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Optimization of RFID Platforms: A Cross-Layer Approach

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1. Introduction

RFID (Radio Frequency Identification) is a technology that uses radio frequency signals for purposes of identification and tracking of objects, humans or animals. Since it allows automated identification and potential new features such as sensing of environmental parameters, RFID is gaining preference over legacy identification technologies. RFID is also being implemented in future mobile terminals, thereby paving the way for new ubiquitous applications. RFID is thus expected to enable the concept of the Internet-Of-Things by closing the gap between the worlds of computer networks and physical objects (Darianian & Michael (2008)).

As any emerging application, RFID at the item level is facing several obstacles towards massive consumer adoption. These obstacles include: high implementation costs, standards in early stages of adoption, privacy and security threats, low consumer acceptance levels, and reading reliability issues (Jahner et al. (2008)). Dissemination activities have been organized worldwide with the aim of improving end-user knowledge of RFID technology and thus boost both acceptance levels and standard adoption. Furthermore, several improvements on RFID technology have been recently proposed in order to increase reading reliability levels (e.g., Sabesan et al. (2009)), reduce privacy/security threats (e.g., Park et al. (2006)), and lower implementation costs (e.g., Subramanian et al. (2005)).

Despite these advances in RFID technology, optimization of algorithms across different layers, commonly known as cross-layer design, has been scarcely explored in RFID systems. Cross-layer design has been proved crucial in the evolution of conventional wireless networks towards broadband solutions (Srivastaya & Montani (2005)). In the RFID arena, however, only a few solutions using context-aware mechanisms have been shown to significantly improve reading reliability levels (e.g., Ahmed et al. (2007)) and security/privacy features (e.g., Kriplean et al. (2007)). In addition, recent studies suggest that RFID systems would obtain great benefits from using information across different layers (Samano & Gameiro (2009)). Therefore, there is a big potential in using advanced cross-layer design techniques in order to improve existing platforms and propose future algorithms for RFID applications.

Cross-layer design is expected to make most of its impact upon the two lower layers of RFID platforms: medium access control (MAC) and physical layers (PHY)(Samano & Gameiro (2008)). In particular, mobile RFID systems raise new interesting issues that can be appropriately tackled by using cross-layer methodologies. For example, in networks with large numbers of mobile readers, where reader collisions may constantly occur, resolution algorithms with joint power and scheduling control will be required. Furthermore, in mobile terminals with embedded reader functionalities cross-layer optimization can be used to adapt low level reader protocols to bandwidth- and resource-constrained environments. Therefore, cross-layer design will also lead to a better optimization and cost reduction of RFID platforms. The specific objectives of this chapter are: 1) to provide an overview of reading reliability impairments that affect RFID and that need to be tackled by cross-layer solutions (Section 3); 2) to review existing trends and current issues in the design of RFID systems, particularly focusing on identifying algorithms suitable for cross-layer optimization (Sections 2 and 4); 3) to propose a framework for cross-layer optimization and complexity impact analysis that will help in the design and optimization RFID platforms (Section 5); and 4) to propose a set of examples of cross-layer optimization algorithms for RFID (Section 5).

2. RFID system architecture

A typical RFID system consists of tags, readers and back-end processing servers (Chandramouli et al. (2005)). Tags have the only function of responding to readers' requests. Conversely, readers are in charge of responding to requests from application layers, as well as requesting, collecting and processing tag information. Finally, back-end processing servers are in charge of high level information management and application level execution. In mobile RFID systems, additional components might be required to provide networking connectivity and mobility features. A general architecture for cross-layer optimization of RFID platforms showing the potential functionalities of each element is displayed in Figure 1. An optional mobile-proxy entity is used in this figure to provide mobility to a reader platform. For example, a mobile terminal acting as proxy can be used to control nearby readers via Bluetooth and also to relay their data to a remote controller using a 3G data connection.

