. 7 shows an example of pilot tone from the backscattered RN16 in the case of collision of 4 tags. Tags transmitted at BLF set to 320 kHz and using Miller 4 encoding. The presented pilot tone of the preamble was sampled on the output of a real I/Q demodulator. The picture clearly shows that the signal is sinus-shaped, which means that higher harmonics have been rejected by the filter.

B. Preamble-Based Anti-Collision Method

We have shown analytically that the pilot tone in the preamble transmitted by a tag will be observed on an interrogator as a sinus signal with a frequency equal to BLF. In the case that the BLFs from all tags are not equal, a frequency analysis would show different frequency peaks. When performing a frequency analysis on an inphase channel signal from Fig. 7, four different frequencies are obtained. The result of the Fast Fourier Transform (FFT) of the pilot tone is shown in Fig. 8.

Frequencies obtained by using the FFT analysis are 313 kHz, 320 kHz, 330 kHz, and 352 kHz. These frequencies are the first harmonics of binary modulated pilot tones and are the values of the BLFs of the transmitting tags.

The reason for such inconsistency in frequencies from various tags is the uncertainty of the local oscillators inside the

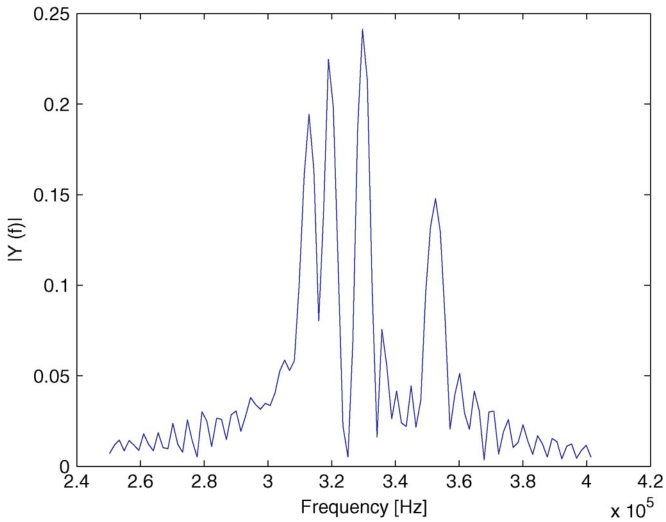

Fig. 8. Frequency analysis of the pilot tone of the I channel.

TABLE I
LINK FREQUENCY UNCERTAINTIES AT VARIOUS DIVIDE RATIOS [5]

Divide ratio	Link frequency BLF (kHz)	Link frequency unceartainty
	640	$\pm15\%$
64/3	320	$\pm10\%$
	256	$\pm10\%$
	230	$\pm10\%$
8	256	$\pm10\%$
	160	$\pm7\%$

integrated circuit of the tags that generate the BLF. The implementation of the oscillator in an integrated circuit is always related to uncertainties of process parameters. For this reason, the local oscillator frequency will vary according to the natural distribution of process parameters.

To avoid problems with BLF uncertainties, the EPCglobal standard specifies the frequency uncertainty for different BLF settings. To meet the requirements, tags have an oscillator with a frequency higher than specified, which is divided down to the desired frequency. Since the divisor for the lower frequencies can be set much more accurately, the frequency uncertainty for lower BLFs defined by the EPCglobal will be smaller (Table I).

Based on the results from Fig. 8 and the specified BLFs from Table I, a new collision resolution method can be developed based on the pilot tone FFT analysis on each received RN16 during the anti-collision phase. In the case of data collision, a number of collided tags can be obtained from the FFT analysis and used to set the frame size at the next frame iteration.

The approach assumes that tags will transmit with different BLFs due to process parameter variations. The problem with such an approach is that the BLFs of the tags will have normal distribution according to the process parameter distribution. This means that the majority of tags will transmit with the BLF close to center frequency, and the probability that tags will transmit with different BLFs due to this reason decreases.

The distribution of tags can be improved if the bandwidth of the BLF uncertainty defined in Table I is equally divided into frequencies and the tags have the ability to randomly select one of these predefined BLFs. The BLFs of the tags of such an RFID system would be uniformly distributed over the entire

TABLE II
FREQUENCY RESOLUTION AND NUMBER OF TAGS THAT CAN BE IDENTIFIED FOR MILLER 8 ENCODING

Link frequency BLF (kHz)	Δf_k (Hz)	Number of tags
640	~ 4700	41
320	~ 2350	28
256	~ 1880	28
160	~ 1180	19

range of the BLF's uncertainty. This can be achieved with local oscillators with higher frequencies so that the divided frequencies are more accurate o set the desired BLF.

