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Research on Anti-Reader Collision Protocols for Integrated RFID-WSNs

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Abstract

Integrated RFID-WSNs (wireless sensor networks) have recently been researched to provide object identities, sensing information, mobile service, and network functionalities. In integrated RFID-WSNs, the reader collision is one of the critical problems. Above all, due to the absence of universally applicable anti-collision protocols and the channel capture phenomenon, the medium access control protocols in integrated RFID-WSNs suffer from reader collision and starvation problems. In this paper, we propose an efficient MAC protocol, called EMP, to avoid the above problems in integrated RFID-WSNs. EMP is a CSMA-based MAC protocol which is compatible with sensor networks operating on integrated nodes which consist of an RFID reader and a senor node. EMP resolves not only the reader collision problem, but also the starvation problem using a power control mechanism. To verify the performance of EMP, we compared it with other anti-reader collision MAC protocols using simulations. As a result, the performance of EMP showed improvements in throughput, system efficiency, and energy consumption compared to the single data channel protocols (CSMA/CA, Pulse, and DiCa) in dense deployment environments.

Keywords: Reader collision, MAC, RFID, WSN, power control

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1. Introduction

Radio frequency identification (RFID) technologies are widely used in industrial and commercial systems such as supply-chains, transport payment systems, tracking, etc. [1][2]. For example, Wal-Mart effectively reduced out of stocks by 30 percent after implementing an RFID system, and Hong Kong's Octopus transport ticketing system is one of the most successful RFID-enabled transportation payment applications. Furthermore, the hardware has become smaller and smarter due to the advances in the major devices and communication technologies and this tiny hardware enables mobile services and networking services to be developed. Recently, an RFID reader was embedded in mobile phones to search objects, and a user with this mobile phone can obtain the information from tags when moving around in shops.

Although technologies related RFID have advanced considerably in recent years, some major hurdles still exist in RFID networks. Sheng and Li [1] mentioned the challenges of RFID such as efficient data management, intelligent data transformation and aggregation, and large-scale application support. Especially, the above mentioned challenges of RFID are important open issues that cannot be resolved until an RFID framework for data integration and processing has been constructed. Cho and Shim [3] also reported on the limits of RFID networks and services using environment-sensitive objects that are very sensitive to the environmental conditions, such as temperature and humidity. In an emergency situation such as an earthquake, the demand for emergency products such as pharmaceutical products and blood pouches can greatly increase, and the loss of emergency products caused by environmental changes is a critical problem. Hence, if the environmental conditions in the storage of emergency products go outside of the acceptable range, the emergency control center must receive notification as soon as possible. In other words, the above situation implies that RFID services have limited ability to provide sensing information. Besides, the existing RFID networks and services cannot provide sufficient network abilities, such as routing, aggregation, and topology control. To overcome the defects of RFID, Cho and Shim presented a novel framework for integrating wireless sensor and RFID networks (SARIF). Wireless sensor networks (WSNs) can collect, aggregate and analyze environmental information, and this ability can allow the above mentioned challenges of RFID networks to be resolved. Hence, integrating RFID networks with WSNs has already been attempted in [4][5][6]. For example, SARIF can also provide richer information about the environments of objects, as well as their locations. As part of an effort to integrate RFID networks and WSNs, we propose an integrated RFID-WSN for mobile RFID and senor nodes. As shown in **Fig. 1**, the whole integrated network comprises sensor nodes, RFID readers, and tags. In this network, the RFID reader can obtain not only the information of the environmental-sensitive objects, but also locations, because the RFID reader is a special node that communicates with the sensor nodes and other RFID readers. For instance, when the RFID reader gets identification from the tags in its read-range, it can also obtain sensing information and locations from the neighboring sensor nodes. The collected information can be aggregated with other sensing data to provide specific services in WSNs, and these data can be delivered to various service platforms via a gateway and backbone networks. Although this architecture can resolve the above mentioned challenges, another critical issue still remains, namely how to deal with reader collision in RFID networks. Reader collisions become a serious problem in integrated RFID-WSNs when the RFID readers are densely deployed.

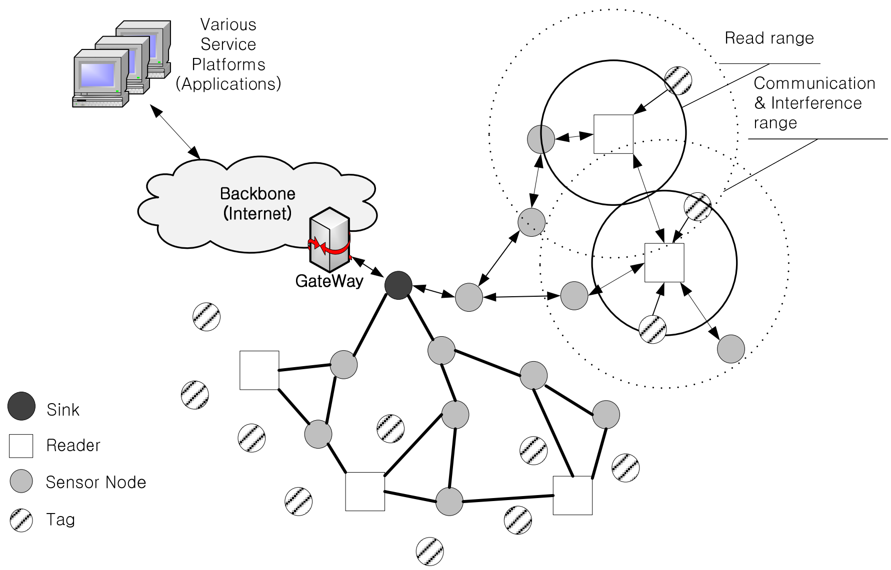


Fig. 1. Conceptual architecture of integrated RFID-WSNs

Reader collisions cause misreading and reading failures that lead to the wastage of bandwidth and a long delay time in the RFID networks. Therefore, avoiding reader collisions is an important issue in RFID network systems.

Generally, there are two types of reader collision.

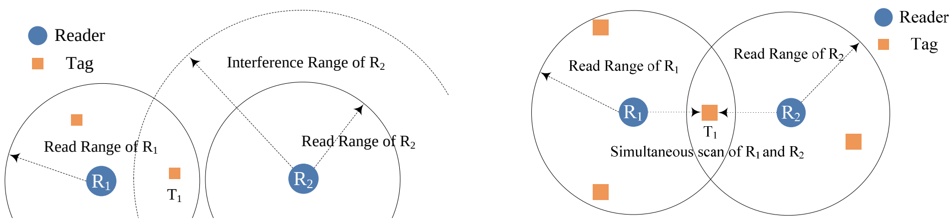


Fig. 2. Reader-to-reader interference **(a)** and Multiple reader-to-tag interference **(b)**

1) **Reader-to-reader interference** occurs when a stronger signal from another reader interferes with the weak reflected signal from a tag. In **Fig. 2-(a)**, tag T_1 lies in the interference region of reader R_2. The response signals of R_1 from T_1 can easily be distorted by the signals from R_2. This interference occurs even when the read range of the two readers do not overlap.
2) **Multiple reader-to-tag interference** occurs when more than one reader try to read the same tag simultaneously. In **Fig. 2-(b)**, the read ranges of R_1 and R_2 are overlapped, and T1 lies in between these two ranges. If R_1 and R_2 simultaneously read T_1, T_1 cannot decipher any queries and the tag is not read by both of R_1 and R_2. In this case, R_1 and R_2 indicate two and one which are the number of tags adjacent to them, respectively.

