RFID SYSTEMS

RESEARCH TRENDS AND CHALLENGES

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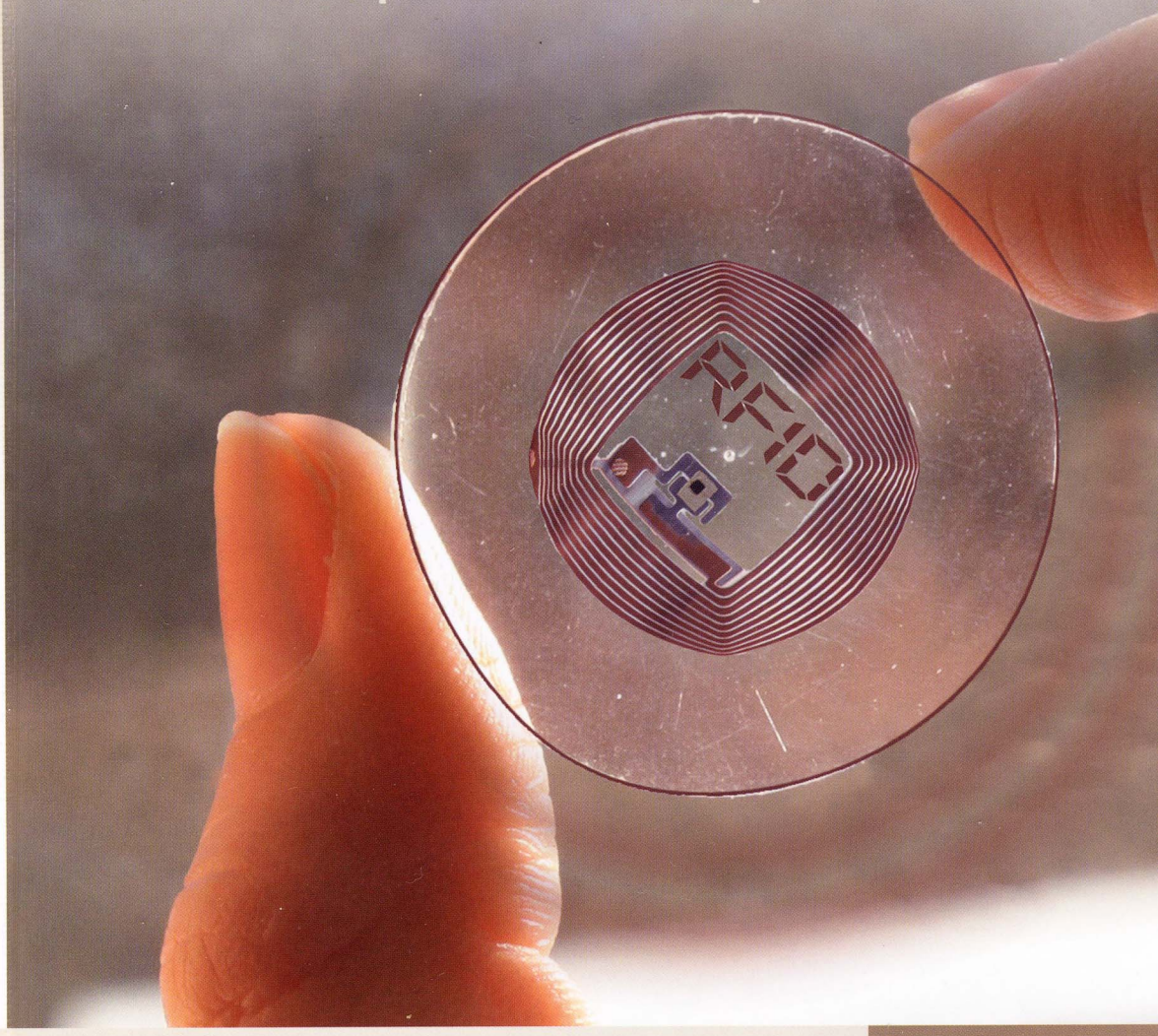

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Reducing Interference in RFID Reader Networks

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11.1 Introduction

RFID is popular in various application areas as a key technology for object tracking. Because of its various advantages, wireless mobile RFID readers are being deployed and stationary readers are becoming more functional. RFID does not require line of sight and can process items at a greater speed than legacy bar code systems. Its diverse applications and numerous advantages are expanding the scope of RFID. For example, RFID is now being used in supply chain management, inventory control systems, manufacturing processes, security systems, warehousing, healthcare facilities, transportation, etc.

All of these diverse applications necessitate the deployment of a large number of readers in small geographical areas. There are some application areas where the readers have to work in close proximity to each other, depending on the space and situation. Furthermore, sometimes mobile readers may inadvertently collect in the same interrogation region. The interrogation region of a reader is the area within which it can read tags.

RFID systems have come to handle a wide range of products and services, including some very important and sensitive sectors (e.g. medical, security, etc.). Consequently, a more sophisticated RFID system is needed, which can provide a high tag read rate with the correct reading of multiple tags in the readers' interrogation region and ensure sufficient quality of service (QoS).

Basically, an RFID system contains three primary components: tags, readers and a data processing subsystem. Figure 11.1 shows an RFID system that consists of a reader, a tag and a back-end system. Tags, which are also called transponders, consist of an integrated circuit with a unique identification information and an antenna to receive/transceive RF

RFID Systems: Research Trends and Challenges Edited by Miodrag Bolić, David Simplot-Ryl, and Ivan Stojmenović

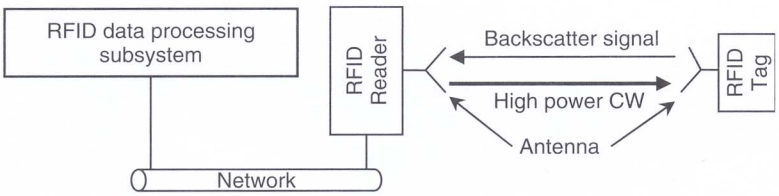

Figure 11.1 Basic RFID operation.

waves. Tags can be active, semi-passive or passive depending on their functionality. Active and semi-passive tags are onboard battery-powered and have a moderate size antenna. They can be read from a great distance, but the onboard battery increases their cost and size and limits their lifetime. Active tags can initiate transmission to readers. Many high frequency tags are passive.