As observed in Figure 1, some of the functionalities of an RFID platform can be hosted by more than one entity. Therefore, it is possible to reduce the complexity of those parts of the network that are limited in processing capacity, and push functionalities towards less critical elements. For example, in centralized architectures most of the operations are performed by a central controller while readers perform only tag processing operations. By contrast, in decentralized architectures readers host most of the processing and middleware functionalities and only report the results to external application layers (Floerkemeier & Sarma (2008)). In a mobile RFID scenario, functionalities can also be hosted by mobile terminals (e.g., the NFC -near field communication- system). These different architectures affect in different ways the interfaces and protocols used for the communication between network entities. This impact is mainly in terms of signaling and monitoring mechanisms which in turn affect the required processing complexity and channel bandwidth. Since these two resources are limited in certain RFID deployments, cross-layer optimization of protocols under bandwidth- and resource-constrained environments will be required. Before addressing this optimization it is first necessary to analyze the impairments to be modeled, to review issues of current RFID solutions, and select potential algorithms that are good candidates for performance and complexity optimization.

3. Reading reliability impairments

The act of reading/writing the information of a tag via a wireless connection, particularly in passive RFID systems, is prone to impairments that may considerably degrade its reliability. Reading reliability is regarded in this document as the ability of an RFID system to maintain

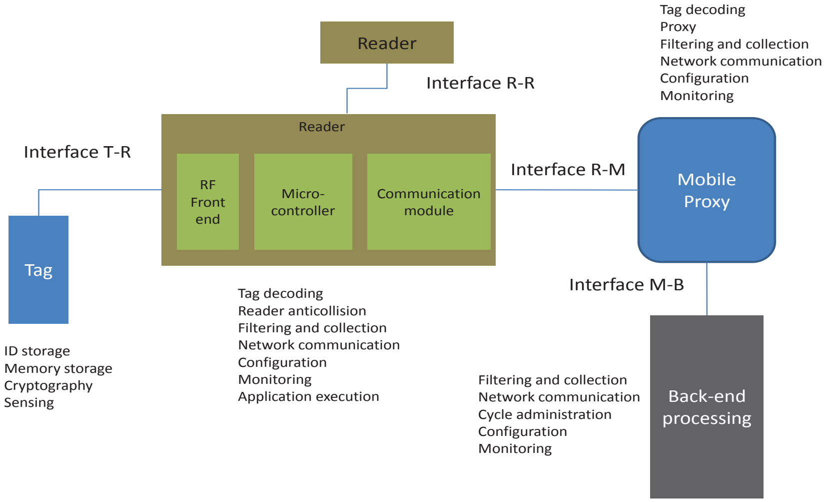


Fig. 1. Reference RFID system architecture

some performance metrics such as correct number of tag readings, reading range, false positive readings, false negative readings, etc. within certain boundaries.

3.1 Physical layer impairments

3.1.1 Propagation channels

Perhaps the most evident impairment in wireless communications is the one of attenuation or path-loss (Sklar (1997)). Signals propagate in different directions distributing the initial power over larger surfaces as waves travel. The free space loss model considers that wave-fronts travel in concentric spheres so the power loss is proportional to the area of such spheres (path loss exponent 2). In RFID systems at low frequencies (e.g., high frequency -HF- bands), where tags use induction coupling to activate their chip, free space loss is a slightly inaccurate assumption as high-order exponent terms tend to appear in induction fields. By contrast, in RFID systems working in the UHF (ultra-high-frequency) band, where tags use backscattering load modulation, free space models fit better as tags are usually located in the far-field of analysis. Other effects such as non-line-of-sight (NLOS) might modify the path loss exponent experienced by some applications. In ultra-wideband (UWB) RFID systems appropriate path loss modeling still has to be accurately studied.

Wireless systems are also prone to the effects of fast fading. Fast fading refers to the fluctuations of the received signal due to random scatterers of small size causing the signal to arrive at the destination with destructive superposition (Sklar (1997)). It is called fast because channel fluctuations occur at a relative high speed with respect to the transmission rate. Since range of RFID systems is relatively short, fast fading is considered only in certain scenarios in combination with line-of-sight components (e.g., Floerkemeier & Sarma (2009)). Furthermore, Doppler effects due to fast moving tags/readers are not expected to cause major impairments except perhaps in applications such as toll payment systems in highways.