To mitigate this phenomenon in RFID networks, various protocols [8][9][10][11][12][13][14][15][16] have been developed over the past few years, but they were not designed for integrated RFID-WSNs. Hence, we present an efficient anti-reader collision MAC protocol, called EMP, for integrated RFID-WSNs. EMP is a CSMA-based

MAC protocol which is compatible with WSNs operating on integrated nodes which consist of an RFID reader and a senor node. EMP resolves not only the reader collision problem, but also the starvation problem using a power control mechanism. The remainder of this article is organized as follows. We first review the features of the existing protocols in related work. Then, we describe EMP and compare its performance with those of the other protocols. Finally, we summarize our work and discuss future directions.

2. Related Work

As mentioned in the introduction section, reader collisions are the key problem leading to misreading and reading failures in dense RFID-WSN networks. In this section, therefore, we describe the history of anti-reader collision protocols and classify them according to their characteristics. Then, we discuss on attributions of the protocol that should be included for integrated RFID-WSNs.

Recently, anti-reader protocols were well defined by Joshi and Kim [7]. They classified anti-reader collision protocols into four groups, which are scheduling based protocols, control based protocols, coverage based protocols, and other approaches. Scheduling based protocols [8][9] assign the available resources, such as the time-slots and frequencies, among the readers to prevent them from transmitting simultaneously. Control mechanism based protocols [10][11] resolve the problem of reader collisions by transmitting notification control packets such as beacon signals. Those readers which receive the control packet wait for the next cycle to avoid reader collisions. Coverage based approaches are divided into adaptive transmission range based protocols [12] and cluster based protocols [13]. Adaptive transmission range based protocols dynamically adjust the read ranges of the readers to reduce the overlapped region among the neighboring readers. Cluster based protocols adjust the coverage ranges of the clusters that are elected to communicate with the server in an *ad-hoc* network. Finally, in other approaches, there are (CC)-RFID [14], ACHA [15] and ARCS [16]. The central cooperator (CC)-RFID system uses a central cooperator that can communicate between the tags and the readers. The central cooperator combines the reading queries of multiple readers into a single signal, and the tag information can be stored and shared among adjacent readers. The central cooperator controls the entire working process of the RFID system. The adaptive channel hopping algorithm (ACHA) combines the listen-before-talk (LBT) algorithm with a specific hopping method. ACHA senses the channel by performing LBT. If the channel is occupied by another reader, the reader may hop to another channel by the mechanism of hopping probability. An array based reader anti-collision scheme (ARCS) prevents collisions by grouping the readers and reducing the read cycle time.

To provide various services, integrated RFID-WSNs should include characteristics such as mobility, simplicity, flexibility, and scalability, and the anti-reader collision protocol for the RFID-WSNs should be designed with these characteristics in mind. From this point of view, although scheduling based protocols can effectively reduce the possibility of reader collisions, they require the system to establish and maintain information on the networks, which is time and energy consuming. Besides, this approach, requiring time synchronization, is not suitable from the viewpoint of the mobility of integrated RFID-WSNs, because topology changes frequently occur in mobile environment such as WSNs. The coverage based approach is also inappropriate from the viewpoint of mobility and simplicity, because it usually needs not only centralized control, but also the calculation of the transmission ranges. Some of the other approaches are very dependent on the system and hardware, which limits their application in various network environments. For example, the above mentioned ACHA 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 quite limited, except in the US. In the case of (CC)-RFID, the central cooperator controls the entire working process of the RFID system.

On the other hand, control mechanism based protocols typically utilize one control channel and one data channel to reduce the number of reader collisions. This scheme is attractive for integrated RFID-WSNs, because a simple mechanism using a control packet or beacon is one of the most widely used methods in WSNs. Moreover, control mechanism based protocols are relatively independent of the above mentioned characteristics, because they do not require specific clustering, time synchronization, and centralized control. Consequently, we focus on control mechanism approaches, and discuss the features of the related protocols.

1) **Pulse** [10] is a CSMA based notification protocol that attempts to mitigate the reader collision problem using two channels in the RFID networks. One channel is used for communicating with the tags and the other channel is the control channel which is utilized to communicate with the neighboring readers. The reading process of the reader is not affected by the transmission of control messages via the control channel, which is separate from the data channel. When the reader wants to communicate with the tags, it goes into the waiting state in which the reader waits for DIFS time. If the reader does not receive any beacon signal, it considers that there are no other reader reading tags and enters the contention phase. In the contention phase, the reader chooses a random backoff time. If the reader receives a beacon during the backoff time, it waits for the next cycle, i.e. until it does not receive a beacon during a DIFS time. On the other hand, if the backoff time expires and it did not receive any beacons, the reader sends a beacon on the control channel and starts communicating with the tags on the data channel. While it is communicating with the tags, the reader periodically sends a beacon every beacon interval. This notifies the neighboring readers so that they do not communicate with the tags.

   Although Pulse mitigates the reader collision problem, it cannot solve the hidden terminal problem and exposed terminal problem completely. In addition, the reader consumes a large amount of energy due to the periodical beacon transmission.

2) **Distributed Tag Access with Collision Avoidance (DiCa)** [11] is similar to the Pulse protocol, but it copes with the hidden and exposed terminal problems by adjusting the control channel range at twice the radius from the first reader. DiCa also has two independent channels, which are a data channel and a control channel. Each reader contends for the reading of tags in the control channel, and the winner of the contention process reads the tags. The others wait until the channel is idle. When the reader completes the reading process, it sends a BRD_END packet to notify its neighbor readers. If another reader sends a BRD_WHO packet for the purpose of reading the tags during this time, the reader reading the tags sends a BUSY packet to prevent a reader collision.

   DiCa takes into consideration the hidden and exposed terminal problems as well as the energy consumption. Besides, the network model for DiCa is very appropriate for integrated RFID-WSNs. However, DiCa does not consider the starvation problem caused by channel capture and collisions among the control packets.

The proposed EMP also controls the reader collision problem through two channels, while effectively overcoming the drawbacks of the above two control mechanism based protocols using three handshaking and power control. The simulation results prove that EMP efficiently handles the hidden and exposed terminal problems, as well as channel capture phenomenon.

The following section gives an overview of the EMP algorithm and describes the sub-functions of EMP.

3. Efficient MAC Protocol for Anti-Reader Collision

We devised a method of resolving the drawbacks of the existing control mechanism based protocols in integrated RFID-WSNs. Firstly, we adopt three-way handshaking to resolve the hidden and exposed terminal problems. Secondly, we utilize a slot allocation method, called EDSA, to reduce the collisions among the control packets. Finally, power control is utilized to handle the starvation problem in a dense environment.

3.1 Overview of EMP

In integrated RFID-WSNs, the reader should be able to communicate with the tags and other readers, as well as with sensor nodes. Hence, EMP was designed based on unslotted CSMA/CA, which is a MAC protocol of the IEEE 802.15.4 standard [17], and takes into consideration of compatibility with WSNs and the mobility of the reader.