Most ultra high frequency (UHF) tags are passive and operate without an onboard battery. The readers transmit a higher power continuous wave (CW) to energize the passive tag, which contains a very small antenna. The higher power CW is just enough to obtain the information from the tags by means of the signals backscattered to the reader over a very small distance as compared to active and semi-passive tags. The tag receives the energy and transmits the stored data by backscattering communication with the reader. The information from the tags is modulated onto the reader carrier signal and reflected back to the reader in the backscatter communication. Passive tags only respond to the reader; they cannot initiate any communication. Most commodities are equipped with low functionality passive tags, because they are inexpensive, small in size and as thin as a banknote.

11.2 Interference Problem in RFID Reader Networks

When there are a number of RFID readers which are deployed in or enter the same interrogation region, they form a dense RFID System. The formation of a dense RFID System is more prone to occur in the case of mobile RFID systems. This dense RFID system introduces a number of new challenges. In a dense RFID system, the lack of information exchange among the different RFID readers causes signal interference. Generally, one reader cannot know the status of the other readers, because they do not exchange their information with each other. Passive tags, which lack frequency tuning circuitry, cannot distinguish between readers and also cause reader interference. In this way, they reduce the efficiency and reliability of the RFID system, resulting in misreading, unsuccessful reading and an increase in the tag interrogation time. It is very important in any tracking system to achieve perfect accuracy, but such interference can prevent the readers from achieving the desired read rate with accuracy.

There are two types of reader interference: (1) frequency interference, which occurs when two or more readers communicate on the same frequency at the same time. This type of interference is called reader–reader collisions; and (2) tag interference, which arises when two or more readers attempt to communicate with a particular RFID tag at the same time regardless of the differences in frequency. This type of interference is

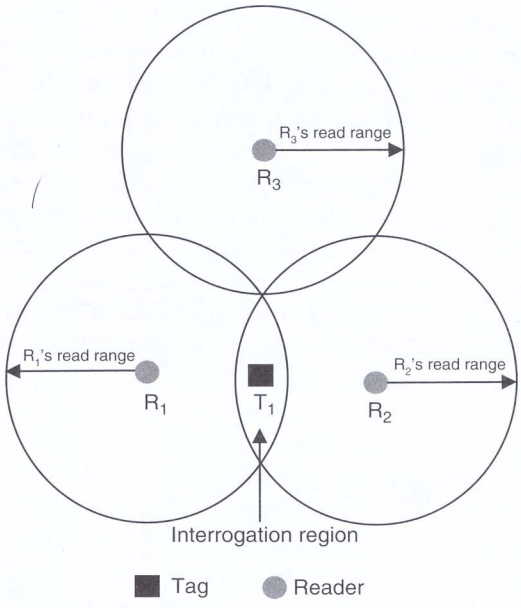

Figure 11.2 Reader-to-tag collision.

called reader–tag collisions. Both types of reader interference caused by the operation of an RFID reader are referred to as reader collisions [1]. In this chapter, we refer to the reader interference and reader collision problems interchangeably. Figures 11.2 and 11.3 illustrate the reader collision problems in detail. In Figure 11.2., tag T_1 is in the same interrogation region as the two readers, R_1 and R_2. When both readers R_1 and R_2 try to read the tag T_1 at the same time, tag T_1 cannot respond to either of the queries.

In Figure 11.3(a), tag T_1 is in the interference region of reader R_2. The in-band backscattering signal from tag T_1 to reader R_1 can be distorted by the interrogation signal from reader R_2. 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. Similarly, T_1 is in the interference range of R_2 and the read range of R_1. When reader R_1 wants to read T_1 and R_2 wants to read a tag within R_2's read range at the same time and at the same frequency, their signals may interfere with each other and, thus, R_1 cannot read tag T_1. In Figure 11.3(b), reader R_1 and reader R_2's interference ranges overlap and cannot communicate at the same time and at the same frequency. These reader collisions persist in RFID systems [10–17, 38].

The reader collision problem is related to the frequency assignment problem [2–8]. The problem of allocating frequencies over time to RFID readers has been well studied and presented in [8]. Let the RFID reader network be an undirected multigraph G(V, E), where set of vertices V is the set of RFID readers and set of edges E is the set of frequency interference between readers. The frequency assignment problem is equivalent to the simple graph coloring problem that is a well-known NP problem [9]. In addition to the reader

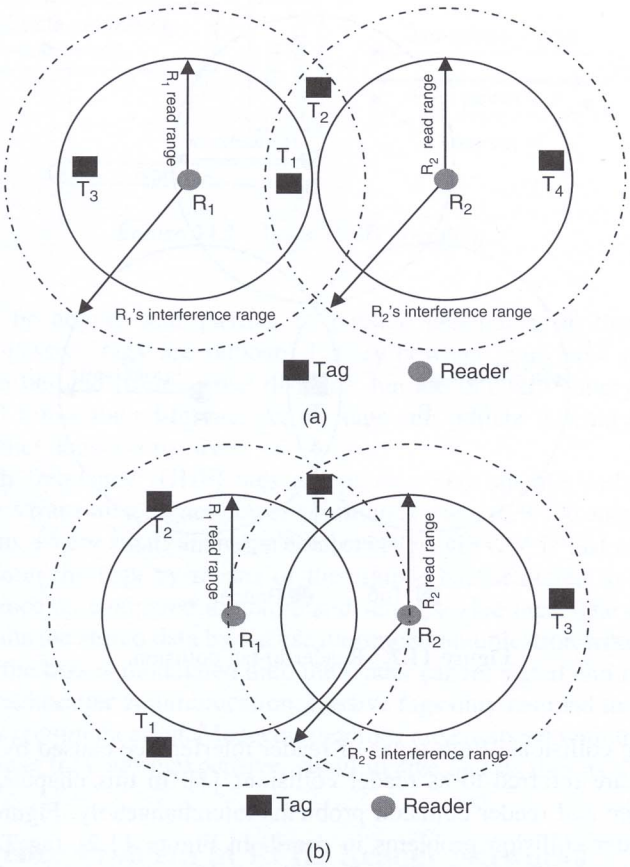

Figure 11.3 Two kinds of reader–reader collision.

anti-collision algorithm, many other algorithms have been proposed to solve the frequency assignment problem. Some examples of these algorithms are neural networks, simulated annealing, genetic algorithms, localized approximation algorithms, reader synchronization algorithm, and distributed power control algorithm [32–36].