The number of identifiable tags with such an approach is related to the number of identifiable frequencies within a given channel band pass. This can be explained by the Fourier Transform Theory. The Discrete Fourier Transform is defined as

$$X(\omega_k) = \sum_{n=0}^{N-1} x(t_n) \cdot e^{-j\omega_k t_n} \tag{10}$$

where $X(\omega_k)$ represents a spectrum, $x(t_n)$ is input signal amplitude at sample t_n, ω_k is k-th frequency sample, and N is the number of samples. The frequency sample is further defined as

$$\omega_k = k\frac{2\pi}{NT} \tag{11}$$

where T is the sampling interval. Let us define $\Delta f_k = 1/TN$ as a spectrum sampling interval, which can be explained as frequency resolution of the Discrete Fourier Transform. Increasing the time of the signal observation will decrease the spectrum sampling interval and thereby the frequency resolution. The conclusion is that that the number of tags that can be determined by the frequency analysis of the pilot tone is limited by the length of the pilot tone and allowed BLF deviation.

Table II shows the calculated spectrum sampling intervals (Δf_k) for the most commonly used BLFs specified in the EPCglobal standard. The right column shows the number of tags that can be identified by using the pilot tone frequency analysis, when tags are equally distributed over the entire bandwidth frequency uncertainty range from Table I. The calculated number of tags is based on the requirement that there is a frequency bandwidth of at least one spectrum sampling interval Δf_k between two neighboring frequencies.

According to Table II, as many as 41 tags can be distributed over the frequency range if the Miller 8 type of encoding and prolonged preamble is used at BLF of 640 kHz. Based on this observation, a new algorithm for setting the optimal frame during the anti-collision phase can be created. The new proposed Preamble-Based Anti-Collision Method (PBACM) is shown in Fig. 9.

The algorithm performs an FFT analysis of the pilot tone on each received RN16 during the anti-collision phase. Based on the FFT results, the number of tags in an analyzed slot can be determined. In the case of an empty slot, an interrogator can continue with a new slot or perform a regular decoding in the case of a single tag presence. In the case of two or more detected tags, the interrogator should skip the decoding and increase the number P, which represents the number of the remaining

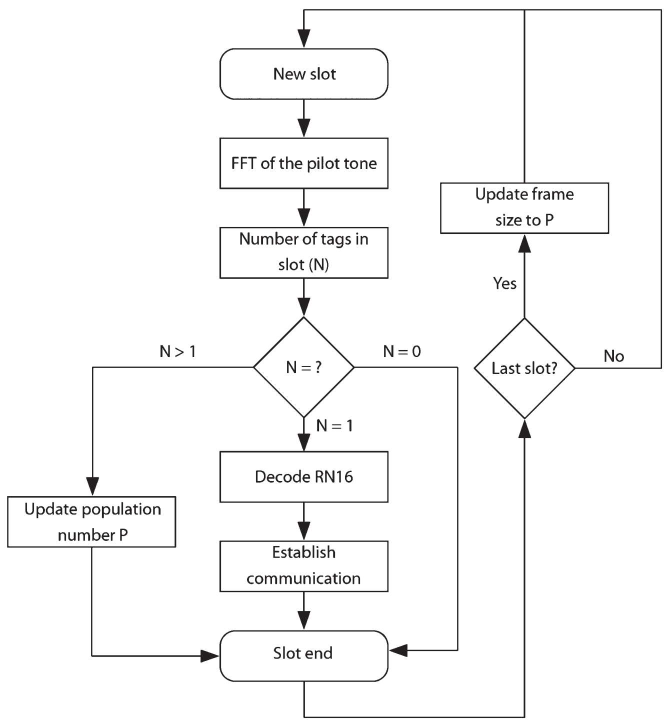

Fig. 9. PBACM algorithm.