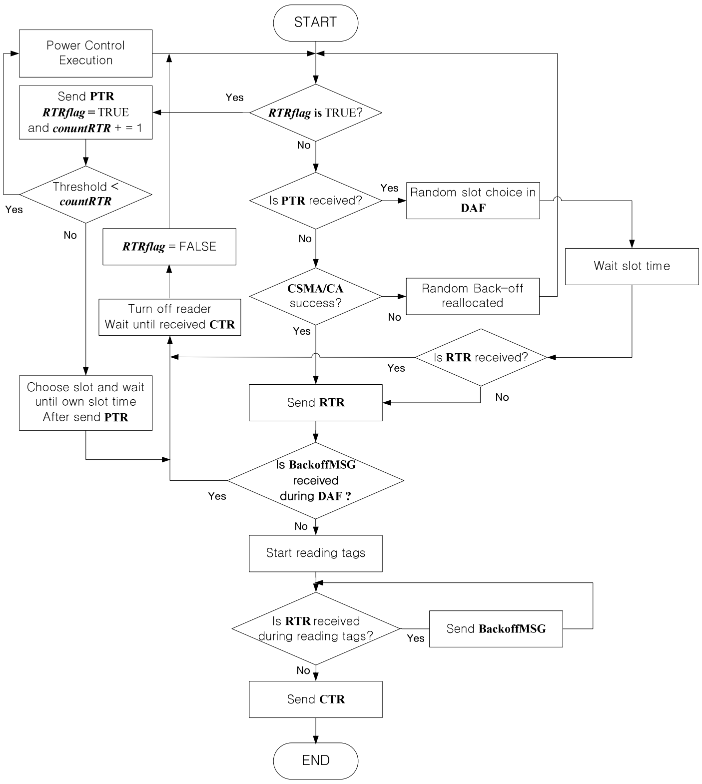


Fig. 3. Flow chart for EMP

EMP uses a three-way handshaking method with *RTR-PTR-CTR* messages to avoid the problem of reader collisions. *RTR* means that a reader requests its neighboring readers to read the adjacent tags. *RTR* includes simple information such as the size of the dynamically allocated frame, called the *DAF*, and identification. *PTR* is the response of the neighboring readers to the *RTR*. *CTR* is the notification that the channel is idle. **Fig. 3** shows the process of EMP in integrated RFID-WSNs. When a reader wants to read its adjacent tags, it broadcasts an

RTR to its neighboring readers after performing unslotted CSMA/CA, which is a MAC protocol to mitigate the packet collision problem in WSNs. If any of the neighboring readers are not currently reading tags, they send a *PTR* to the reader and then they go into the wait phase or sleep mode until the reader broadcasts a *CTR*. The reader starts reading the tags after a *DAF* time, which is a short time to prevent the collision of the control packets. On the other hand, if a reader currently reading tags exists in the interference range of the reader sending the *RTR*, it sends a *BackoffMSG*, and the reader sending the *RTR* waits for a *CTR*.

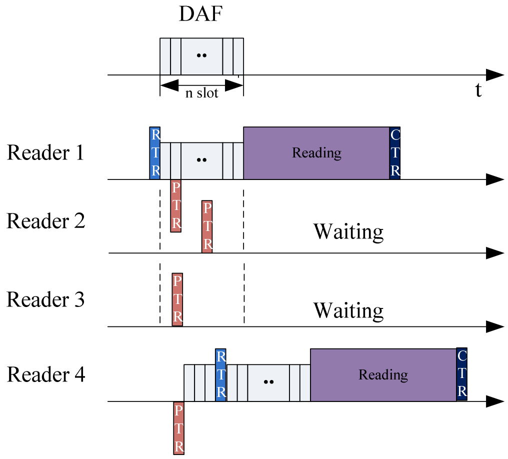


Fig. 4. Three way handshaking in EMP

Another characteristic of EMP is that it gives the neighboring readers the chance to read the tags by overhearing the *PTR*. This is illustrated in **Fig. 4**. Reader 1 is a neighbor of reader 2 and 3, and reader 4 is a neighbor of reader 3. Readers 2 and 3 send a *PTR* in response to the *RTR* of Reader 1. The *PTR* of Reader 3 is also sent to Reader 4, because Reader 4 is also a neighbor of Reader 3. If the channel is idle, Reader 4 immediately sends an *RTR* and readies itself to read the tags. **Fig. 5** shows the readers able to read the tags after the handshaking with *RTR-PTR*. If R_1 broadcasts an *RTR* after CSMA/CA, then the adjacent R_2, R_3 and R_4 send a *PTR* and store the ID of R_1, which is used to discriminate duplicated packets. The other readers ($R_{5,7,8,\ and\ 10}$) also store the ID from the *PTR*, and send an *RTR* again. If these readers, except R_6, do not receive any other packets or a *PTR* they can simultaneously read the tags. R_6 should enter sleep mode, because it received an *RTR* from R_5. In such a way, EMP increases the reading probability of the readers.

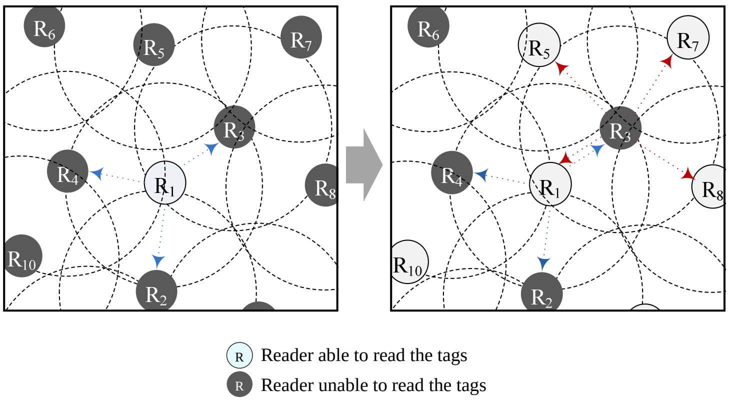


Fig. 5. The readers able to read the tags after the handshaking with *RTR-PTR*

3.2 EMP Algorithm Description

Fig. 6 shows the algorithm for EMP. This description illustrates how a reader operates in integrated RFID-WSNs. According to the condition, EMP performs five procedures as follows.

EMP protocol

```
Begin EMP
RTRflag is FALSE:
    if CAMA/CA_func is TRUE then
        goto sending RTR
    else CSMA/CA_func execution
    end if
RTR received:
    do RTRflag is set TRUE;
    do countRTR += 1
    if Threshold < countRTR then
        do powerControl_func execution
    else send PTR
    end if
    goto waiting CTR
PTR received:
    do randomly choose one of slot in DAF
        while slot time is false
                if RTRflag == TRUE then
                        goto waiting CTR
                end if
        end while
    goto sending RTR
waiting CTR:
    do turn off reader
    while CTR is false
        do wait CTR
    end while
    do RTRflag is set FALSE
sending RTR
    do broadcast RTR
        while DAF is not expired
                if BackoffMSG is true then
                        goto waiting CTR
                end if
        end while
        while readingTags_func is not over
                if RTRflag is set TRUE  then
                        do send BackoffMSG
                end if
        end while
    do send CTR
```

Fig. 6. Algorithm for EMP protocol

- ***countRTR is zero*:** If *RTRflag* is false, where *RTRflag* is a flag which is set when a reader receives an *RTR*, and the *CSMA/CA* function returns TRUE, the reader goes to ***sending RTR***.

- ***RTR received*:** If the reader receives the *RTR*, it adds one to *counterRTR* and *RTRflag* is set to TRUE. At this time, if *countRTR* is larger than a threshold value, it executes *powerControl_func* which is illustrated in section 3.4. Otherwise, the reader sends a *PTR* and goes to ***waiting CTR***.