11.3 Access Mechanism, Regulations, Standards 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 to various readers and tags. As passive 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 at different time slots in order to avoid simultaneous transmission. The available channel capacity is divided for the readers in the same interference range chronologically in such a way that each reader is assigned to a time slot wherein it can read tags in its range, while the rest of the readers remain silent during that period, thus avoiding any interference or collision. 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. Graph coloring is an assignment of colors to the vertices of a graph such that any two adjacent vertices do not have the same color. The smallest number of colors needed to color a graph G is called its chromatic number, $\chi(G)$, of the graph. Determining the chromatic number of an arbitrary graph G is called simple graph coloring problems. Computing the chromatic number is a well-known combinatorial problem which is NP-hard [39].

Assigning time slots to readers is equivalent to the graph coloring problem. Determining the pairs of interfering readers and assigning TDMA slots is relatively easier in the fixed RFID readers' scenario. But, in the mobile scenario, non-interfering readers may move closer and start interfering which will require reshuffling of time slots in a dynamic topology. Having such dynamically distributed time slots will reduce the read rate of the RFID system.

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

CSMA avoids collisions by detecting whether the channel is busy or idle and waiting in the contention mode to access the channel. 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 were functional in another system.

11.3.1 Regulations

Although frequency selection in RFID depends upon the application, there are certain regulations which need to be applied when it comes to selecting the frequencies. These regulations are necessary to avoid interference between different radio systems. To provide worldwide interoperability, a particular set of 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 are most commonly adopted in RFID systems, are 135 kHz, 13.56 MHz, and 2.45 GHz [18] for the low, intermediate, and high frequency bands, respectively.

11.3.1.1 ETSI 302 208

Listen-Before-Talk (LBT) is a multiple access scheme that works on the principle of CSMA. LBT senses the carrier of channels before transmission. If a reader finds that the channel is idle, it occupies the channel by the contention with other readers. LBT was standardized as ETSI EN 302 208 [19] according to European regulations. ETSI EN 302 208 allocates the frequency band of 865–868 MHz that is divided into 15 sub-bands, each spanning a total of 200 kHz. However, if a reader is operating at the maximum total radiated power, which is 2 W ERP (Effective Radiated Power) or equivalently 3.2 W EIRP (Effective Isotropic Radiated Power), only 10 sub-bands are available, while the remaining 5 are used as guard bands in which only a low ERP is allowed. In this standard, all readers must listen to the ongoing transmission in the channel before accessing it.

The listen time comprises a fixed period of 5 ms plus a random time of 0 to 5 ms in 11 steps. If the sub-band is free, the random time is set to 0 ms [19]. To perform communication efficiently, the channel is occupied for up to 4 sec, after which it must release that 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. Due to the rapid development in RFID industry, multiple readers can transmit simultaneously on the same channel. Therefore, in the current version of European standard, EN 302 208-1 Ver. 1.3.1 (Electromagnetic compatibility and radio spectrum matters (ERM); radio frequency identification equipment operating in the band from 865–868 MHz with power levels up to 2 W), the use of LBT is optional [20].

11.3.1.2 FCC

In the Title 47 Part 15.247 of the FCC (Federal Communication Commission) regulations, a given spectrum is divided into different frequency bands and uses the frequency hopping spread spectrum (FHSS) [21]. 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. FHSS significantly reduces the frequency interference, but cannot overcome the tag interference issues, as it hops between the different channels used by the readers. Nevertheless, there are different regulations in different countries and there is no single global public regulation for RFID.

11.3.2 Standards

11.3.2.1 EPC Class 1 Generation 2 UHF RFID Protocol

The EPC Radio-frequency Identification Protocol, a Class 1 Generation 2 UHF RFID Protocol [22], is an open and global standard protocol developed by EPCglobal [23] for RFID systems operating in the 860–960 MHz frequency range. EPCglobal is a non-profit organization formed as a joint venture between GS1 (formerly EAN International)

and GS1 US (formerly Uniform Code Council, Inc.). This 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 the reader-to-tag collisions should 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.

11.3.2.2 ISO 18000 Standards for RFID

The International Standards Organization (ISO) defines the air-interface communication between RFID readers and tags. Unlike EPCglobal, which addresses only the UHF specification, ISO has defined a standard range of frequencies to be used. The ISO 18000 standards [24] for RFID are summarized in Table 11.1.

11.3.3 Reader Anti-Collision Algorithms

Many reader anti-collision algorithms have been developed and published in the literature to reduce interference in RFID reader networks. Some of the existing anti-collision algorithms and their functionalities are discussed below.

11.3.3.1 Classification of Reader Anti-Collision Algorithms

Each reader anti-collision algorithm proposed in the literature has its own unique properties and functionalities. 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 11.4 shows the classification of the existing approaches and examples of some of the well-known protocols.

Table 11.1 The ISO 18000 standards for RFID.

ISO 18000 standard	Frequencies	Spectrum
ISO/IEC 18000-2:2004	Below 135 kHz	Low frequency
ISO/IEC 18000-3:2008	At 13.56 MHz	High frequency
ISO/IEC 18000-4:2008	At 2.45 GHz	Microwave
ISO/IEC 18000-6:2004	At 860 MHz to 960 MHz	UHF
ISO/IEC 18000-7:2008	433 MHz	UHF

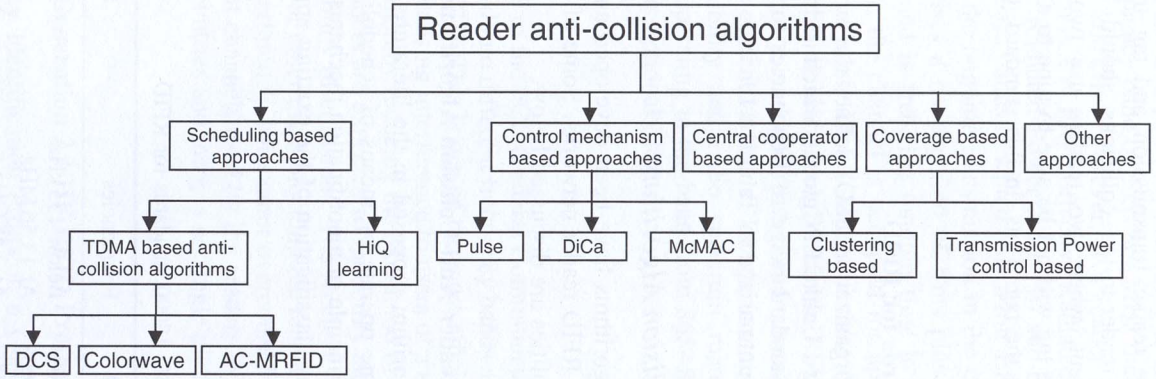

Figure 11.4 Classification of existing RFID reader anti-collision algorithms.