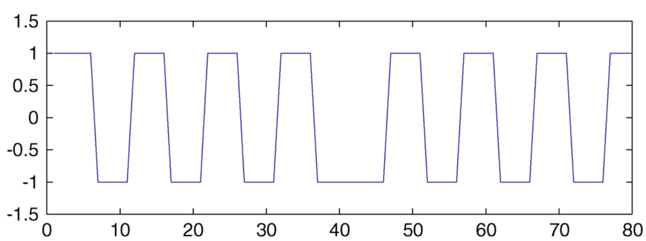

Fig. 10. Miller 8 encoded binary value 1.

unidentified tags in the field. At the end of the last slot in a frame, the number P is used to set the size of the next frame.

C. Enhanced Probability of the Capture Effect

The distribution of the tags over a certain frequency range also increases the probability of the decoding success of the applied capture effect methods. The common approach to decode the demodulated signal is to use a matched digital filter [13], [15], [16]. The matched filter maximizes the signal-to-noise ratio on its output when a specified signal of interest arrives at its input. If a signal of interest x_s is $N-1$ samples long, then an impulse response $h(k)$ of the matched filter is

$$h(k) = x_s(N-k-1). \tag{12}$$

By using a matched filter, we perform pattern recognition, where a pattern is the signal of interest. The matched filter can also be used for decoding the Miller encoded signal so that the filter has a peak response on the phase change of the Miller code. Fig. 10 presents the Miller 8 encoded binary value 1, which can be used as the signal of interest x_s.

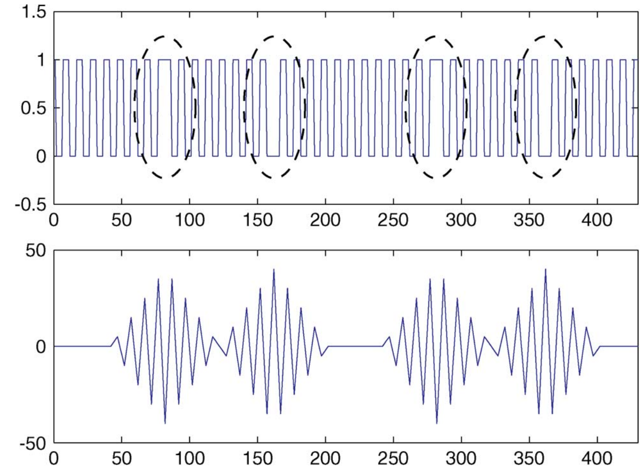

Fig. 11. Matched filtering of Miller 8.

Fig. 11 shows an example of the Miller 8 encoded signal and the filtering result. The matched filter was set so that the Miller encoded signal from Fig. 10 was used as the signal of interest.

As can be seen from Fig. 11, the maximum peak response of the filter is positioned on the center of the phase transition of the Miller code. Measuring the distance between the filter response peaks allows the data to be decoded.

The matched filtering process can be explained by the cross correlation theory. The basic requirement of cross correlation is that the noise is not correlated with the signal that is being decoded.

Such problems also arise in the case of data collisions in the RFID system, where tags represent correlated sources. In this case, the correlation is related to the frequency and amplitude of the contamination signal in comparison to the signal of interest.

The presented method proposes that the tags should transmit with different BLFs. By implementing the proposed method, we would also decrease the correlation over frequency and thereby increase the probability of successful data recovery in the case of collision slots when the capture effect method is used.

V. Measurement Results

The measurements were performed on the RFID system using the EPCglobal interrogator [11] and tags [17]. The tags had the ability to set the internal oscillator of the BLF. The purpose of the measurements is to prove that the proposed anti-collision resolution algorithm can be realized by using the FFT of the pilot tone and that the proposed method enhances the probability of data decoding success in the case of use of the capture effect method.

Fig. 12 shows an example of the FFT of the pilot tone from a collision slot. It can be observed in the picture that three different tags have transmitted in the collision slot with BLFs at 313 kHz, 320 kHz, and 330 kHz. The calculated spectrum sampling interval for the used settings is 16 kHz. Although the frequency distance between frequencies 313 kHz is 320 kHz is only 7 kHz, the frequencies are clearly visible. This proves that the spectrum sampling interval can be used as the minimum