- ***PTR received*:** If the reader receives the *PTR*, it randomly chooses one of the slots in *DAF* and waits for a slot time. At this time, if the reader receives the *RTR*, it goes to ***waiting CTR***. Otherwise the reader goes to ***sending RTR***.

- ***waiting CTR*:** In ***waiting CTR***, the reader turns off its reader-part for the purpose of energy saving and waits until it receives a *CTR*. Then the reader sets *RTRflag* to FALSE and goes to the initial phase.

- ***sending RTR*:** In the ***sending RTR*** phase, the reader broadcasts a *RTR* and waits for *DAF*. At this time, if the reader receives a *BackoffMSG*, it goes to ***waiting CTR***. If not, it executes *readingTags_func* which causes the reader to read the tags. If the node receives an *RTR* while it is reading the tags, it sends a *BackoffMSG* to guarantee that it can continue to read the tags without any interference from the other readers. Finally, the reader sends a *CTR* after reading the tags.

3.3 Slot Allocation Method

As mentioned above, if the readers broadcast the *RTR* and *PTR* at the same time, the throughput will be greatly reduced by collisions among these packets. On the other hand, if the control packets are not sent simultaneously, this problem can be resolved. Consequently, we use a slot allocation scheme, which is a kind of dynamic framed slotted ALOHA [18][19][20]. The slot allocation scheme enables the reader to allocate a different slot when the neighboring readers send a control packet. In a mobile environment, even if the number of neighboring readers varies with time, it can dynamically adjust the number of slots during each cycle.

Generally, slot allocation methods are used for mitigating the collisions between the reader and tags. They estimate the number of tags and randomly allocate the optimal slots to the tags. Given N slots and n tags, r tags in one slot are binomially distributed with parameters n and $1/N$:

$$B_{n,\frac{1}{N}}(r) = \binom{n}{r}\left(\frac{1}{N}\right)^{r}\left(1-\frac{1}{N}\right)^{n-r} \tag{1}$$

Herein, we regard the tags as readers and the value of r as the number of neighboring readers in one slot. P_{empty} and P_{succ} are the generated probabilities of the empty slot and the successful slot, respectively. These values are derived from equation (1), and the equations are as follows:

$$P_{empty} = B_{n,\frac{1}{N}}(0) = \binom{n}{0}\left(\frac{1}{N}\right)^{0}\left(1-\frac{1}{N}\right)^{n} = \left(1-\frac{1}{N}\right)^{n} \tag{2}$$

$$P_{succ} = B_{n,\frac{1}{N}}(1) = \binom{n}{1}\left(\frac{1}{N}\right)^{1}\left(1-\frac{1}{N}\right)^{n-1} = \left(\frac{1}{N}\right)\left(1-\frac{1}{N}\right)^{n-1} \tag{3}$$

The optimal number of slots is equal to the number of neighboring readers ($\therefore\ L_{optimal} = n$). Consequently, we need to estimate n to derive $L_{optimal}$. There are existing estimation methods, such as the lower bound [18] and maximum throughput [19]. Their goal is to estimate the optimal value of n with the result of the read cycle $c = < c_0, c_1, c_k >$ where the elements quantify the empty slots, the slots filled with one reader, and the slots with collisions respectively. The optimal value of n is obtained by the following simple estimations:

$$n_{LowerBound} = 2 \times c_k\,(Number\ of\ collided\ slot) \tag{4}$$

$$n_{MaximumThroughput} = 2.39 \times c_k\,(Number\ of\ collided\ slot) \tag{5}$$

However, these methods significantly reduce the collision ratio, but tend to allocate excessive number of slots and this can decrease the throughput.

We designed EDSA, which estimates the number of neighboring readers to derive the optimal number of slots, N_{DAF}. Initially, EDSA sets the marginal collision ratio C_{MCR} and initial N_{DAF}, and EDSA calculates the collision generation ratio C_{CGR} for each transmission of a control packet. C_{CGR} is calculated by

$$C_{CGR} = \frac{c_k}{L_i} \times 100 \tag{6}$$

where c_k is the number of slots with collisions and L_i is the number of slots in the *i*-th cycle. The cycle is repeated until C_{CGR} is equal to C_{MCR}. If $C_{CGR} < C_{MCR}$, then $L_i = L_{i-1}+1$. If $C_{CGR} > C_{MCR}$, then $L_i = L_{i-1}-1$. Therefore N_{DAF} is derived as follows.

$$L_i = \begin{cases} L_{i-1}+1 & if \;\; C_{CGR} > C_{MGR} \\ L_{i-1} & if \;\; C_{CGR} = C_{MGR} \\ L_{i-1}-1 & if \;\; C_{CGR} < C_{MGR} \end{cases} \tag{7}$$
$$N_{DAF} = L_i, \qquad when \; C_{CGR} = C_{MGR}$$

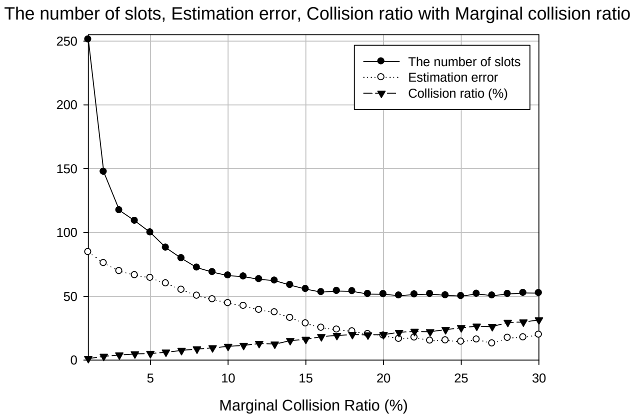


Fig. 7. The total number of slots, estimation error, and collision ratio with C_{MCR}: Initial Slot N_{init} = 10, 0 ≤ Marginal collision ratio C_{MCR} (%) ≤ 30

We consider three performance indices to examine the efficiency of EDSA according to C_{MCR}. These three performance indices are the number of slots, N_{DAF}, estimation error, e_{est}, and collision generation ratio, C_{CGR}. e_{est} is defined as the difference between the estimated number of slots and the actual number of adjacent nodes. **Fig. 7** shows the variation of N_{DAF}, e_{est}, and C_{CGR} with C_{MCR}. Clearly, C_{MCR} affects the performance of EDSA. If C_{MCR} is small, then C_{CGR} is decreased and N_{DAF} is increased. On the other hand, if C_{MCR} is large, then C_{CGR} is increased and N_{DAF} is decreased. Therefore, we should find the value of C_{MCR} that gives the best performance of EDSA. The ideal performance has the lowest values of N_{DAF}, e_{est} and C_{CGR}, but it is impossible to achieve this due to the tradeoff among these values. Consequently, we use a statistical examination using weighted values to find the optimal value of C_{MCR}, which is given by

$$\tau_{MCR} = w_s N_{DAF} + w_e e_{est} + w_c C_{CGR}, \quad w_s + w_e + w_c = 1 \tag{8}$$

where w_s, w_c and w_e denote the weighted factors on N_{DAF}, e_{est}, and C_{CGR}, respectively. The determinant factor τ_{MCR} is calculated as the sum of the product of each weighted value and the corresponding results are N_{DAF}, e_{est}, and C_{CGR} according to C_{MCR}. The set of τ_{MCR} is $\tau_{MCR} = \{\tau_{1\%}, \tau_{2\%}, \tau_{3\%}, \cdots, \tau_{100\%}\}$, and the optimal τ_{MCR} becomes $\tau_{opt} = \min\{set\ of\ \tau_{MCR}\}$. Finally, we can derive the optimal C_{MCR} with τ_{opt}. In the examination with $w_s = 0.4$ $w_c = 0.4$ and $w_e = 0.2$, EDSA shows the best performance when $C_{MCR} = 18$ (%).