11.3.3.2 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. The following algorithms fall in this category.

TDMA-Based Anti-Collision Algorithms

In the TDMA-based anti-collision algorithm, time slots are divided into reader-to-tag communication period and reader-to-reader communication period. Figure 11.5 shows the time slot structure of TDMA-based anti-collision algorithm. By the reader-to-reader communication in the reader-to-reader communication period, each reader decides its time slot for transmission. The reader-to-tag period is used for reading the tags of a reader.

The following are the distributed TDMA-based RFID reader anti-collision algorithms. The goal of these algorithms is to color a reader network so that each reader node has the smallest possible number of adjacent nodes with the same color. A color is a periodic reservation for collision-free transmission of data.

DCS

Distributed color selection (DCS) [11, 12] allows easy reservation of time slots. A reader with a queued request for transmission transmits only in its color (time slot). If the transmission collides with another reader, the transmission request is discarded and the reader chooses a new color and reserves it. If any of neighboring readers has the same color, it has to choose another color, thereby clearing the time slot for the reader the next time the reader needs to transmit. This switch and reservation action is referred to as a "kick." In DCS, the maximum number of colors is fixed. Each reader keeps track of what color it believes the current time slot to be. Figure 11.6 shows subroutines to manage collision, color reservation, and kick resolution.

For example, in Figure 11.3(b), two readers R_1 and R_2 are neighbors. Assume that reader R_1 has a queued request for transmission. First of all, it waits for its color time slot and starts transmission. If the transmission experiences collision, reader R_1 selects one of the colors from the maxcolor (DCS requires 8–10 average colors to achieve 98% successful transmissions at 100% transmission [12]). Reader R_1 broadcasts kick packet with newly selected color. Also, if reader R_2 receives the same color as its current color, it randomly changes to different color within maxcolor. DCS is a "greedy" algorithm – a node's chances of colliding immediately after experiencing a collision are minimized at the expense of its neighbors.

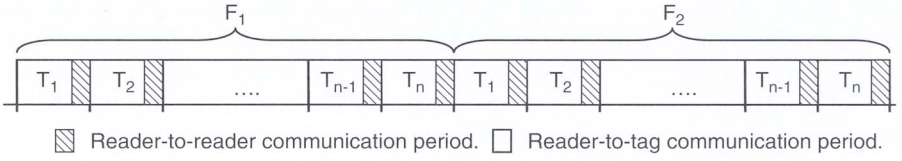

Figure 11.5 Frame structure of TDMA-based anti-collision algorithm.

```
DCS Subroutine
  • If experienced collision
      current color == random(maxcolors)
          broadcast kick with new color
  • If kick packet received with current color
      select different color randomly within maxcolors
```

Figure 11.6 DCS pseudocode.

Variable-maximum Distributed Color Selection (VDCS or Colorwave)

The maximum colors variable is fixed and does not change throughout the algorithm's execution in DCS. A single input for color does not provide flexibility to RFID reader networks with variable transmission probability. Thus, a mechanism for dynamically changing the maximum number of colors at a reader is needed. In [11, 12], Colorwave was suggested as an advanced version of DCS. In Colorwave, each reader monitors the percentage of successful transmissions. Five inputs to the algorithm determine when a reader changes its local value of maximum number of colors (maxcolors):

1. **UpSafe**: the safe percentage at which to increase maxcolors.
2. **UpTrig**: the trigger percentage at which to increase maxcolors if a neighboring reader is also switching to a maxcolors higher than that of this reader.
3. **DnSafe, DnTrig**: analogues of UpSafe, UpTrig, except that they are used for decreasing maxcolors.
4. **MinTimeInColor**: the minimum number of time slots before the Colorwave algorithm will change the value of maxcolors again after initialization or changing maxcolors.

Each reader chooses a random color from 0 to maxcolors to transmit. If it collides, it selects a new time slot and sends a kick (small control packet) to all of its neighbors to indicate the selection of a new time slot. If any neighbor has the same color, it chooses a new color and sends a kick, and so on. In DCS, as described above, each reader keeps track of what color it believes the current time slot to be. However, all the participating readers monitor the percentage of successful transmissions in Colorwave.

When a reader executing Colorwave reaches a Safe percentage to change its own value for maxcolors, it will send out a kick to all of its neighboring readers. If the phenomenon that is causing it to exceed a Safe percentage is local to that reader, the other readers will not have passed their own Trig percentages and will not respond. However, if the phenomenon causing the collision value to exceed a Safe threshold is widespread, neighboring readers will most likely have exceeded their own Trig thresholds, and a kick wave will ensure. As kicks spread from the initiating reader throughout the entire system, a large portion or all of the readers in the system may change their value of maxcolors. Colorwave is built upon DCS algorithm.

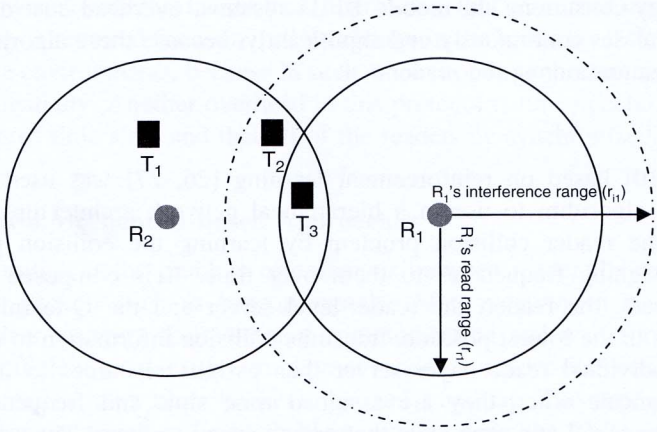

Figure 11.7 An illustration of the AC-MRFID protocol.

Anti-Collision Algorithm for Mobile RFID (AC-MRFID)

Similar to Colorwave, AC-MRFID [25] is also a distributed TDMA-based algorithm, where each reader chooses a random time slot to transmit. Colorwave works fine in the case of fixed or barely moving RFID readers. However, in the case of Mobile RFID readers, reader collisions may occur frequently when they form a dense RFID system and, hence, the value of maxcolors becomes unnecessarily high. An improved version of Colorwave, AC-MRFID, controls the number of time slots allocated to a reader in a frame by setting its value according to the number of readers, which are located in the interference range of the reader.

As shown in Figure 11.7, r_{i1} is the interference range and r_{r1} is the read range of reader R_1. If reader R_1 attempts to read tag T_3 and collides with reader R_2, reader R_1 calculates the number of time slots in a frame by Equation (11.1) and changes the value of max_timeslots. In Equation (11.1), α is the number of readers in the read range.

$$\max\_timeslots = \alpha + \left\lfloor \alpha \times \frac{\left(r_i^2 - r_r^2\right)}{r_r^2} \right\rfloor + 1 \tag{11.1}$$

At the same time, because reader R_2 also experiences a collision, it also changes its number of timeslots in a frame to max_timeslots by calculating Equation (11.1). After changing their numbers of time slots, readers R_1 and R_2 randomly select their time slot (current_timeslot) for reading tags in the next frame and let the other readers, which are located in their interference ranges, know their selection of current_timeslot by broadcasting the information. If a reader, except for the readers that are broadcasting (in this case, readers R_1 and R_2), receives information including a new current_timeslot, it randomly selects its new current_timeslot within the limit of its max_timeslot.

DCS, Colorwave and AC-MRFID are simple, and distributed protocols. However, it requires the system to establish and maintain information over the network, which is

time- and energy-consuming. In mobile RFID systems, overhead cost due to time slot reselections increases continuously and significantly, because these algorithms need tight time synchronization among the readers.

HiQ-Learning

HiQ-learning [10] based on reinforcement learning [26, 27] was used to develop an online learning algorithm to use in a hierarchical network architecture. HiQ provides a solution to the reader collision problem by learning the collision patterns of the readers and assigning frequencies to them over time. It is composed of three basic hierarchical layers: the reader, the reader-level server and the Q-learning server. The reader, which is in the lowest position, transmits collision information to the reader-level server. Each individual reader-layer server then assigns resources to its readers. The readers communicate when they are assigned time slots and frequencies. They are aware of the frequency and 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. Each reader stores the number of collisions it has experienced. This information is known to the reader-level server, as the reader directly communicates with it. Q-servers allocate the resources to the server below them, that is, to the reader-level 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. Figure 11.8 shows the hierarchical structure of Q-learning.

In Figure 11.8, readers R_1, R_2, R_3 and R_4 are within the interrogation range of reader R_5. Whenever reader R_5 has to read the tags, it sends the request for frequency and time. It starts reading after getting frequency and time. At the same time it also pings other readers in the same interrogation zone. Reader R_1 is responsible for collision detection processing. After getting the ping, readers R_1, R_2, R_3 and R_4 send back the response with their current state, that is, whether they are reading or not and which frequency and time slot they are using.

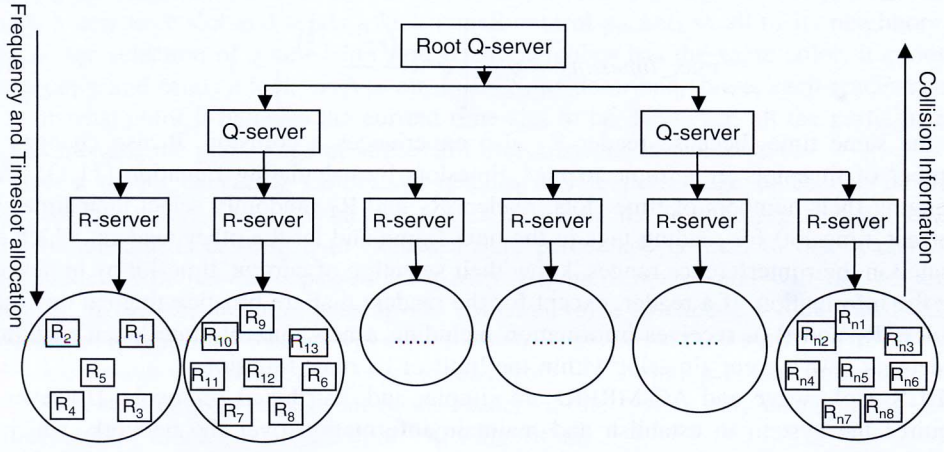

Figure 11.8 Hierarchical structure of Q-learning.

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 to 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 time slots and that all of the readers be synchronized.

11.3.3.3 Control Mechanism-Based Approaches

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 solves 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. The following algorithms fall into this category.

Pulse Protocol

Pulse [13, 14] 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 that is used for reader-to-reader communication. Broadcasting messages in the control channel does not affect the ongoing communication in 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 (DCF Interframe Space) 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 a beacon signal in the control channel. The beacon range is equal to the interference range. After reading the tag, it goes back to the waiting state.

Pulse mitigates the reader collision problem significantly, but the hidden terminal problem and exposed terminal problem still exist. Since a beacon does not have any destination address in its structure, it is just a broadcast message on a control channel. When the validity time of a beacon has 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. Furthermore, 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.

DiCa (Distributed Tag Access with Collision Avoidance)

DiCa (Distributed Tag Access with Collision Avoidance) [15] 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 use of the data channel through the control channel. The winner reads the tags through the data channel while the other readers wait until the channel is idle. The following packets are exchanged for the purpose of collision avoidance:

- *BRD_WHO*: Packet used to identify whether a reader reading tags exists in the same network or not.
- *BUSY*: To indicate that the reader is now reading tags.
- *BRD_END*: Packet used to indicate that the channel is idle after the tags have been read.

A reader that has to read tags (say, R_1) broadcasts the BRD_WHO message to the readers in the same interrogation area to discover the presence of other readers reading tags. After getting the BRD_WHO message, the reader in the same interrogation area (say, R_2) sends back a BUSY message if it is reading tags. Now, R_1 has to wait until it gets BRD_END from reader R_2. If R_1 does not receive a BUSY message after sending a BRD_WHO message for a certain period of time, it assumes that the data channel is free and it starts reading tags. Each reader sends a BRD_END message after completion of reading process. After receiving a BRD_END message, readers wait for random back-off time before sending a BRD_WHO message.

Unlike Pulse protocol, DiCa takes into account the hidden and exposed terminal problems by adjusting the control channel range to twice the radius from the first reader. This channel adjustment in DiCa reduces the energy consumption, so it is more suitable for energy-constrained mobile RFID systems. DiCa consumes less energy than Pulse, CSMA, and ALOHA.

DiCa requires sufficient time to exchange the contention message. It has no fixed tag data size and with a small data size there may not be sufficient time to exchange contention messages, which increases the collision probability.

Multi-Channel MAC Protocol (MCMAC)

The Multi-Channel MAC protocol (MCMAC) [16] 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 through the data and control channels.

As shown in Figure 11.9 (MCMAC's working principle), MCMAC works in a similar fashion to the conventional LBT. MCMAC broadcasts a control message after it wins contention in a control channel and thereby gains access to the data channel. The control message informs other neighboring readers within the interrogation zone that this 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.

This approach mitigates the reader-to-reader problem significantly. However, the reader-to-tag problem still exists with this approach. Since passive RFID tags are unable to discriminate between two data channels, multiple data channels cannot be used directly in a passive tag environment.

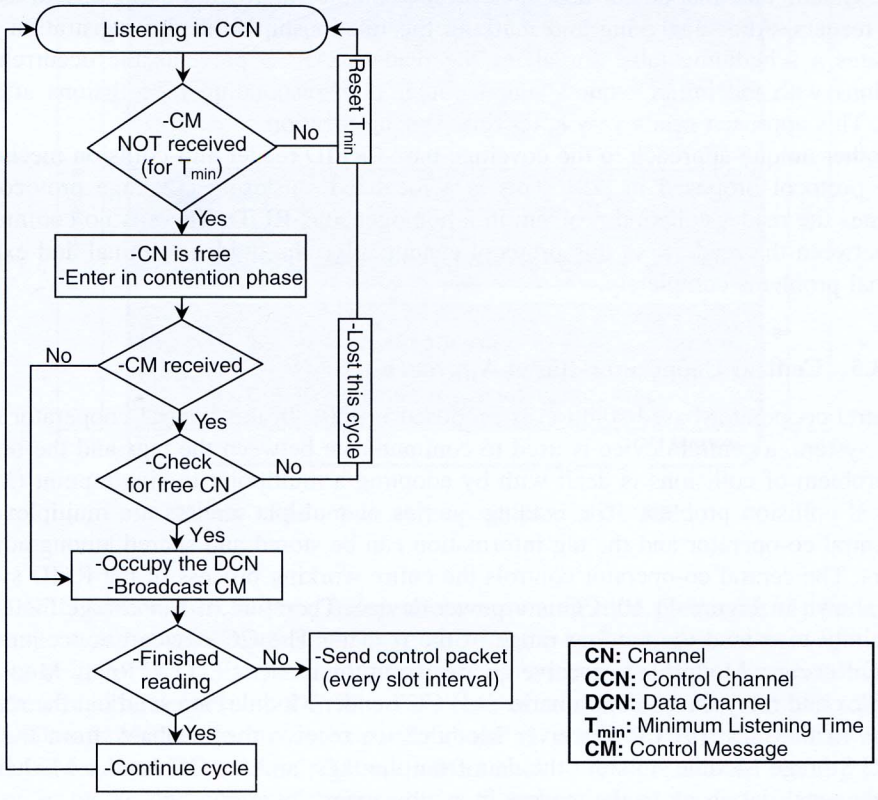

Figure 11.9 MCMAC working principle.

11.3.3.4 Coverage-Based Approaches

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 [17]. This approach is nevertheless energy-efficient.

An example of this approach is the array-based reader anti-collision scheme (ARCS) [28]. This scheme prevents collisions by grouping the readers and reducing the read cycle time. In ARCS, a reader agent controls every reader, that is, it turns the reader on or off according to the ARCS procedure. The reader agent is an interface that connects the physical reader device and the middleware. At first, ARCS turns on all the readers sequentially and synchronizes them. Each reader scans the tags and registers them in the registration table. Then it makes a network topology array of the

RFID system that marks the tags that present in the interrogation regions of two or more readers. After analyzing and marking the relationship from the registration table, it creates a scheduling table for all of the readers. ARCS prevents the occurrence of collisions with the initial request signal, rather than responding to collisions after the event. This approach needs very strict time synchronization.

Another unique approach to the coverage-based RFID reader anti-collision mechanism is the protocol proposed in [29]. This is a localized clustering coverage protocol that mitigates the reader collision problem in a homogeneous RFID. There is no communication between the readers, so this protocol cannot solve the hidden terminal and exposed terminal problems completely.

11.3.3.5 Central Cooperator-Based Approach

A central cooperator-based solution is proposed in [30]. 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 dealt with by adopting a multipoint to single point (MP2P) classical collision problem. 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.

As shown in Figure 11.10, CC is a power device. Therefore, it can charge the tags in its vicinity to extend the reading range of the readers. The CC device has six modules: (1) CC Receiver Module1: to receive queries from the readers; (2) CC Relay Module: to multiplex and relay the readers' queries; (3) CC Sender Module1: to send out the readers' queries to the tags; (4) CC Receiver Module2: to receive the feedback from the tags; (5) CC Storage Module: to store the data from the tags; and (6) CC Sender Module2: to send the tags' data back to the readers in a sub-carrier.

As shown in Figure 11.11, two kinds of working schemes are proposed for two different RFID application environments: (1) CC-RFID scheme one; and (2) CC-RFID scheme two. CC-RFID scheme one is proposed for highly mobile tag environment. Multiple readers compete for the access to the channel and send their reading requests to CC. Then CC demodulates the request information and multiplexes them into a single reader's query. CC sends the multiplexed query to read tags and the tags respond with their identification information. After receiving the identification information, CC selects the tags' response information by examining the original requests from readers and sends it to each reader separately.

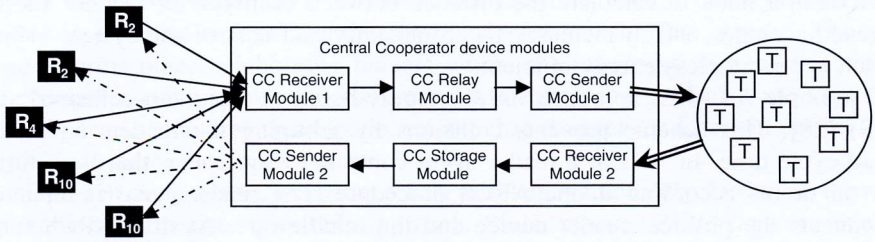

Figure 11.10 CC-RFID system architecture.