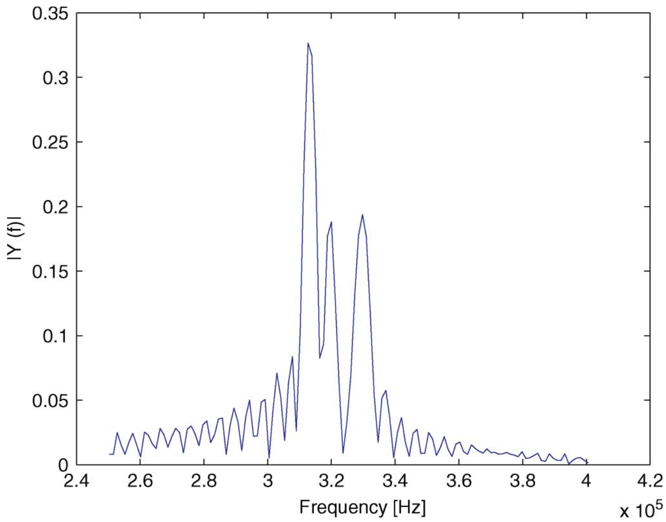

Fig. 12. Result of the FFT on pilot tone.

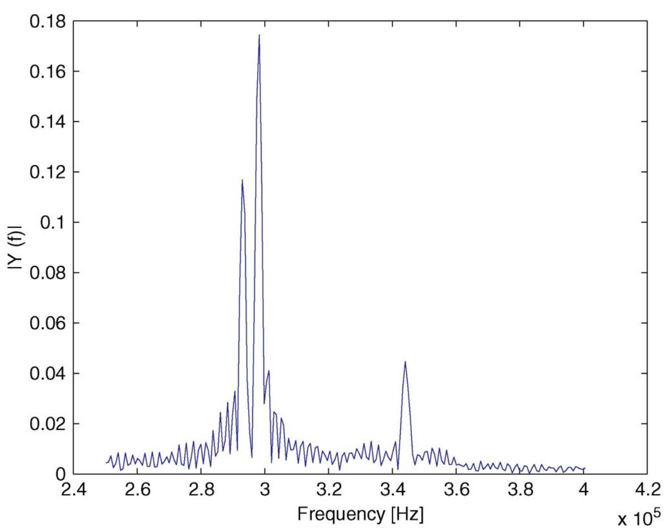

Fig. 13. Result of the FFT on pilot tone.

frequency distance between two backscattered frequencies in the proposed method.

Since the EPCglobal enables transmission with the BLFs within a certain bandwidth and thus allows the uncertainties in the BLF due to aforementioned process parameter variations, we also tried to prove that, due to these uncertainties in BLF, the proposed method can also be used on the existing tags. For this reason, we used one of the commercially available tags [18] which use different integrated circuits from those shown in Fig. 12. The results are presented in Fig. 13 which depicts the BLFs of three tags at frequencies of 296 kHz, 302 kHz and 345 kHz. This indicates quite a vast frequency range in which pilot tones of the tags and consequently a good frequency distribution of the available tags can be expected. It may be inferred from the results that the proposed method can also be used on the existing tags.

The second part of measurements is focused on proving that distributing the tags that transmitted in the same slot over the frequency range increases the probability of used capture effect methods. For this reason, we created an experiment where we

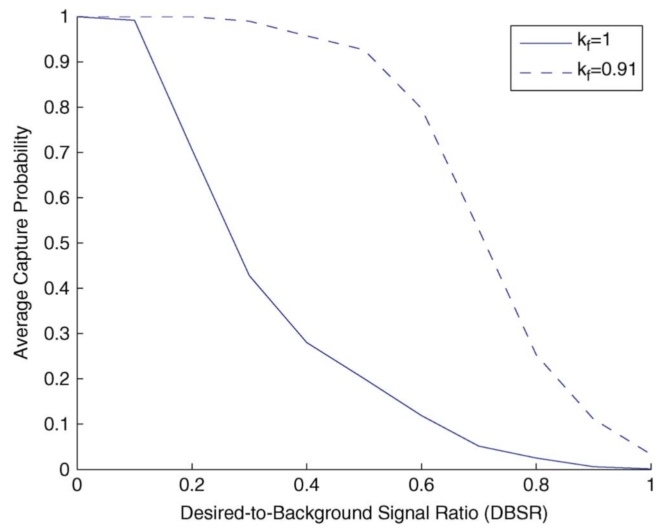

Fig. 14. Normalized decoding success rate in case of Miller 4.

observed the decoding success rate when two tags transmit at the same time. The decoding was performed by the matched filter described in the Section IV.

During the experiment, we observed the effect of the desired-to-background signal amplitude ratio (DBSR) and signal frequency correlation (k_f) on capture capability.

$$DBSR = \frac{Desired\ Tag\ Signal\ Level}{Background\ Tag\ Signal\ Level} \tag{13}$$

$$k_f = \frac{BLF\ of\ the\ Desired\ Tag}{BLF\ of\ the\ Background\ Tag}. \tag{14}$$

The desired signal represented the tag that we tried to decode, while the background signal was another tag that transmitted at the same time. Each point in the graph was evaluated with approximately 1000 trials of decoding. The average capture probability was defined as

$$Average\ Capture\ Probability = \frac{Succesful\ Trials}{All\ Trials}. \tag{15}$$

The average capture capability was evaluated in two circumstances: In the first case, both tags transmitted with the same BLF $(k_f = 1)$ at 304 kHz. In the second part of the experiment, the BLF of the tag that generated background signal was increased to 333 kHz $(k_f = 0.91)$. Fig. 14 shows the results of the experiment in the case of Miller 4 coded signal. It is clear from the plot that when the BLF of the background signal is different, the success rate is increased.

For the purpose of comparison, an experiment was performed with Miller 8 encoding (Fig. 15) to observe the effect at different Miller codes.

By comparing the results from Figs. 14 and 15, we can observe that the increase of the capture effect capability is lower in Miller 8 code and thus the frequency difference of the background signal is less significant than in the case of Miller 4. This is due to the fact that the use of higher Miller codes increases the observation time of the signal of interest used in the matched filter.

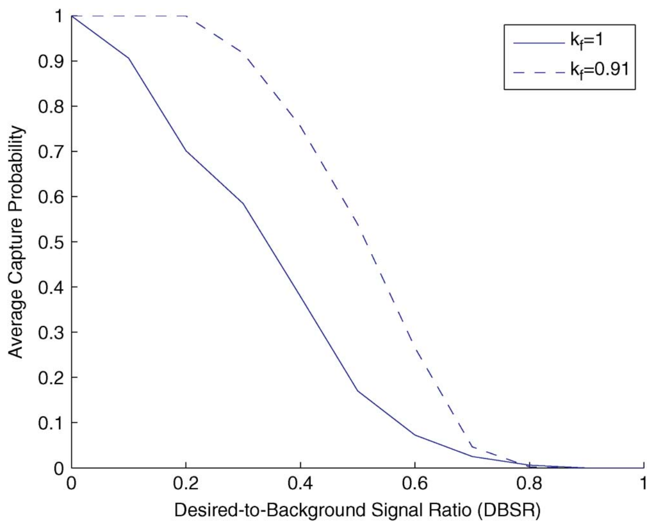

Fig. 15. Normalized decoding success rate in case of Miller 8.

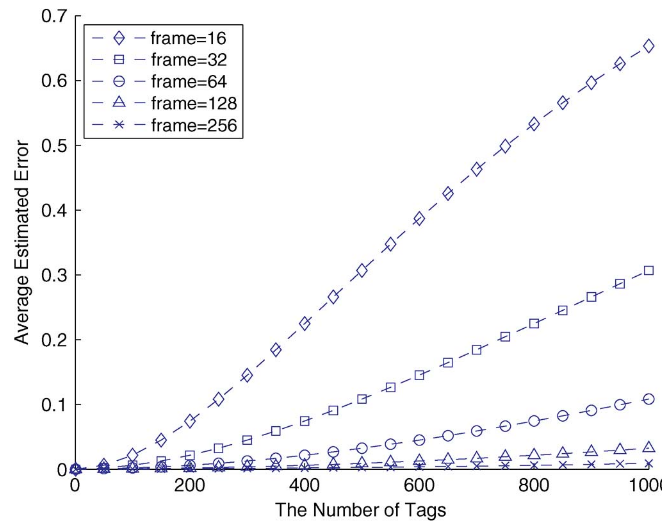

Fig. 16. Average estimated error at various frame sizes.

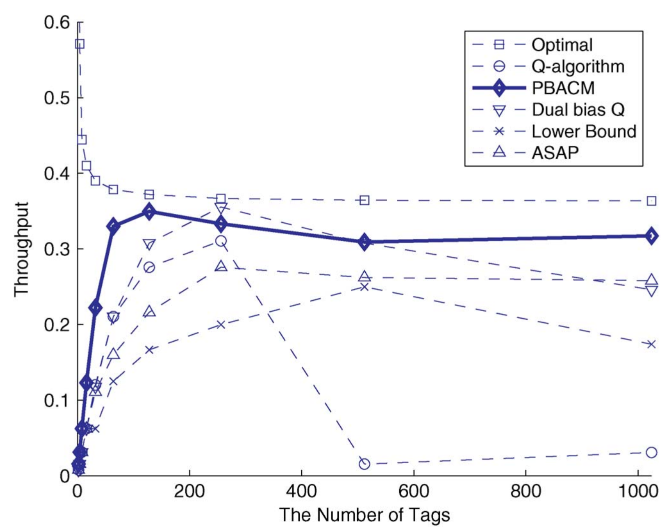

Fig. 17. Normalized throughputs for five different methods.

The presented measurements show that the assumptions in Section VI are correct. We have demonstrated that the presence of a single tag can be determined if other tags transmitted with the BLFs that are larger or smaller by at least the frequency sampling interval. Moreover, we have also shown that the presented approach increases the probability of recovery when applying the capture effect-based method to the collision slots.

VI. Algorithm Evaluation

The main focus of this work is to present a new method that improves the estimation of the number of tags in the field of an interrogator and thus increase the throughput of the system by setting the optimal frame size. This means that the proposed method belongs to the same group as different modifications of the Q-algorithm and the RCS methods.

Moreover capture effect-based methods were presented. As explained in Section III, the capture effect methods should be applied only as an additional improvement to the previously mentioned methods and cannot be used as standalone approaches. For this reason, we will omit the comparison to this type of methods and focus the comparison on the previously mentioned methods.

As already shown, the RCS methods cannot be applied to an RFID system based on the EPCglobal. Further, the authors [7] claim that the maximum number of tags whose presence can be identified is 4, while in the case of the newly proposed method this number is 41.

To run a comparison with different MAC algorithms used in the EPCglobal, we need to determine the optimal initial frame size for the proposed method. A large initial size will improve the convergence with a large number of tags, but it will also cause poor performance with a small number of tags since many slots in the initial frame will be empty.

Fig. 16 shows the result of a simulation, where we estimated the average error of the estimated number of tags in the initial frame. The results show that the optimal initial frame set should be set between 64 and 128 slots. Based on further simulations and by setting the target range of the number of tags between 1 and 1000, we found that the most optimal initial frame size is 128.

The proposed method was compared with the Lower Bound [20], ASAP [21] and Dual bias Q [22]. The methods were evaluated on the basis of the normalized throughput for various initial numbers of tags. The normalized throughput (16) was defined as a ratio between the successful slots and all slots needed to identify all the tags in the initial group

$$Throughput = \frac{Succesful\ Slots}{All\ Slots}. \tag{16}$$

Fig. 17 shows a comparison of the various methods including the Q-algorithm proposed by EPCglobal. The graph shows a comparison between four methods. We also added the *Optimal* method that represents the maximum throughput as if the algorithm always knew in advance the number of unidentified tags. As shown by the graph, the proposed PBACM shows the steadiest and best performance in the range of the various initial numbers of tags.

VII. Conclusion

This paper presents a new approach to improving the collision resolution algorithm of the EPCglobal standard. The improvement is focused on determining the tag population number and setting the optimal frame size. The aim of these improvements is to increase the throughput of the protocol during the anti-collision phase.

At the beginning of the paper, we presented the EPCglobal standard and three possible approaches that improve the throughput of the system from two perspectives. Based on the measurements, we showed why methods based on the RCS cannot be used in the EPCglobal system and similar RFID systems that employ channel hopping.

In the continuation of the paper, we presented a new approach to determining the optimal frame size. The proposed method uses the FFT analysis of the pilot tone to determine the number of tags, which is used for optimal frame adjustment. This method can be applied to all DFSA-based protocols that use the pilot tone. Moreover, we also proposed that tags should have the ability to randomly select the BLF.

We explained that the proposed approach would not only affect the detection of the tag presence but also enhance the capture effect capability for solving the collision slots.

The concept of the proposed method was proven on real measurement traces where we demonstrated that the implementation is not only possible but can be used on the existing RFID systems. The measurements also show that such distribution of tag over frequency represents a good foundation for any applied capture effect method.

At the end, we performed an evaluation of the method. We showed that the proposed tag population estimation method based on the frequency method outperforms the existing methods.

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