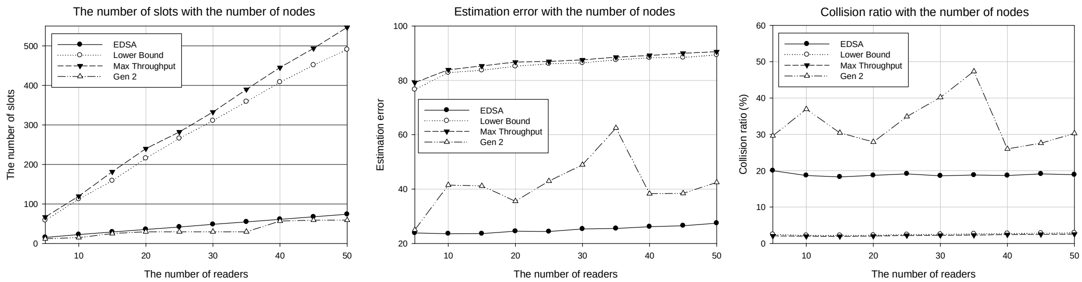


Fig. 8. The total number of slots, estimation error, and collision ratio with C_{MCR}: Initial Slot N_{init} = 10, C_{MCR} (%) = 18%, 0 ≤ the number of neighbor readers ≤ 30

We compare EDSA with Lower Bound, Maximum Throughput and Gen2 [21]. **Fig. 8** shows the number of slots N_{DAF}, estimation error, e_{est}, and collision ratio, C_{CGR}, with the four methods. EDSA and Gen2 have similar values of N_{DAF}, but EDSA achieves much better performance than Gen2 in terms of e_{est} and C_{CGR}. Lower Bound and Maximum Throughput show good performance in terms of C_{CGR}, but have much lower performance than EDSA and Gen2 in terms of N_{DAF} and e_{est}. These results prove that EDSA achieves good performance in all aspects.

3.4 Power Control of EMP

If the density of the readers is increased, it can lead to channel capture, because of mutual control packets. The channel capture effect happens when one node continues to "win" the link [22]. This phenomenon causes the starvation problem. In this case, power control is one of the methods which can mitigate effectively the capture problem. Power control can also offer better throughput by reusing space. Consequently, we designed a power control mechanism in EMP. In **Fig. 9-(a)**, R_1 suffers from the effect of adjacent nodes, R_2, and R_3, which continuously win the channel. At this time, R_1 sends a power control message to its adjacent readers through the control channel and, if R_2, and R_3 receive this message, then they turn down the transmission power of both their data and control channels. **Fig. 9-(b)** shows the situation where the reader is able to read the tags after power control.

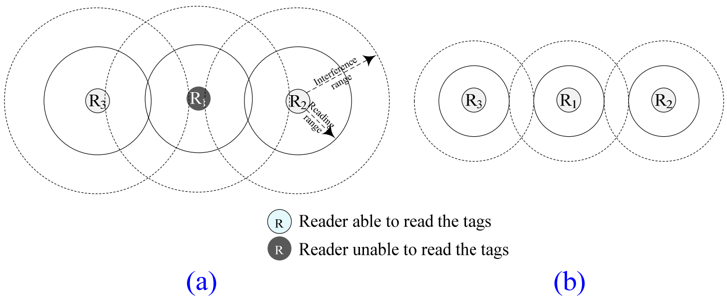


Fig. 9. Channel capture effect (a) and after power control (b)

Fig. 10 shows the power control algorithm of EMP. The reader has power-levels ranging from 1 to L, and the power at level i is denoted by P_i, where $P_i \in P_A=\{P_1, P_2, P_3, \cdots, P_L\}$ and P_L is the maximum power. Power control process is determined by the number of received *RTR*, called *countRTR*. When *countRTR* is larger than the threshold value (the *RTR* threshold value is set to 8 based on an experiment to optimize the system efficiency.), the reader sends a power control message *pwrCtrlMsg* to its adjacent nodes, goes into the ***DEC*** state and then turns down its current power, P_{cur}. Those nodes which received the *pwrCtrlMsg* also go into the ***DEC*** state. On the other hand, power control can deteriorate the link connectivity by decreasing the transmission power. To avoid this problem, the reader should increase its transmission power again. The flag *transFail* is set to TRUE when the reader fails to send data because of its disconnection from the adjacent nodes. In this case, the reader sends a *pwrCtrlMsg* to its adjacent readers, goes into the ***INC*** state and increases own P_{cur}. The flag *ctrlType* in the received *pwrCtrlMsg* is used to select the mode of the power control. If *ctrlType* is TRUE, then this *pwrCtrlMsg* is for the purpose of decreasing the power.

Power control algorithm description for EMP

```
Begin Power control
    if countRTR > threshold then
        do ctrlType is set as TRUE broadcasting pwrCtrlMsg
        goto DEC
    else if transFail is TRUE
        do ctrlType is set as FALSE broadcasting pwrCtrlMsg
        goto INC
    else if pwrCtrlMsg is TRUE then
        goto Received pwrCtrlMsg
    end if
    DEC:
    if P_cur is not equal to P_1 then
        do P_cur = P_cur-1
    end if
    do countRTR = 0
INC:
    if P_cur is not equal to P_L then
        do P_cur = P_cur+1
    end if
Received pwrCtrlMsg:
    if ctrlType is TRUE then
        goto DEC:
    else goto INC
    end if
```

Fig. 10. Algorithm for power control of EMP

4. Performance Evaluation

This section shows a comparison of the performance of the various protocols, EMP, CSMA/CA, Pulse, and DiCa, through the simulation results. First, the assumptions made for the purpose of achieving an objective performance analysis are presented in section 4.1, and section 4.2 shows the simulation environment. The performance metrics for the performance evaluation are presented in section 4.3. Finally, we analyze the simulation results and discuss the performance evaluation in section 4.4.

4.1 Assumption

We make three assumptions for the objective performance analysis, which are as follows:

1) **RFID readers:** In the proposed network in section 1**,** each reader is an integrated hardware device that is interfaced with a sensor node and a reader, and has two channels that are a data channel and control channel. According to the protocol, the sensor node part in the reader controls the operation of the reader part.
2) **Communication range and reading range:** Each reader uses an omni-directional antenna and, for the simplicity of the simulation**,** we consider that the communication range d_c is equal to the interference range d_i and is double the reading range d_r. ($\therefore d_c = d_i = 2d_r$)
3) **Energy consumption:** Energy is consumed when each reader reads tags and sends and receives control packets.

4.2 Simulation Environment

We previously designed an integrated reader, called UBICON, for integrated RFID-WSNs. UBICON is comprised of an RFID transceiver (Intel R1000 [23]), micro controller (ATMEGA 128 [24]), and RF transceiver (CC2420 [25]). A small footprint and low power requirement is appropriate for integrated RFID-WSNs. **Fig. 11** shows the hardware architecture of UBICON.

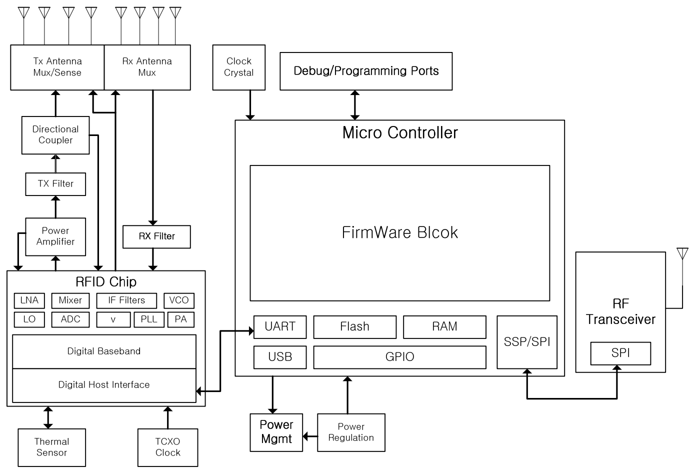


Fig. 11. Hardware architecture of UBICON

UBICON has a data channel and control channel with frequencies of 915MHz and 2.4GHz, respectively. The maximum read range is 2 meters with an external antenna. The RFID transceiver communicates with a host micro-controller through a UART interface and the host micro-controller controls the RFID transceiver using ASCII and binary commands. The controller can also read and write to the reader's memory and system registers to handle power on/off for the purpose of saving power. The RF transceiver is CC2420, which is well known in the sensor network area. CC2420 is a single-chip RF transceiver for low-power wireless applications. CC2420 includes a digital direct sequence spread spectrum (DSSS) baseband modem providing a spreading gain of 9dB and an effective data rate of 250 kbps. It is connected to a micro-controller with SPI bus.

We simulated each protocol with the hardware characteristics of UBICON. In a square of 10 by 10 meters, readers (UBICON) are uniformly distributed. The number of tags is 400 and the number of readers ranges from 4 to 44. The moving speed v_m of the mobile readers was from 0.3 to 1*m/s*, and mobile readers were randomly determined with 50% probability of all readers except readers which are reading tags and have traffic. The traffic is generated with an exponential inter-arrival time t_{ei} having an average value of 50*ms*. In the simulation, each protocol has the same initial topology for fairness. **Table 1** shows parameters in the simulation.

Table 1. Simulation parameters

Symbol	Description	Values in simulation
Tags	Number of tags	400
Readers	Number of readers	8 ~ 44
Scale	Simulation space size	$100m^2$
Velocity	Moving speed of mobile readers	0.3 ~ 1*m/s*
Read range	Initial range of reading tags	2*m*
Communication & Interference range	Initial range of communication with other readers	4*m*
Inter-arrival time	Exponential inter-arrival time of the traffic	50*ms*

4.3 Performance Metrics

The proposed EMP is evaluated using three metrics, viz. the energy efficiency, throughput, and efficiency.

Table 2. Symbols used in energy analysis and typical values for an 802.15.4 radio (CC2420) and a Gen2 RFID reader (Intel R1000)

Symbol	Description	Values in specification	Values in simulation
P_{tx}	Power in transmitting	Varying	Varying
P_{rx}	Power in receiving	56.4*mW*	56.4*mW*
P_{listen}	Power in listening	56.4*mW*	56.4*mW*
P_{reding}	Power in reading	1.5*W*	1.5*W*
t_B	Time to Tx/Rx a byte	32μs	32μs
t_{slot}	Time of EDSA slot	-	100μs
T_1	Time from interrogator transmission to tag response	MAX(RTcal, 10T_{pri})	10 T_{pri} = 93.75μs
T_2	Time from tag response to interrogator transmission	$3.0T_{pri} \leq T_2 \leq 20.0T_{pri}$	10 T_{pri} = 93.75μs
T_3	Time an interrogator waits after T1 before it issues another command	$0.0T_{pri}$	0μs
T_4	Minimum time between interrogator commands	2.0RTcal	75μs
r_{data}	Tag-to-interrogator link data rate	LF, if FM0 modulation	LF = 107kbps
L_{ctrl}	Control packet length (RTR, PTR, CTR)	-	2byte
n	Number of neighbors	Varying	Varying

1) Energy Efficiency:

As mentioned in section 4.1, we consider the energy that is consumed by reading the tag and sending control packets. **Table 2** summarizes all of our terms and gives the typical values for the 802.15.4 radio (CC2420) and Gen2 RFID reader (Intel R1000). The expected energy consumption of a reader i during total time t_{total} is given by

$$E_i = \sum E_{query} + \sum E_{tx} + \sum E_{rx} \quad (9)$$

E_{query} is the energy that is successfully consumed in sending the query and reading the tag. E_{tx} and E_{rx} are the energy that is consumed by sending and receiving control packets, respectively. The expected values of E_{query} is calculated as

$$E_{query} = E_{RTR} + E_{DAF} + nE_{rx} + E_{RD} + E_{CTR} \quad (10)$$

where E_{RTR} and E_{CTR} are the energy consumed in sending RTR and CTR, respectively, and are equal to E_{tx} as follows.

$$E_{tx} = E_{RTR} = E_{PTR} = E_{RTR} = P_{tx} t_{tx} \quad (11)$$

where P_{tx} is the transmission power. t_{tx} is the time taken to transmit the packets, which is

$$t_{tx} = t_{rx} = L_{ctrl} t_B \quad (12)$$

E_{DAF} is the energy consumed by listening during the DAF time, t_{DAF}. E_{DAF} is given by

$$E_{DAF} = P_{listen} t_{DAF} \quad (13)$$

where P_{listen} is the listening power. t_{DAF} can be derived as $t_{DAF} = N_{DAF} t_{slot}$. N_{DAF} is the number of DAF slots and t_{slot} is the unit time per slot. The term nE_{rx} is the energy consumed in receiving PTR packets from the neighbors. n is the number of neighbors. The receiving energy is calculated as $E_{rx} = P_{rx} t_{rx}$. E_{RD} is the energy consumed by reading the tags. The expected energy consumed in the reading state is

$$E_{RD} = P_{reading} t_{reading} \quad (14)$$

where $t_{reading}$ is the time spent reading tags. The reading time $t_{reading}$ is calculated by the Gen2 scenario [21] and is given by

$$t_{reading} = N_t / (r_{data} / 8bit) + T_4 + (Rnd + 2) \times (T_1 + T_2 + T_3) \quad (15)$$

where the total number of slots, N_t, is derived by the Q algorithm in Gen2. The QueryAdjust command of the Q algorithm sets the number of slots, L_i, and Rnd is incremented whenever the reader sends this command. Therefore, the total number of slots becomes

$$N_t = \sum_{i}^{Rnd} L_i \quad (16)$$

T_1, T_2, T_3, and T_4 are given by the Gen2 scenario. To calculate the slot time, the data rate, r_{data}, is divided by the tags information, which is assumed to be 1byte, and N_t is divided by this term. In the network, the total energy is equal to the sum of the consumption of each reader and is given by equation (19).

$$E_{total} = \sum E_i \quad (17)$$

Finally, to evaluate the energy efficiency of each protocol, we denote the energy efficiency as follows.

$$EnergyEfficiency(mW) = \frac{E_{total}}{\sum Q_i^{succ}} \quad (18)$$

The energy efficiency means the energy required by each protocol to send a query and, hence, the lower the value that is measured, the better the performance.

2) System Throughput:

The throughput is an important metric that directly presents the system performance. A high throughput means that the readers get a lot of information from the tags at the same time. An improvement in the throughput corresponds to an improvement in the read rate. The throughput is defined as the number of successfully sent queries per second as follows.

$$SystemThroughput = \frac{\sum Q_i^{succ}}{t_{total}} \tag{19}$$

3) System Efficiency:

The efficiency reflects the ability of a protocol to detect the possibility of collisions and hence, to avoid unnecessary transmissions. Therefore, an improvement in efficiency means a reduction in the number of collisions. The efficiency is denoted as the percentage of all queries that were successfully sent, as follows.

$$SystemEfficiency(\%) = \frac{\sum Q_i^{succ}}{\sum (Q_i^{succ} + Q_i^{fail})} \times 100 \tag{20}$$

4.4 Simulation Results

In this section, we show the simulation results and compare the various protocols. **Fig. 12** shows the number of successful queries that is counted whenever each reader successfully sends a query.

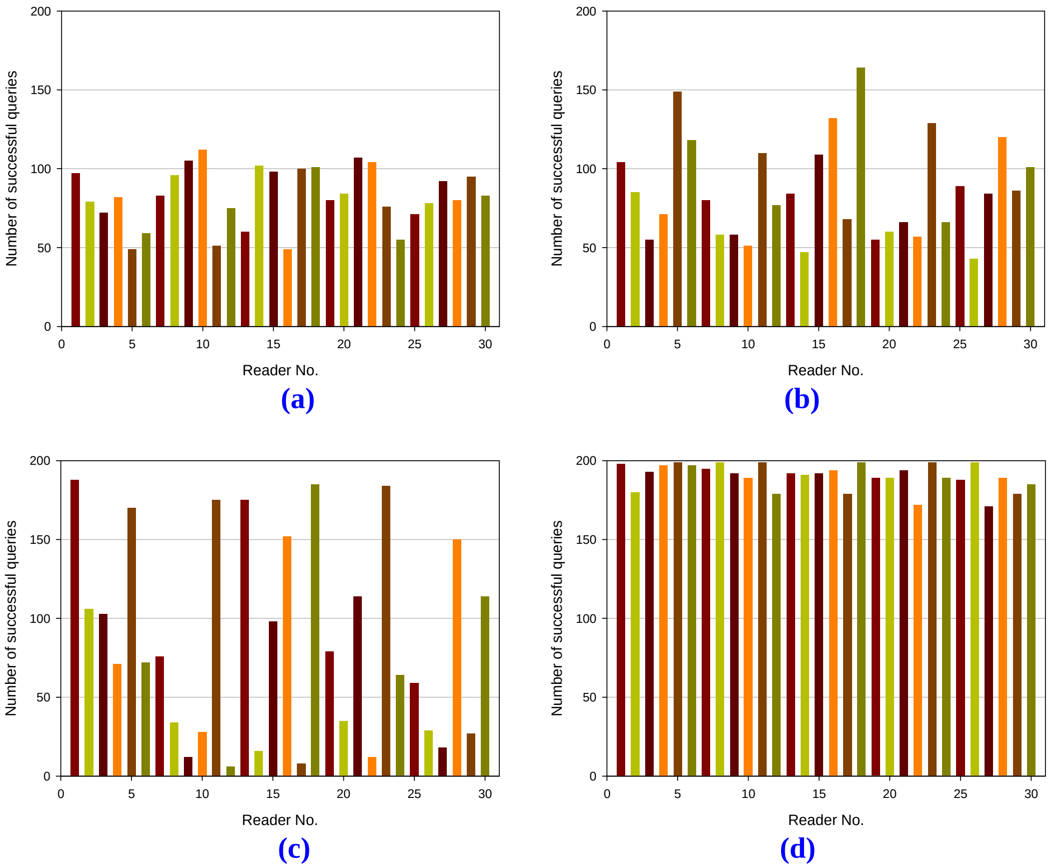
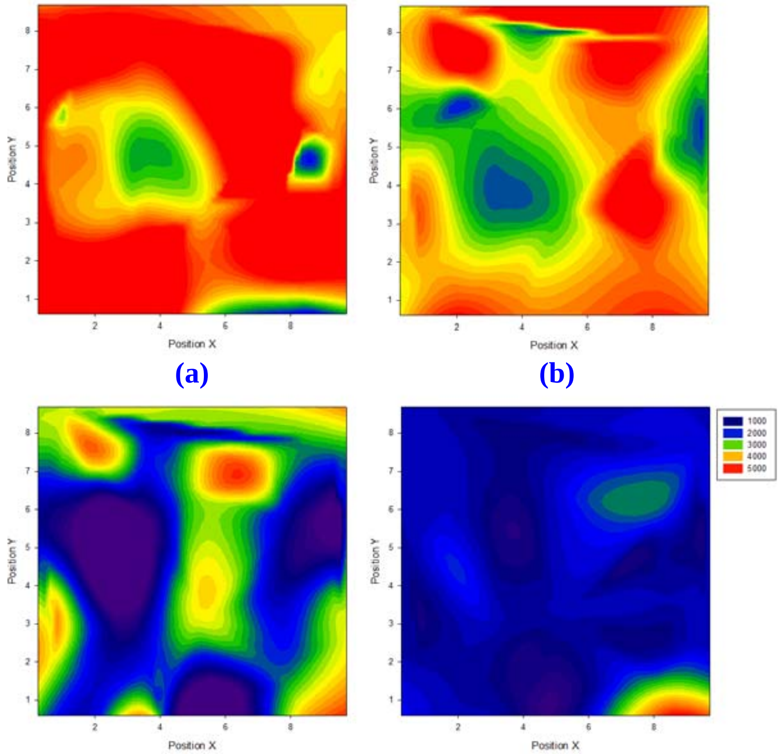


Fig. 12. The number of successful queries of each reader: (a) CSMA, (b) Pulse, (c), DiCa, and (d) EMP t_{total} = 10*sec*, t_{ei} = 50*ms*, and the number of readers = 30.

The number of readers is 30 and they are randomly deployed in an area of 10 by 10 meters. The simulation is continued for 10*sec* and the inter-arrival time t_{ei} is 50*ms*. To accurately measure the degree of starvation and load balancing, there are no mobile nodes. In this simulation, we can see that the successful queries of EMP are uniformly distributed, as shown in **Fig. 12-(d)**, while Pulse and DiCa show large deviation of the number of successful queries among readers as shown in **Fig. 12-(b)** and **(c)**, respectively. In CSMA/CA, each reader generally has fewer queries than in the other protocols. The above results show that EMP handles the channel capture effect more appropriately than the other protocols.



(a) **(b)** **(c)** **(d)**

Fig. 13. Contour of the energy distribution of each reader: (a) CSMA, (b) Pulse, (c), DiCa, and (d) EMP t_{total} = 10*sec*, t_{ei} = 50*ms* and the number of readers = 30.

Fig. 13 shows the distribution of the energy consumption of the readers in the same simulation environment. In CSMA/CA, almost all of the readers consume a lot of energy, as shown in **Fig. 13-(a)**. CSMA/CA does not exchange sufficient information among the readers, and this causes the hidden and exposed terminal problems. Consequently, CSMA/CA suffers from collisions and consumes much energy to send a successful query. Pulse exchanges information among the neighbors through a beacon message, but still consumes a large amount of energy due to the periodical sending of beacons, the exposed terminal problem, and the starvation problem, as shown in **Fig. 13-(b)**. DiCa overcomes the exposed terminal problem to a considerable extent compared to Pulse. However, it shows high energy consumption in some regions, as shown in **Fig. 13-(c)**, because it cannot adequately deal with the channel capture effect. Although EMP has more control packets than the other protocols, each reader sends more queries on average, as shown in **Fig. 12**, because the readers exchange sufficient information. This means that EMP avoids collisions more effectively than the other protocols. Furthermore, EMP achieves load balancing and spatial reuse by resolving the starvation problem. As a result, all of the readers uniformly use a low amount of energy, as shown in **Fig. 13-(d)**.

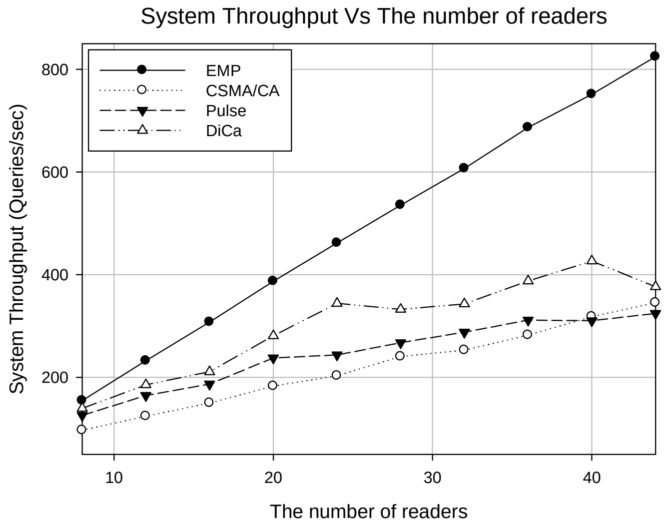


Fig. 14. System throughput: t_{total} = 30*sec*, t_{ei} = 50*ms*, 0.1*m/s* ≤ v_m ≤ 0.6*m/s*, and 4 ≤ the number of readers ≤ 44.

As mentioned in section 4.3, we discuss the performance of each protocol with three metrics. **Fig. 14** shows the system throughput. CSMA/CA shows the worst performance in **Fig. 14** because it does not have any message exchange for anti-reader collisions. As mentioned above, the exchange of messages is a good method of mitigating the hidden and exposed terminal problems. Although Pulse and DiCa achieve better performance than CSMA/CA through message exchange, they have lower performance than EMP. This is because they do not resolve the control packet collision and starvation problems, while EMP handles these problems through EDSA and power control, respectively. Furthermore, EMP improves the system throughput by finding a reader able to read a tag by overhearing the messages. As shown in **Fig. 15**, EMP also shows the best performance in the system efficiency. As mentioned above, a high system efficiency means that it has a good ability to detect collisions and no unnecessary transmissions. Therefore, this shows that EMP improves the ability to detect collisions through three-way handshaking and EDSA. Finally, the energy efficiency is presented in **Fig. 16**. CSMA/CA shows low performance due to the large number of collisions and unnecessary transmissions. Pulse consumes more energy than DiCa and EMP, due to the exposed terminal problem, periodical beacon transmission and channel capture effect. DiCa shows good energy efficiency, but almost all of the energy is consumed at the edges, as shown in **Fig. 13**, because of the starvation problem. This shows that the energy is utilized inefficiently. On the other hand, EMP shows the best performance in the energy efficiency. EMP has a power control mechanism for the channel capture effect, and this mechanism mitigates the starvation state of the readers in a dense environment. As shown in **Fig. 13**, this proves that EMP is robust to the channel capture effect and properly achieves spatial reuse without broken links. As a result, EMP achieves the best performance in the energy efficiency, as shown in **Fig. 16**. Thus, the simulation results demonstrate that EMP outperforms the other anti-reader collision protocols, in aspects of the system throughput, system efficiency, and energy efficiency.

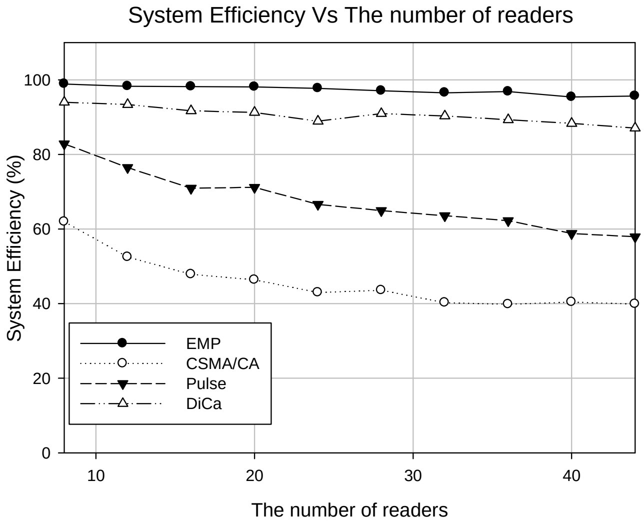


Fig. 15. System efficiency: t_{total} = 30*sec*, t_{ei} = 50*ms*, 0.1*m/s* $\leq v_m \leq$ 0.6*m/s*, and 4 $\leq$ the number of readers $\leq$ 44.

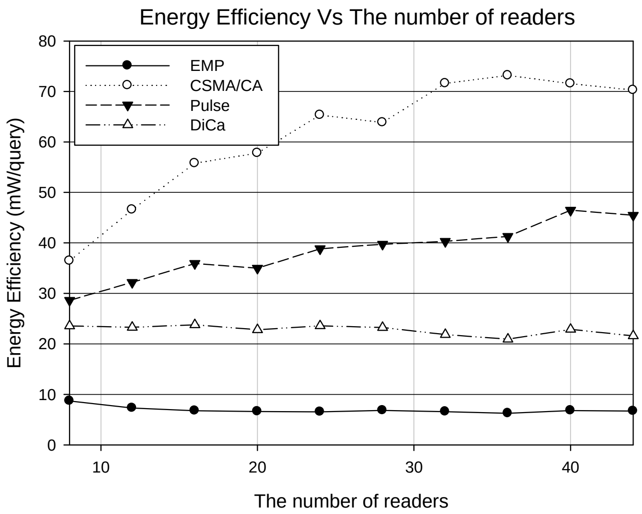


Fig. 16. Energy efficiency: t_{total} = 30*sec*, t_{ei} = 50*ms*, 0.1*m/s* $\leq v_m \leq$ 0.6*m/s*, and 4 $\leq$ the number of readers $\leq$ 44.

5. Conclusions

We proposed an anti-reader collision MAC protocol for integrated RFID-WSNs. The goal of our proposal is to integrate RFID and WSN, while avoiding reader collisions. To do so, we designed an integrated RFID-WSN network architecture and an integrated module (UBICON). The components of the proposed network architecture include sensor-nodes, tags, and UBICON which is a unit that interfaces between a sensor-node and a reader. It can communicate not only with the sensor-nodes but also with the tags. UBICON enables the integrated network to perform functions such as ad-hoc routing, aggregation and environmental sensing. These functions enhance the capacity of RFID networks. To prevent collisions in our network architecture, we implemented EMP, a CSMA-based MAC protocol utilizing three-way handshaking, which enables several readers to simultaneously read the tags. In addition, EMP provides a slot allocation algorithm, called EDSA, to mitigate the problem of collisions among control packets. We also adopted a power control mechanism to alleviate the channel capture phenomenon. In the performance evaluation, we compared EMP with CSMA/CA, Pulse and DiCa. As a result, EMP was found to show the best performance in system throughput, system efficiency and energy efficiency.

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