RFID systems can also be affected by shadowing, which arises when large obstacles "shadow" the received signal. Shadowing causes variations on the signal that change at a relative slow speed with respect to transmission rates (Sklar (1997)). In RFID, shadowing can affect supply chain applications where large objects may block the line of sight between readers and tags. Shadowing modeling, however, needs to be studied in more detail in RFID settings.

Another source of impairment is multi-path propagation. Multi-path propagation results from signals traveling through different paths that experience random delays within the order of a symbol duration. Multi-path propagation causes inter-symbol interference at the receiver, which can only be overcome by means of complex equalization (Proakis (1997)). Since RFID tags cannot, in general, host advanced equalization schemes multi-path propagation usually has a negative effect in reading reliability. Multi-path will be mainly considered at high frequencies (UHF bands) where its effects are more evident than at lower frequencies.

The problem of interference can also reduce reliability figures of RFID systems. Interference is caused by signals of other devices being transmitted at the same time and in the same frequency band of the desired signal. In RFID systems, interference can be caused by other readers or by electronic devices operating nearby. Therefore, methodologies are needed to mitigate the effects of interference (e.g., Kim et al. (2009)). The work in (Cheng & Prabhu (2009)) presents a detailed report of EMI (Electro-Magnetic Interference) measurement of an industrial floor environment with machines that interfere with RFID systems. It was observed that reliability levels were reduced up to 40% for typical RFID deployments, thus concluding that design of RFID systems must consider the effects of local EMI sources.

NLOS environments also affect RFID signal reception. However, existing approaches focus on simple models with free space loss and Rice channels (e.g., Floerkemeier & Sarma (2009)) without making clear distinction between line-of-sight (LOS) and NLOS conditions. Other studies have been carried out to tune RFID parameters according to particular application and environmental conditions (e.g., Hariharan & Bukkatapatman (2009)). More accurate propagation models, such as those used in conventional wireless systems, are still required in RFID systems. For example, multi-slope propagation models for LOS-to-NLOS transitions have been extensively analyzed in (WINNER (2007)) for typical wireless systems. Indoor propagation models such as the well known multi-wall floor (MWF) propagation model in (COST 231 (2006)), which includes the loss of waves traveling through different materials, could also be proposed in RFID supply chain settings with pallets and boxes.

3.1.2 Impairments due to technical issues

Impairments on reading reliability also arise due to imperfections of RFID technology. Several issues currently affect tag, readers and middleware designs. At the tag side electromagnetic decoupling, inappropriate material for tag construction, inefficient power utilization and high chip activation thresholds may reduce performances of reliability and reading range. At the reader side, low sensitivity and inefficient isolation between the down-link and up-link chains can be mentioned as the main sources of impairments (Wang et al. (2007)).

3.1.3 Metallic environments and other effects

Metallic plates reflect electromagnetic waves, thereby increasing the number of multi-path components in indoor environments and causing further fading phenomena (Wagner et al. (2007)). When tags are attached to a metallic surface the antenna port may suffer from grounding, which affects the signals received by the tag (Qing & Chen (2007)). In addition, metallic obstacles may also affect the operational frequency of the tags or they can simply shield the tags from reader's signals.

The authors in (Qing & Chen (2007)) presented the analysis of proximity effects of metallic environments on the properties of HF tag antennas. Resonant frequency of the antenna was found to be shifted in the presence of metallic surroundings, thereby reducing its efficiency. The magnitude of these effects was found dependant on the size of the metallic plates, distance to the metallic plate, and tag orientation. Thus RFID systems can be tuned according to the particular metallic environment. A similar work has been presented in (Wagner et al. (2007)). Three main effects were analyzed: reflections, shielding, and de-tuning of the tag at different distances from a metallic plate. Guidelines to the design of RFID systems to reduce the effects of metallic environments were further provided. For example, a dielectric material between the tag and the metallic plate was proposed to avoid tag grounding.

Reading reliability can also be affected by the relative orientation of tags, material absorption, the influence of other tags (mutual impedance), and the bending of the tag when attached to irregularly-shaped objects. RFID tags are commonly designed as flat antennas. However, tagged objects often have irregular shapes so tags have to be deformed to fit the shape of the object, thus reducing the effectiveness of RF power conversion. The authors in (Siden et al. (2001)) have calculated the performance loss of a dipole UHF antenna under different angles of bending. While the work in (Siden et al. (2001)) used theoretical analysis based on the method of moments (MoM) and the finite element method (FEM), the authors in (Leung & Lan (2007)) have proposed a new definition of effective antenna area to predict the performance of loop antennas for inductive coupling RFID tags over curvilinear surfaces.

In some RFID applications electromagnetic interactions between neighbor tags may also arise. The authors in (Chen et al. (2009)) have analyzed electromagnetic interaction between stacked NFC tags and they have concluded that considerable losses are obtained only in some regions of the space. The authors in (Lu et al. (2009)) have reached similar conclusions using both mutual impedance and radar cross-section (RCS) calculations.

3.2 Medium access control layer impairments

3.2.1 Tag-to-tag collision problem description

In RFID, readers broadcast a signal that can be received by a group of tags. Several tags inside this group may simultaneously respond to the same request causing the potential loss of information. A collision resolution algorithm is thus required. These algorithms rely on retransmission of the information by the involved tags. This retransmission process requires extra power and transmission resources, which further reduces reading reliability. Therefore, resolution algorithms that reduce the number of retransmissions of each tag and ensure the reliable reading of all the contending tags are potentially good candidates for RFID applications (Samano & Gameiro (2008)).

3.2.2 Reader collision problem

RFID tags may receive signals from one or more readers at the same time. When two readers transmit with enough power to interfere with each other, then the tag is not able to decode the information from any of the readers (Birari & Iyer (2005)). This is known as the multiple-reader-to-tag collision problem. Several schemes have been proposed in the literature including solutions with power control or scheduling. Another type of interference is called reader-to-reader, in which the signal received by a reader from a tag can be degraded by the signal from another active reader nearby (Birari & Iyer (2005)).

3.3 Upper-layer impairments

3.3.1 Security and privacy issues

The possibility of malicious users tracking consumer shopping habits in retailers or scanning personal information from tagged passports represent examples of privacy issues of RFID (Juels (2006)). An eavesdropper reader located at even hundreds of meters can be listening to the transmissions of another reader and deduce tag-related information (Xiao et al. (2006)). Another common example is an unauthorized reader requesting information from tags. Since tags usually have limited processing capabilities, complex authentication and encryption mechanisms cannot be employed. Conversely, tags might also contain malicious code that can be used to pose security threats to middleware applications. The area of security/privacy issues of RFID has attracted loads of attention in recent years (see Juels (2006)).

3.3.2 Middleware and networking issues

Middleware platforms have to be designed to deal with the particularities of RFID systems. Impairments may arise when RFID specific procedures fail. The main functionality of an RFID middleware platform is that of filtering and aggregating RFID raw data to cope with incorrect tag readings due to the low reliability of physical layer interfaces (Floerkemeier et al. (2007)). Therefore, when middleware procedures fail reliability can be seriously compromised. Similarly, incorrect forwarding and routing of the information, particularly in mobile RFID, cannot only cause reliability problems but also privacy and security issues (e.g., Park et al. (2006)). The design of an appropriate middleware and networking architecture to ensure reliability as well as security and privacy features is crucial in RFID systems.

4. Algorithms to improve reading reliability

4.1 Physical layer schemes

4.1.1 Signal processing schemes

Due to recent advances in wireless communications, a wide set of tools generated in this framework can be used to improve the PHY layer of RFID systems. Among these tools, signal processing algorithms exploiting the concept of diversity stand as promising options. Diversity refers to the ability of transmitting/receiving the information via two or more independent sources that when correctly combined help to improve the correct reception of the information. Diversity sources may span frequency, code, time, or space domains. Space diversity can be achieved by means of multiple antennas at the transmitter, at the receiver or at both ends. Space diversity can also be achieved via relaying, where the signal is received by relay nodes that forward the signal towards the destination. For example, a tag antenna with two ports that can be used to implement a receive diversity algorithm has been presented in (Nikitin (2007)). Another example is the work in (Quiling (2007)) where the authors propose spread spectrum techniques for RFID to achieve diversity in the code domain. However, since the processing capabilities of passive tags are limited, diversity mechanisms will be more efficient at the reader side. Multiple antennas can be used to implement maximum ratio combining (MRC), successive interference cancelation (SIC), parallel interference cancelation (PIC) and multiuser detection (MUD) schemes. The authors in (Angerers et al. (2009)) have tested an MRC receiver at the reader side that is used to increase diversity and thus reliability. Beam-forming or smart antennas with fixed or adaptive beams can also be used to improve reliability of the reading process. In addition, smart antennas can be used to direct the radiated energy towards a desired area while suppressing signals radiated towards insecure zones with potential eavesdropper readers. For example, the authors in (Chia et al. (2009)) have designed a multi-band (900 MHz and 2.4 GHz) integrated circuit which is suited for electronic beam steering. The beam steering design allowed improving the performance of a reader in the 900 MHz band. Another smart antenna system for RFID readers has been reported in (Kamadar et al. (2008)) where the authors proved the benefits of this type of technology by improving RFID reading rates. Another type of antenna deployment for RFID is the one called distributed antenna system (DAS). DAS systems have been used in RFID in (Sabesan et al. (2009)), where an increase of 10dB on the received tag signals as compared to a switched multi-antenna system was reported. Unlike conventional approaches with co-located antennas, in DAS the antennas are spaced by long distances and are interconnected to a controller via a coaxial or optical link, thereby achieving large diversity gains (Choi & Andrews (2007))

Channel coding can also be used to improve reliability of RFID. Since tags have limited capabilities, aggressive channel coding is more feasible in uplink rather than in the down-link. However, only those coding schemes with simple encoding rules such as FEC (Forward Error Correct) codes can be potentially implemented in tags.

Additional signal processing capabilities have an impact on the complexity of reader and tags. Therefore, it is necessary to estimate such complexity for an appropriate technical-economical evaluation. Complexity of multiuser detection schemes can be expressed in terms of the number of users (K) and the number of stages (P). In comparison with multiuser detection schemes, whose complexity orders are in the range from K to K^3, PIC and SIC have complexity orders of PK and K, respectively, with acceptable performance results (Andrews (2007)).

Summarizing, in the down-link the most attractive schemes were beam-forming (smart-antennas) and DAS in terms of performance and backwards compatibility. Other solutions such as polarization diversity, Alamouti space-time coding, spread spectrum, and forward error codes (FEC) are also attractive but depend on changes in tag designs. The down-link is the most critical in RFID since tag sensitivity is the main limitation. By contrast, the uplink can be enhanced by several techniques such as multiuser detection, interference cancelation, maximum ratio combining, and also smart and distributed antennas. Distributed antennas and interference cancelation schemes are also promising schemes in terms of low hardware complexity.

4.1.2 Antenna and integrated circuit design

In general, there are three main types of passive tags: chip-based tags using induction coupling at low frequencies, chip-based tags using backscattering at high frequencies, and chip-less tags based on SAW (surface acoustic waves) filters. While the main limitation of chip-based tags is the power threshold required to activate the chip, SAW-based tags are based on a continuous piezoelectric effect that allows operation under any power level. The only limitation of these tags is thus given by the reader's sensitivity, which is generally better than chip-based tag's sensitivity. Therefore SAW tags have better reading ranges than passive tags (Hartman & Clairborne (2007)). Their main disadvantage is their inability to have cryptographic features or memory registers to write information.

At low frequencies tags are relatively small with respect to the operational wavelength. Thus, antennas should be designed to operate in the induction field of the interrogator. Induction-based passive tags store the energy radiated by the interrogator by means of a capacitor and use it to activate a chip that will transmit a signal back to the interrogator carrying the ID of the tag using load-based modulation (Weinstein (2005)). Design of these induction-based tags is focused on the efficiency of the coil antenna (e.g., Leung & Lan

(2007); Nummela (2007)). Reliability levels of inductive RFID systems can be improved by an appropriate electromagnetic design of antenna and modulation circuits.

At high frequencies sizes of tags become comparable to the operational wavelength. Thus antenna design should consider far field analysis. Antennas at high frequencies are designed by using either aperture or linear antenna theory assisted by the method of moments (MoM) or the finite element method (FEM) (Balanis (2000); Siden et al. (2001)). An increase on the electric aperture or length of the antenna is translated into increased gain. Improved gain of the antenna is directly related to longer reading rages and higher reliability levels. However, size of the antennas is also limited by the size of the tag. Thus another way of increasing the gain of the antenna without increasing its size is by improving its efficiency. The work in (Rautio (2010)) uses advanced electromagnetic tools in the analysis of RFID tags. Impedance analysis of RFID tags can also be found in (Qing et al. (2009)), where the authors have proposed a methodology to matching impedances of UHF RFID tags with the underlying circuits thereby obtaining enhanced reading ranges. Other antenna designs for UHF tags can be found in (Chen et al. (2009); Chen (2009); Gao et al. (2009); Guo et al. (2006); Leung & Lan (2007); Nikitin (2007); Pillai et al. (2007)). The effects of antenna properties on the reliability and reading range of RFID systems at high frequencies have been addressed in (Tang et al. (2009)). The authors have performed an analysis of the effects of antenna properties (gain, radar cross-section, half power beam-width, etc.) on the reading reliability of RFID systems.

On chip antenna technology (OCA) allows building antennae together with application chips considerably reducing size and production costs. For example, the authors in (Guo et al. (2006)) present an OCA design of a UHF inductive coupling tag with 1mm reading distance for access control applications. Dielectric materials used for antennas have also reduced their cost, thereby allowing reduction of price of passive tags. However, materials such as paper, which is common in consumer goods, have been found to decrease tag performances.

Regarding metallic environments the results reported in (Qing & Chen (2007)) suggest that RFID systems and antennas can be designed according to the constraints of particular metallic environments. Another work on this subject was carried out in (Wagner et al. (2007)), where the authors study the effects of metal on the final performance of RFID systems and propose the use of a dielectric material to avoid grounding of the antenna port. Other approaches to avoid the effects of metal using antenna design can be found in (Chen et al. (2009); Chen (2009); Gao et al. (2009)). The authors in (Gao et al. (2009)) have also designed an antenna with a dielectric substrate that avoids the antenna port to be grounded. A different approach is followed in (Chen et al. (2009)), where the authors design the antenna directly over a metallic plate using an I-shaped hole or feed port, thereby avoiding metal grounding. Since the size of antennas for metallic objects can result quite large, the authors in (Chen (2009)) have proposed a method to reduce the size of this type of antenna by introducing a conducting line that increases the inductance of the antenna without the need of increasing its size.

Since UHF tags are limited by the activation threshold of the chip and by the efficiency of the energy harvesting mechanism, lowering power consumption is crucial in improving reliability (Hartman & Clairborne (2007)). Reduction of power consumption can be achieved in different ways. For example, reducing voltage and reducing clock rate of the tag have been proposed in (Wang et al. (2007)) and references there in. Power consumption of the analog devices in the tags has also been discussed, particularly of local oscillators and voltage regulators. Mechanisms developed in other papers are claimed to provide further reduction in power consumption. The design of efficient voltage rectifiers with efficiencies as high as 37% is proposed as another way to further reduce power consumption. A low power tag design has been reported in (Pillai et al. (2007)) where the authors describe an ultra low power UHF and microwave tag that can be used as active or passive tag. The tag design allows achieving ranges of more than 24 m at 900 MHz and 3.5 m at 2.4GHz.

At the reader side, the main challenge to improve reading reliability is to avoid the problem of carrier leakage (Wang et al. (2007)), which is due to the continuous transmission of carrier waves from the reader to the tags while the reader is overhearing tag responses. Carrier leakage can be reduced by means of efficient isolators or dynamic interference cancelation schemes. Reader improvement schemes may also include low power consumption designs, improvement in receiver sensitivity, antenna design (which may include smart and distributed antennas) and improved algorithms for reader collision.

4.2 MAC-layer schemes

4.2.1 Tag anti-collision algorithms

Tag anti-collision algorithms in RFID have been limited to ALOHA and binary tree schemes. ALOHA protocols are the simplest of all: they consist of allowing users to transmit at free will, and in case of collision each user enters into a back-off random retransmission state (Abramson (1970)). The implementation simplicity of ALOHA algorithms comes at the expense of a low channel utilization and stability problems. The non-slotted version of ALOHA only reaches 18% (e-2) of channel utilization, while the slotted version only reaches 36%(e-1) (Bertsekas & Gallager (1992)). In addition, ALOHA without appropriate retransmission strategy has been proved unstable. Thus, tags need either to adapt their retransmission schemes according to traffic load, or use a fixed retransmission scheme at the expense of losing stability and reduce even more reading reliability. ALOHA schemes can be also improved by optimizing the retransmission strategy with context information. For example, if large numbers of tags are expected in one of the readers, the retransmission strategy can be adapted accordingly to reduce collisions during back-off periods.

In RFID a modified ALOHA protocol called Framed-ALOHA has been implemented to allocate different tags in consecutive frames thereby avoiding tags being detected in consecutive slots (see Burdet (2004)). A further improvement on Framed-ALOHA has been presented in (Liu (2009)) where frames of different sizes are used in order to reduce the effects of idle and non-successful slots. The work is also an evolution of TEM techniques (tag estimation method) that are used to improve performance of RFID MAC algorithms. ALOHA protocols are usually improved by using carrier-sense or resource reservation approaches (Bertsekas & Gallager (1992)). However, these schemes are unfeasible if we desire to keep tags as simple as possible. By contrast we have the area of splitting tree protocols (see citeCapetanakis79a,bertsekas92). Unlike ALOHA, these algorithms have the ability of being stable under favorable channel conditions. In these algorithms tags are allowed to transmit at free will too, but once a collision has been detected they split into two or more groups by means of a binary/m-ary decision. Tags in one group are allowed to retransmit in the next slot while the others remain silent. The procedure is repeated until all the contending tags are decoded free of collisions. Despite their good stability properties tree algorithms may suffer from delay as compared to ALOHA and they also reach limited channel utilization. Binary algorithms reach at most 34% of channel utilization, while the well known FCFS (First Come First Served) algorithm has been proved to reach 48% of channel utilization (Bertsekas & Gallager (1992)). Tree algorithms are also prone to eavesdropper readers that listen to the feedback broadcast by the reader. Since the reader transmits at higher power levels than tags, the information can be overheard by eavesdropper readers at long distances. Thus security mechanisms for the feedback of tree algorithms have been proposed (Xiao et al. (2006)).

Further improvements can be achieved by using dynamic tree algorithms (e.g., Capetanakis-a (1979)). The ability of these schemes is to act as ALOHA protocols at light traffic loads thereby achieving low delay figures, and act as TDMA protocols at high traffic loads thus reducing the number of collisions. For example, the adaptive binary splitting (ABS) protocol proposed in (Myung et al. (2006)) exploits the information collected from previous collision periods to avoid starting with sets of multiple tags in the next contention period. This scheme allows reducing access delay and outperforms previous binary splitting algorithms for RFID applications. A similar approach has been used by the authors in (Yan & Zhu (2009)) where they enhance the performance of a binary tree algorithm by estimating the tag population of the next time slot and thus adapt the variables of the tree algorithm accordingly. Another example of population estimation for RFID can be found in (Xue et al. (2009)) where a fuzzy logic algorithm is used to group tags and improve collision resolution algorithms.

4.2.2 Reader collision resolution algorithms

Reader collision resolution algorithms can be broadly classified here as scheduling-based or coverage-based (power-control), and also as centralized or decentralized, depending on whether a central server schedules the different readers or they autonomously decide when to transmit.

RFID standards have defined schemes for reader collision resolution. For example, early versions of EPC (Electronic Product Code) RFID standards considered a simple frequency division multiple access (FDMA) scheme for reader collision avoidance. By contrast, ETSI (European Telecommunication Standards Institute) standards have used an ALOHA-based reader anti-collision algorithm with carrier sense features, also known as the Listen-before-talk (LBT) algorithm. However, ALOHA efficiency is not as high as required in RFID applications, while carrier-sense features are prone to hidden/expose terminal problems and also suffer from complexity issues at the reader side in order to implement the sensing mechanism (Birari & Iyer (2005)). A proposal for a medium access technique for RFID readers is provided in (Quan et al. (2008)) and is referred to as Slotted-LBT (S-LBT). Based on carrier-sensing or LBT, this algorithm makes use of several channels, and in case the selected channel is sensed as busy, a new channel is considered for the transmission. Slotted LBT does not require any control from the middleware, but the readers must implement a reader-to-reader communication protocol in order to synchronize themselves.

The scheme called Colorwave implements a distributed time division multiple access protocol where readers select at random a particular slot or color to transmit. If a collision occurs the reader is able to detect it and to retransmit in other color/slot while informing its neighbors of such a change (Waldrop et al. (2003)). Unfortunately this type of solution relies on collision detection schemes at the readers and also requires environments with relatively low numbers of readers. Furthermore, collision detection and stabilization mechanisms require feedback from tags, which is not yet supported by current commercial technologies.

Another reader anti-collision algorithm, referred to as Pulse (Birari & Iyer (2005)), has been proposed for mobile RFID reader scenarios. Pulse uses two non-interfering channels, one for control and another one for data transfer. The control channel is used to inform neighbor readers of possible transmissions and thus avoid collisions. Power of the control channel is adjusted to make sure other readers hear the beacon signals. However, collisions between pulses may still arise. Pulse has been proved effective against the collisions among readers,

even in mobility scenarios. The disadvantage of Pulse is the deployment of additional channels that need to be decoded by readers. A similar approach to Pulse has been followed in (Eom et al. (2009)) where a control server is in charge of organizing a semi-decentralized resource allocation algorithm. Each reader follows the commands transmitted by the server and also transmits a beacon to identify collisions with neighbor readers. The algorithm reduces the large overhead required by other solutions. In (Hsu et al. (2009)), an improved version of Pulse has been proposed. The transmission range of the control channel is dynamically adjusted based on the density of the neighbor readers estimated by each device.
A learning algorithm called HiQ has been proposed in (Junius (2003)) where dynamic solutions to the reader collision problem are obtained by learning the collision patterns of the readers and by effectively assigning frequencies over time. HiQ relies on a centralized server called Q-server that runs the learning algorithm and that assigns resources in order to minimize collisions. Another approach to solve both reader and tag collisions is presented in (Kim et al. (2009)) where the authors have presented a master-slave algorithm for both readers and tags with different frequency hopping sequences. The algorithm reduces both reader and tag collisions at the expense of complexity to switch to different frequency hopping sequences.
Two approaches can be found in coverage-based algorithms: those that reduce the overlapping area between neighbor readers (e.g., Kim et al. (2009)) and that also aim at reducing the interference from multiple readers to tags, and those that monitor the interference between readers and adapt the transmit power of each one of them accordingly (e.g., Cha et al. (2007)). The work in (Kim et al. (2009)) has addressed two problems: a homogenous case where all readers have the same computing power and a heterogeneous case where readers are allowed to have different computing powers. The algorithm assumes a centralized server where the LLCR algorithm (low energy localized cluster for RFID) is run with the information retrieved from every reader (position and energy state). The algorithms are divided into two phases: one for initial phase control and another one for iterative policy. Two optimization rules were used: non-linear programming (NLP) and vector computation (VC). The algorithm has shown good results in reducing overlapping areas between readers thereby reducing the problem of multiple-readers-to-tag collision. A slightly different approach is followed by (Cha et al. (2007)) where the proposed scheme aims at reducing the interference from reader-to-reader. The authors present a novel distributed and adaptive power control algorithm followed by a selective back-off algorithm.
The complexity of collision algorithms can be determined by the number of operations per unit of time or per reading rate. ALOHA schemes are the simplest and the complexity increases as additional functionalities such as carrier-sensing, tag estimation and control channels are implemented. Distributed algorithms and context aware improvements also require additional feedback channels to be supported by readers.

5. Cross-layer algorithms

During the last century wire-line communication systems experienced considerable success and technological development. