Survey, Nomenclature and Comparison of Reader Anti-Collision Protocols in RFID

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Abstract

Radio-frequency identification (RFID) has attracted a great deal of attention, due to its wide range of applications in the fields of logistics and supply chain, medicine, inventory, stock, asset management etc. Mobile readers in RFID have become available, while stationary readers are becoming more functional. In a workplace where readers are deployed densely, multiple RFID readers try to access the same tag at the same time. The situation, where multiple readers are in each others' interference region, reader-to-tag communication, leads to a reader collision problem and thus inhibits the communication with the tag. Passive tags are cheaper and are widely used, but they lack frequency selectivity. In such an environment, the problems of reader-to-reader and reader-to-tag collision occur, which lead to the reduction of the efficiency and reliability of the RFID system, resulting in the misreading or failure to read the tag and an increase in the tag interrogation time. The existing standards do not allow this problem to be overcome efficiently. Hence, many reader anti-collision algorithms have been proposed in the literature. We survey the existing works on RFID reader collisions and compare their proposed solutions, based on their performances.

Keywords:
Frequency assignment problem, RFID, RFID reader collision problem, LBT, Tag collision, Reader anti-collision algorithm

1. Introduction

Due to the rapid development in the field of wireless communication, portable, convenient and inexpensive devices such as RFID readers have become available. Devices such as RFID have a wide range of uses in warehouse applications, tracking, hospitals etc. It provides a quick, flexible and reliable way to electronically detect, track and control a variety of items [1]. Figure 1 shows an RFID system that consists of an interrogator (reader), transponder (tag) and backend system. The reader transmits a high power CW (continuous wave) to energize the passive tag, which does not have an on-board energy supply. The tag receives the energy and transmits the stored data by back-scattering communication with the reader. The data received from the tag is processed in the backend database system.

Tags can be passive, semi-passive or active, depending on their functionality. Most commodities are equipped with low functionality passive tags, which lack frequency tuning circuitry.

RFID readers and tags are being increasingly used in various application areas. Many applications require the readers and the tags to be in close proximity to each other, with the result that their signals may interfere with each other. The lack of information exchange among the different RFID readers leads to the problem of reader collision. Generally, one reader cannot know the status of the other readers, because they do not exchange their information with each other.

There are two types of reader-to-reader interference: (i) frequency interference, also called reader-reader collision, which occurs when two or more readers communicate on the same frequency at the same time; and (ii) tag interference, also called reader-tag collision, which arises when two or more readers attempt to communicate with a particular RFID tag at the same time. Both types of reader interference caused by the operation of an RFID reader are referred to as reader collisions [2]. These reader-reader collisions and reader-tag collisions persist in RFID systems [3]-[5], [20]-[24].

The reader collision problem is related to the frequency assignment problem [6]-[11]. The problem of allocating frequencies over time to RFID readers is well studied and presented in [32]. The frequency assignment problem is equivalent to the simple graph coloring problem, which is a well-known nondeterministic polynomial (NP) time problem [12].

1.1 Denser Reader Medium

When a number of readers are deployed in a predetermined place to provide for the highly reliable and correct reading of tags, they form a dense reader medium. In

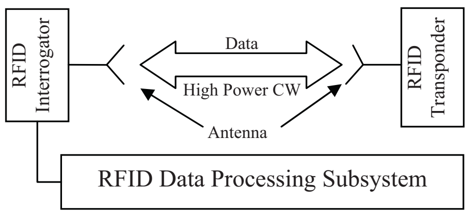

Figure 1: Basic RFID operation.

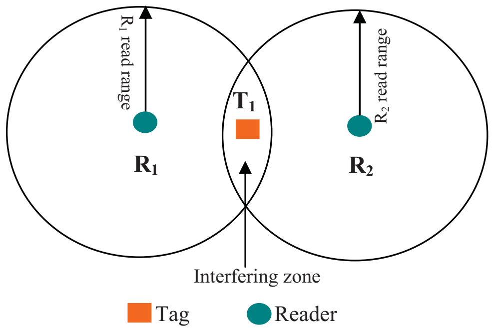

Figure 3: Reader-to-tag collision.

conventional systems, a single reader is sufficient to read multiple tags within the interrogation zone. However, a single reader cannot simultaneously provide a high tag read rate and the correct reading of multiple tags streaming into the reader's reading zone. For example, misreading and reading failure leading to wastage of bandwidth and a long delay time are common in RFID applications. In order to improve the coverage, read rate, and accuracy, several readers are deployed together to form a denser reader environment.

1.2 Reader-to-reader Collisions

When two or more readers come into close proximity to each other, they may try to read the same tag at the same time and in the same frequency band, and this may lead to collisions. Alternatively, while one reader is reading a tag within its target region, it may receive stronger signals from other readers. Therefore, the strong signal reflected from the reader may interfere with the weak signal from the tag. This is called the frequency interference problem in RFID.

In Figure 2, T1 is in the interference region of reader R2. The signals from tag T1 to reader R1 can be distorted by the signals from reader R2. This kind of interference can arise when there is an unwanted transmission from a nearby reader, even when the read ranges of the two readers do not overlap.

1.3 Reader-to-tag Collisions

Reader-to-tag collisions occur when a tag hears multiple readers' queries at the same time. In such a situation, the tag might not be able to respond to any reader at all.

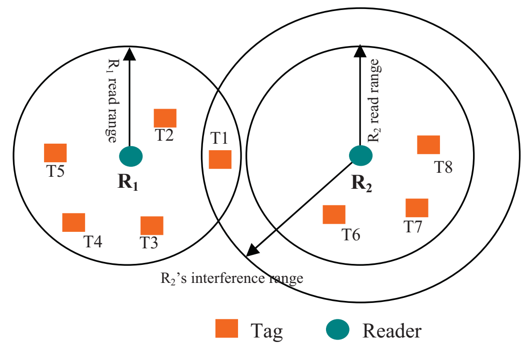

Figure 2: Reader-to-reader.

In Figure 3, the two readers, R1 and R2, are in the same workplace. When both readers R1 and R2 try to read tag T1 at the same time, neither of them is able to do so. The reader-to-tag collision problem is called the tag interference problem in RFID.

Reader anti-collision algorithms mitigate both the reader-to-reader and reader-to-tag collision problems. The system RFID is used in very sensitive business areas, so a highly reliable, efficient and accurate system is needed. In literature, various reader anti-collision algorithms have been proposed, which perform limitedly and cannot fully satisfy performance requirements, thus leaving room for improvement. Thus, in the following sections, we survey the existing literature, in order to assist researchers in the field of RFID.

2. Basic Principles, Problems, Regulations and Algorithms

Many multiple access schemes such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Carrier Sense Multiple Access (CSMA) have been proposed to solve the collision problem. However, these existing schemes cannot be used directly in RFID systems because of the following problems:

In FDMA, several transmission channels using various carrier frequencies are allocated for various readers and tags. As RFID tags cannot choose a particular frequency, they cannot select a particular reader to establish a communication link.

In the TDMA scheme, the RFID reader and tags are allocated different time slots, in order to avoid simultaneous transmission. This scheme is similar to the graph theory of allocating different colors, where the frequency represents the color, such that none of the readers can pick the same color. This reduces co-channel interference. However, only one ID should be transmitted in each time slot, in order to avoid collisions.

The scheme CDMA uses the spread spectrum modulation techniques, based on pseudo random codes. It spreads the data over the entire spectrum. While CDMA would be ideal in many ways, it adds a lot of complexity and would be computationally too much of an overhead for RFID tags. It requires extra circuitry, which is not cost effective for low cost, practical RFID tags.

Through detecting whether the channel is busy or idle and waiting in the contention mode to access the channel, CSMA avoids collisions. However, carrier sensing is not very effective in RFID systems, because of the well-known hidden terminal problem. The traditional collision avoidance techniques such as RTS (request to send) and CTS (clear to send) cannot be applied directly to RFID systems, because when one reader sends an RTS to the tags in its reading range, multiple tags respond with the CTS message. Another collision avoidance mechanism would be required to avoid collisions among the RFID tags, thus making the system more complicated. Moreover, the carrier sensing mechanism shuts down lots of sub-bands, even if such bands are functional in other systems.

Since, RFID system is increasingly deploying in a range of products and services including very important and sensitive sectors (e.g. medical, security etc.), a more sophisticated RFID reader anti-collision protocol is needed, which can provide high tag read rate with correct reading of multiple tags into the readers' interrogation region, and can ensure sufficient quality of service by mitigating the reader collision problem.

2.1 Regulations

Although, frequency selection in RFID depends upon the application, there are certain regulations which need to be applied to select the frequencies. These regulations are necessary to avoid interference between different radio systems.

To provide worldwide interoperability, some particular frequencies are allocated, which are called ISM (industrial scientific and medical) frequencies. The three most common ISM frequencies, which are available in most countries and which are most commonly adopted in RFID systems, are 135 kHz, 13.56 MHz, and 2.45 GHz [13] for the low, intermediate and high frequency bands, respectively.

2.1.1 ETSI EN 302 208

Listen-Before-Talk (LBT) is a multiple access scheme that works on the principle of CSMA. This is standardized as ETSI EN 302 208 [14], according to the European regulations. ETSI EN 302 208 allocates the frequency band of 865 to 868 MHz, which is divided into 15 sub-bands. In this standard, all readers must listen to the on-going transmission in the channel before accessing it. The listen time comprises a fixed period of 5 ms plus a random time of 0 ms to 5 ms, in 11 steps. If the sub-band is free, the random time shall be set to 0 ms [14]. To perform communication efficiently, the channel will be occupied for up to 4 sec, after which it must free the sub-band for at least 100 ms. Since the time, delay and collision probability are high in this standard, it is inefficient for dense RFID systems.

2.1.2 Class 1 Generation 2 UHF Protocol

Electronic product code (EPC) Radio-frequency Identification Protocol Class 1 Generation 2 UHF RFID Protocol [15] is an open and global standard protocol developed by EPC global [16] for RFID systems operating in the 860 MHz - 960 MHz frequency range. EPC global is a non-profit organization formed as a joint venture between GS1 (former EAN International) and GS1 US (former Uniform Code Council, Inc.). Class 1 Generation 2 UHF RFID protocol describes the spectrum management of RFID operations in a dense reader environment. Frequency hopping is suggested for efficient frequency utilization. In a dense reader environment, interrogator transmissions operate in even-numbered channels and tag backscatters are located in odd-numbered channels.

This protocol separates the reader transmission and tag transmission into separate frequency channels, so that reader-to-tag collisions never happen. However, in a dense reader environment, when two readers use two separate frequencies to communicate with the tag, the tag will not be able to tune to a particular frequency and, hence, collisions can occur at the tag. Thus, in this standard, the reader to tag collision problem remains unsolved.

2.1.3 Frequency Hopping Spread Spectrum (FHSS)

In the FCC (Federal Communication Commission) regulations, a given spectrum is divided into different frequency bands [17]. This is one of the most efficient ways to avoid the effect of interference and to avoid causing interference to users of a shared spectrum. The transmitted energy is distributed, thereby reducing the likelihood of interference arising with other systems. Likewise, all readers are expected to randomly alternate between these bands, in order to reduce the probability of collisions. The receiver frequency varies continually, in order to avoid the effects of other users blocking the reader's receiver. Frequency Hopping Spread Spectrum significantly reduces the frequency interference, but cannot overcome the tag interference issues, as it hops between the different channels used by the readers.

2.2 Anti-collision Algorithms

Each reader anti-collision algorithm proposed in literature has its own unique properties and functionalities.

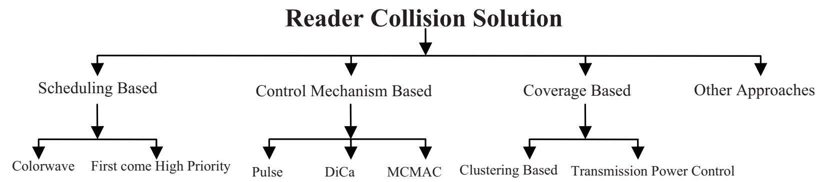

Figure 4: Classification of existing RFID reader anti-collision algorithms.

Some operate by means of scheduling, some in a distributed way and some work on the principle of a notification mechanism of broadcasting control packets. Figure 4 shows the classification of the existing RFID reader anti-collision algorithms.

2.2.1 Scheduling Based Approaches

The available system resources such as the frequencies and time are allocated among the readers to prevent them from transmitting simultaneously. This kind of approach can reduce the possibility of reader collisions effectively. However, it requires the system to establish and maintain information over the network, which is time and energy consuming.

2.2.1.1 Colorwave

The Colorwave reader anti-collision algorithm [4] is a distributed TDMA based approach. In this algorithm, each slot is allocated with a different color. Each color ranges from [0, Maxcolors] and the readers in the network randomly choose a color from [0, Maxcolors]. A reader with a queued request for transmission can transmit data in its color timeslot. If the transmission collides with that of another reader, the transmission request is discarded and the reader randomly chooses a new color and reserves it. If the neighbor has the same color, it chooses a new color and transmits a control packet (called a kick packet). Each reader synchronizes with the other readers by continuously tracking the current time slot. The value of Maxcolors varies according to the network situation.

Colorwave is a simple, very flexible and distributed protocol. However, there is no tag side consideration in Colorwave. A reader cannot detect collisions in the network without being aware of the tag. Further, in mobile RFID systems, overhead due to time-slot reselection increases continuously and significantly, because Colorwave needs the tight time synchronization among the readers.

2.2.1.2 HiQ – learning

HiQ-learning [3] based on reinforcement learning [18],[19] was used to develop an online learning algorithm for use in a hierarchical network architecture. HiQ provides a solution to the reader collision problem by learning the collision patterns of readers and assigning frequencies to the readers over time. It is composed of three basic hierarchical layers: the reader, the reader-level server and the Q-learning server. The reader is in the lowest position and transmits collision information to the upper layer server. An individual upper layer server then assigns resources to its readers. The readers communicate when they are assigned time slots and frequencies. The readers are aware of the frequency and the time slots that are allocated to them. They detect collisions by communicating with the other readers in the overlapped interrogation zone. If two readers communicate using the same time slot and frequency, they will experience both tag and frequency interference. The reader stores the number of collisions experienced. This information is known to the R-server, as the reader directly communicates with it. Q-servers allocate the resources to the server below them, i.e. to the R-servers. Regardless of the number of Q-servers, there is always a root Q-server that has global knowledge of the frequency and time and is able to allocate them.

The main drawback with this hierarchical approach is that additional management of the overall hierarchy is required for even a slight change in the lower layer. It is not favorable for highly mobile environments, because in such an environment the management overhead increases exponentially. Another overhead in this protocol is time synchronization, which requires the use of timeslots. Besides, all the readers also need to be synchronized.

2.2.2 Control Mechanism Based Approach

This approach mitigates the problem of collisions between readers, by transmitting notification control packets such as beacon signals. After receiving a beacon signal, the interfering readers interrupt their ongoing communication and wait for the next cycle. This approach efficiently covers the problem of reader to reader collisions. However, the actual communication takes place between the reader and tag. This type of protocol does not address the reader to tag collision problem, which lowers the RFID performance.

2.2.2.1 Pulse Protocol

Pulse [20],[21] is a CSMA based notification protocol that attempts to solve the reader collision problem using two separate channels in the RFID system. One channel, called the data channel, is used for reader to tag communication and the other is the control channel, which is used for reader to reader communication. Broadcasting messages in the control channel does not affect the ongoing communication on the data channel. This protocol mitigates the reader collision problem by continuously transmitting beacon signals through the control channel, while the reader is communicating with the tag through the data channel.

Each reader goes into the waiting state and waits for a DIFS time. If it does not receive any beacon signal, the reader concludes that there is no other reader reading the tag. In this case, it enters the contention phase. If the reader receives the beacon signal at this stage, then it waits for a DIFS time in the next cycle, until a randomized back-off time is over. If the reader does not receive any beacon signal, it starts reading the tag. While it is reading the tag, it sends the beacon in the control channel. After reading the tag, it goes back to the waiting state.

The beacon range is equal to the interference. The throughput of the pulse protocol is calculated as follows.

$$T_h = R_Q/T \tag{1}$$

Where T_h is the throughput, R_Q is the total number of queries sent successfully by all readers and T is the total time.

Pulse mitigates the reader collision problem significantly, but it cannot solve the hidden terminal problem and exposed terminal problem completely. Since a beacon does not have any destination address in its structure, it is just a broadcast message on a control channel. When a beacon is elapsed, the reader concludes that there is no other reader in the neighborhood,, which is reading the tag. A beacon is just a means of solving the collision problem. Therefore, a beacon may collide with another beacon from another reader.

Further, whenever two channels are used, a transceiver may be required for each channel. A large amount of energy is consumed during carrier sensing, receiving the beacons, and overhearing the beacons.

2.2.2.2 *Distributed Tag Access with Collision Avoidance*

Distributed Tag Access with Collision Avoidance (DiCa) [22] is a distributed and energy efficient collision avoidance algorithm. Similar to the Pulse protocol, it also has a data channel and a control channel. Each reader contends for the use of the data channel through the control channel and the winner reads the tags through the data channel, while the others wait until the channel is idle. The following packets are exchanged for the purpose of collision avoidance

- BRD_WHO: Packet used for identifying whether a reader reading tags exists in the same network or not.
- BUSY: Used for indicating whether the reader is reading tags.
- BRD_END: Packet used for indicating that the channel is idle after the tags have been read.

DiCa considers the hidden and exposed terminal problems by adjusting the control channel range at twice the radius from the first reader. This channel adjustment in DiCa reduces the energy consumption. Therefore, it is more appropriate for mobile RFID systems. DiCa consumes less dissipated energy than Pulse, CSMA and ALOHA. The dissipated energy can be calculated as follows

$$\text{Dissipated Energy} = \text{Active Time (s)} \times \text{Current (mA)} \times \text{Voltage (v)} \tag{2}$$

However, DiCa has some shortcomings. It requires sufficient time to exchange the contention message. Also, it tries to solve the collision problem after it takes place, rather than acting preemptively. The tag data size is not fixed in DiCa and with a small data size, there may not be sufficient time to exchange contention messages, which increases the collision probability. Thus, it cannot solve the collision problem completely.

2.2.2.3 *Multi-Channel MAC Protocol (MCMAC)*

The multi-Channel MAC protocol (MCMAC) [23] is a contention based MAC protocol for RFID systems. In MCMAC, there are N-1 non-overlapping data channels with the same bandwidth and a control channel. Similar to the Pulse protocol, the control channel is a sub-band of the RFID spectrum and is only used for reader-to-reader communication. Readers can communicate simultaneously with the data channel and control channel.

MCMAC works in a similar manner to the conventional LBT. MCMAC broadcasts a control message after it wins contention in a control channel and gains access to the data channel. The control message informs other neighboring readers within the interrogation zone that the particular channel is occupied for a certain time. After receiving a control message from a neighboring reader, the other readers do not use that channel for a certain period of time and try to gain access to another channel.

Despite the fact that this approach can mitigate the reader-to-reader problem, it cannot solve the reader-to-tag problem. Passive RFID tags are unable to discriminate between two data channels. Therefore, multiple data channels are basically not applicable in a passive tag environment. Also, the additional control channel assignments in this approach may lead to the hidden and exposed terminal problems.

2.2.3 *Coverage Based Approach*

Adaptive transmission range based RFID anti-collision protocols and cluster based RFID anti-collision protocols come under this approach. In the cluster based approach, the coverage ranges of the clusters are dynamically adjusted. A cluster head is elected to communicate with the server in an *ad hoc* network fashion. In adaptive transmission range based RFID anti-collision protocols, the read ranges of the readers are dynamically adapted to reduce the overlapped areas between adjacent readers. This approach usually needs a central node to calculate the distance between each pair of readers and adjust their reading ranges, which increases the complexity and cost of the system [24]. This approach is, nevertheless, energy efficient.

A unique approach to the coverage based RFID reader anti-collision mechanism is proposed in [25]. This is a localized clustering coverage protocol that mitigates the reader collision problem in homogeneous RFID. There is no communication between the readers; therefore, this protocol cannot solve the hidden terminal and exposed terminal problems completely.

2.2.4. Some Other Approaches

A central cooperator based solution is proposed in [26]. In this central cooperator (CC)-RFID system, a central device is used to communicate between the tags and the readers. The problem of collisions is converted into multipoint to single point (MP2P). The reading queries of multiple readers are multiplexed by the central co-operator, and the tag information can be stored and shared among adjacent readers. The central co-operator controls the entire working process of the RFID system.

The Adaptive Channel Hopping Algorithm (ACHA) [27] is a preliminary approach to RFID anti-collision. This algorithm combines the LBT algorithm with a specific hopping method. When the channel is occupied by another reader, the reader may hop to another channel by calculating hopping probability (HP). To prevent channel hop looping, a hopping sequence to all channels, except the current channel, is given at first. If there is no idle channel, it waits for the current channel to occupy. After selecting it, it senses the channel by performing LBT. This approach works effectively when there are many sub-bands, so that readers can hop from one channel to another; whereas, in the case of RFID, the number of sub-bands allocated in the UHF standard is very limited, except in the US.

An Array based reader anti-collision scheme (ARCS) is proposed in [28]. This scheme prevents collision by grouping the readers and reducing the read cycle time. This approach needs tight time synchronization.

Many algorithms have been proposed to solve the frequency assignment problem. Some make use of centralized control for channel assignment, while others function using distributed control. Some examples of these algorithms are neural networks, simulated annealing and genetic algorithms [29-31].

3. Comparison

In this section, we compare the reader anti-collision algorithms used in RFID systems, based on their nature and operation. These algorithms have many fundamental differences. Some of them rely on centralized control for communication, while others function as distributed algorithms with fixed or dynamic channel assignment.

Table 1 shows a comparison between seven promising algorithms, for resolving the reader collision problem. These algorithms have many fundamental differences. As the reader collision problem is similar to the frequency assignment problem in mobile communication systems, except in the case of CC-RFID, other reader anti-collision algorithms allocate frequencies over time, to a set of readers, to mitigate the collision problem. To eliminate the collision problem, the readers must work in a co-operative manner with the tag side consideration, such that large numbers of tags are covered in each frame.

As shown in Table 1, the major overheads in the RFID anti-collision protocols are as follows. Colorwave requires tight time synchronization (TS) and HiQ-learning has high management overhead (MO) in a mobile environment. In a highly mobile environment, the management overhead increases exponentially. The pulse protocol requires more energy (ME) for contention and the probability of collisions occurring in the control channel is also high. DiCa spends much time in control channel negotiation. MCMAC and ACHA require multichannel (MC) capability and a large amount of computation for channel hopping. Finally, CC-RFID needs special hardware (SH) and a database called the

Table 1: Comparison of reader anti-collision algorithms

Algorithm	Function used	Carrier sensing	Major overhead	Distributed control	Fixed channel assignment	Dynamic channel assignment	Tag side consideration
Colorwave	Color number	×	TS	✓	✓	✓	×
HiQ learning	Cost function	×	MO	×	×	✓	×
Pulse	Beacon frame	✓	ME	✓	✓	×	×
DiCa	Energy aware	✓	TD	✓	✓	×	×
MCMAC	LBT	✓	MC	✓	✓	✓	×
CC-RFID	MP2P	×	SH	×	×	×	✓
ACHA	Probability based channel hopping	✓	MC	✓	✓	v	×

Table 2: Comparison in terms of channel assignment

Criterion → Algorithm ↓	Multi channel	Multi-data channel	Dedicated control channel requirements	Indispensable initiative	Optimization technique
MCMAC	Yes	Yes	Yes	LBT in multi channel	Multiple data channel assignment
ACHA	Yes	Yes	Yes	LBT & channel hopping	Multiple data channel hopping
Pulse	Yes	No	Yes	Beaconing in control channel	Control signaling
DiCa	Yes	No	Yes	Handshaking	Improved control channel range

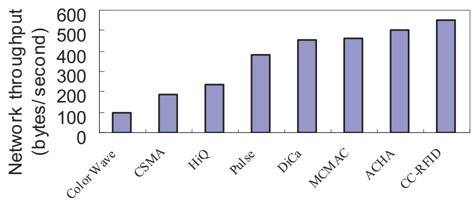

Figure 5: Throughput comparison.

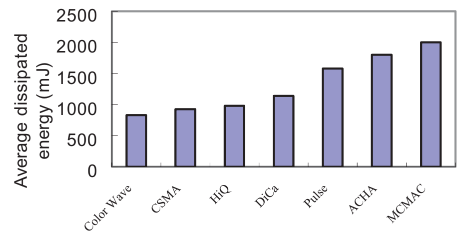

Figure 6: Throughput comparison.

center co-operator.

Table 2 shows a comparison between the different reader anti-collision protocols in terms of their channel assignment. All of the protocols in Table 2 are multichannel protocols. The protocols MCMAC and ACHA use multiple data channels for data communication, whereas Pulse and DiCa use only one data channel. However, all of them need one dedicated control channel for control signal transmission. Pulse and DiCa seem to be promising protocols, except for the fact that a certain amount of time is wasted; they have similar approaches. However DiCa offers some improvement over Pulse.

Figure 5 shows a comparison between different protocols in terms of network throughput. We calculate throughput (T_h) using equation (1). The number of readers is varied, from 2 to 20, and readers are deployed in different random topologies. The result is from a total of 50 simulations per protocol. In Figure 5, except for the special device used protocol (i.e. CC-RFID), Dica gives the highest throughput among single data channel protocols. The protocol CC-RFID shows the best throughput performance. However, CC-RFID needs a special device called central co-operator, as described in section 2. Among the multichannel protocols, ACHA has the highest throughput. Since, it is not fair to compare single data channel protocols and multiple data channel protocols in terms of throughput, it may be said that overall DiCa shows the best performances in terms of throughput.

The graph in Figure 6 shows a comparison between different reader anti-collision protocols in terms of energy consumption. We calculate energy consumption using equation (2). Colorwave, CSMA and HiQ consume lower energy than the other protocols. However, DiCa seems to be an energy-aware protocol, as compared to the rest of the multi-channel protocols. Between multiple data channel protocols, MCMAC consumes more energy than ACHA, because ACHA uses the probabilistic model to hop data channels. The protocol MCMAC is the highest energy consumable, among all the protocols that have been compared, except CC-RFID.

4. Conclusion

We surveyed, illustrated and compared the existing solutions to the reader collision problem in RFID systems. We also classified the current solutions and listed their characteristics, functions, working principles, and limitations. We pointed out the problems that are not addressed by the current standards. We found that many schemes have been proposed as novel solutions to the reader collision problem, but that some improvements still need to be made.

The use of cheap passive tags is one of the reasons that RFID has become popular. However, due to the limited functions, the collision problem still exists and remains to be completely solved. To design a protocol to mitigate the reader collision problem efficiently and entirely, a tag side consideration algorithm needs to be implemented for passive tags, without any modification to their internal circuitry. Also, the delay required for resource usage needs to be reduced.

Among the above protocols, DiCa and ACHA are seen to be promising, in terms of throughput and energy consumption.

We hope this study will be helpful to researchers in this field and provide the impetus required for further research to solve the reader collision problem in RFID.

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