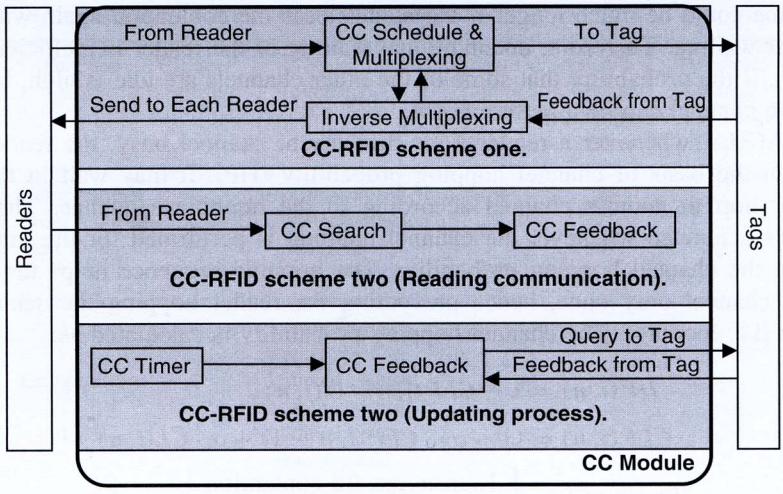

Figure 11.11 Two working schemes of CC-RFID.

CC-RFID scheme two has two independent communication processes: (1) the reading communication between readers and tags; and (2) the updating process between readers and tags (Figure 11.11). In the first communication process, multiple readers compete to send their reading requests to CC. The CC receives readers' requests and looks through the CC Storage Module for the corresponding tags' ID requested by readers. After collecting all the required information, CC sends them back to readers and the reading process is over. In the second communication process, a renewal timer starts to update the tags information stored in CC. As the updated tags' information is necessary, CC sends updating query to read tags and tags respond by sending their latest information to CC. The CC-RFID scheme two is appropriate for static or less mobile tag environments.

This approach has additional overhead associated with the use of an extra device, namely the central cooperator. It might have a scalability problem, because the central device is mounted in a specific place and has a fixed cooperation capacity.

11.3.3.6 Some Other Approaches

The Adaptive Channel Hopping Algorithm (ACHA) [31] is a preliminary approach to prevent RFID collisions. It is multichannel protocol. This algorithm combines the LBT algorithm, a random back-off mechanism with a specific hopping method. In the dense RFID system, where density of readers per channel (number of readers/number of channels) is more than one, simply to select a channel randomly is not efficient, because the reader might perform a lot of channel hopping in order to find the idle channel when the channel utilization is high. If all the channels are busy, readers may keep on hopping to busy channels repeatedly. Furthermore, the reader may check the same channel several times.

A reader waits in the current channel until it becomes idle and it tries to occupy the channel when the current reader finishes the transmission. If the probability that some of the other channels are idle is high, just waiting in that channel is not efficient. The

waiting time could be much longer if the reader loses the contention again with another reader after waiting. Therefore, unconditional waiting of the reader is inefficient. On the other hand, if the probability that some of the other channels are idle is high, hopping to find an idle channel can be a better choice.

So, in ACHA, whenever a reader finds the current channel busy, the reader takes a decision on the basis of channel hopping probability (HP). It may wait in the current channel or hop to another channel according to the hopping sequence. The hopping sequence is generated whenever the channel hopping is performed for the first time by calculating the channel hopping probability. The hopping sequence helps the reader to check the channel only once, hence preventing the reader hopping the same channel repeatedly (i.e. looping). The channel hopping probability is calculated as:

$$HP(i,n) = 1 - CLP(i,n) \cdot U(i,n) \tag{11.2}$$

$$CLP(i,n) = (1-\alpha) \cdot CLP(i,n-1) + \alpha \cdot CL(i,n) \tag{11.3}$$

$$Where,\ CL = \left\{ \begin{array}{l} 1, \text{unsuccessful contention} \\ 0, \text{successful contention} \end{array} \right\}$$

And,

$$U(i,n) = (1-\alpha) \cdot U(i,n-1) + \alpha \cdot U_t(i,n) \tag{11.4}$$

where i is the reader's ID and n is the number of calculations. CLP is contention loss probability, and U_t is the channel utilization for a certain period of time. U is the channel utilization, that is, how long the channel is occupied. Equation (11.3) uses the exponential averaging method that applies weighting factor to the recent value.

After selecting a particular channel, it senses the channel by performing LBT. This approach improves performance and reduces waiting time significantly. 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.

11.4 Comparison

As discussed in Section 11.3, the existing reader anti-collision protocols used in RFID systems 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 11.2 shows a comparison between eight promising protocols for resolving the reader collision problem based on their nature and operation. As the reader collision problem is similar to the frequency assignment problem in mobile communication systems, most reader anti-collision algorithms allocate frequencies over time to a set of readers to mitigate the collision problem. To eliminate the collision problem in a dense RFID system, the readers should work cooperatively with the tags.

As shown in Table 11.2, the major overheads in the RFID anti-collision protocols are as follows. Colorwave and AC-MRFID require tight time synchronization. HiQ-learning has high management overhead in a mobile environment. In a highly mobile environment,

Table 11.2 Comparison of reader anti-collision algorithms.

Algorithm	Function used	Carrier sensing	Major overhead	Distributed control	Fixed Channel Assignment (FCA)	Dynamic Channel Assignment (DCA)	Tag side consideration for collision avoidance
Colorwave	Color number	×	Time synchronization	√	√	√	×
AC-MRFID	Color number	×	Time synchronization	√	√	√	×
HiQ Learning	Cost function	×	Management overhead	×	×	√	×
Pulse	Beacon frame	√	Energy consumption and additional channel resource	√	√	×	×
DiCa	Energy aware	√	Additional channel resource and time	√	√	×	×
MCMAC	LBT	√	Additional channel resource and computational overhead	√	√	√	×
CC-RFID	MP2P	×	Special hardware	×	×	×	√
ACHA	Probability based channel hopping	√	Multiple channel resources	√	√	√	×

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the management overhead increases exponentially with increasing the numbers of readers. The pulse protocol requires more energy for contention and the probability of collisions occurring in the control channel is also high. DiCa spends a lot of time in control channel negotiation. MCMAC and ACHA require multichannel capability and a large amount of computation for channel hopping. Finally, CC-RFID needs special hardware and a database called the central cooperator.

Table 11.3, taken from [37], shows a comparison between the different reader anti-collision protocols in terms of their channel assignment. All of the protocols in Table 11.3 are multichannel 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 that a certain amount of time is wasted. They have similar approaches, however, DiCa offers some improvements over Pulse.

Figure 11.12, taken from [37], shows a comparison between the different protocols in terms of the network throughput. Some of the representative protocols discussed above (Colorwave, 1-persistent CSMA, HiQ, Pulse, DiCa, McMAC, ACHA and CC-RFID) are compared. The number of readers varies between 2 to 20 and the readers are deployed in different random topologies. The result shown is for a total of 50 simulations per protocol. Tags are also varied from 100 to 400 and are placed in a grid for the simulations in 10 × 10 meter area. In case of ACHA, the total number of channels are 4, LBT time is 5 ms, waiting time after transmission is 0.1 sec, and trigger distribution of the reader is Poisson distribution. Read range and interference range of the readers are 1.6 meter and 5.4 meter respectively. In Figure 11.12, except for the protocol using a special device (i.e.

Table 11.3 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

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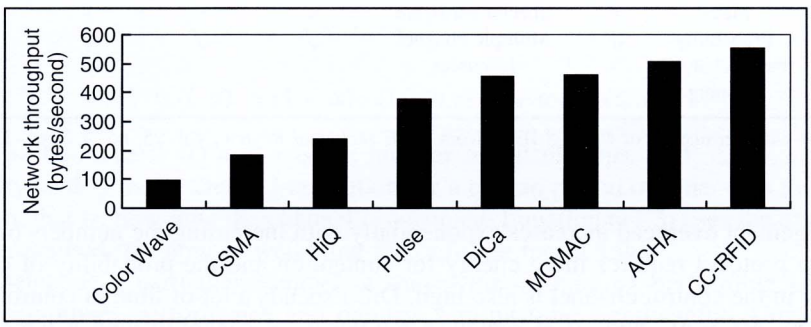

Figure 11.12 Throughput comparison. Reproduced with permission of © 2008 IETE from *IETE Technical Review,* vol. 25, no. 5, Sept.–Oct. 2010.

CC-RFID), DiCa gives the highest throughput of the single data channel protocols. CC-RFID shows the best throughput performance of all of the protocols. However, CC-RFID needs a special device called a central cooperator, as described above. 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 their throughput, in overall, DiCa shows the better performances.

11.5 Conclusion

In this chapter, the reader collision problem in RFID systems has been discussed. The existing solutions to the reader collision problem are surveyed and the current regulations and standards are outlined. The current solutions are also classified and their characteristics, functions, working principles, and limitations are listed. The problems that are not addressed by the current standards are pointed out. It is found that although many schemes have been proposed as novel solutions to the reader collision problem, still some more

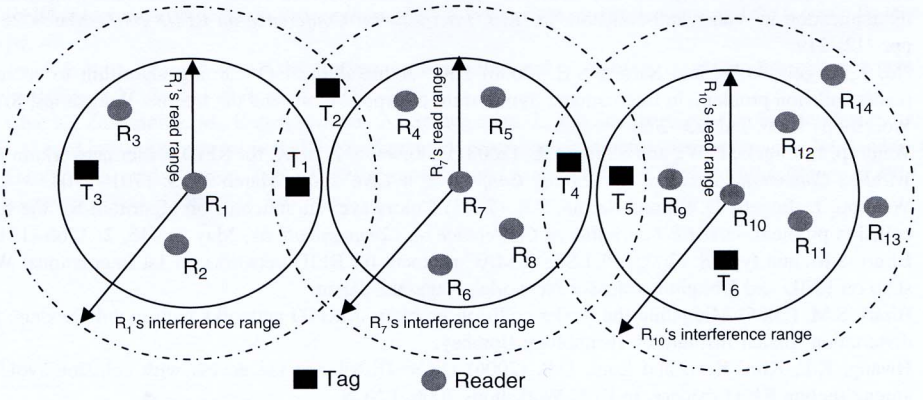

Figure 11.13 Deployment of UHF RFID readers and tags.

improvements need to be made. The use of inexpensive passive tags is one of the reasons why RFID has become popular. Nevertheless, due to their limited functions, the collision problem still exists and needs to be completely solved. Of the above-mentioned protocols, AC-MRFID, DiCa and ACHA seem to be the most promising protocols in terms of the throughput.

Problems

1. What is the main difference between DCS, Colorwave and AC-MRFID?
2. Consider Figure 11.13, which shows UHF RFID readers and tags. Assume that all the readers are homogenous having a read range of 2 meter and an interference range of 3 meter. For AC-MRFID, calculate the maximum time slot for reader 1, reader 7 and reader 10.

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RFID SYSTEMS

RESEARCH TRENDS AND CHALLENGES

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This book provides an insight into the 'hot' field of Radio Frequency Identification (RFID) Systems

In this book, the authors provide an insight into the field of RFID systems with an emphasis on networking aspects and research challenges related to passive Ultra High Frequency (UHF) RFID systems. The book reviews various algorithms, protocols and design solutions that have been developed within the area, including most recent advances. In addition, the authors cover a wide range of recognized problems in the RFID industry, striking a balance between theoretical and practical coverage. Limitations of the technology and state-of-the-art solutions are identified and new research opportunities are addressed. The book is authored by experts and respected researchers in the field, and every chapter has been peer reviewed.

Key Features:

- Provides the most comprehensive analysis of networking aspects of RFID systems, including tag identification protocols and reader anti-collision algorithms
- Covers in detail major research problems of passive UHF systems such as improving reading accuracy, reading range and throughput
- Analyzes other "hot topics" including localization of passive RFID tags, energy harvesting, simulator and emulator design, security and privacy
- Discusses design of tag antennas, tag and reader circuits for passive UHF RFID systems
- Presents EPCGlobal architecture framework, middleware and protocols
- Includes an accompanying website with PowerPoint slides and solutions to the problems (http://www.wiley.com/go/bolic_rfid)

This book will be an invaluable guide for researchers and graduate students in electrical engineering and computer science, and researchers and developers in the telecommunications industry.

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ISBN 978-0-470-74602-8

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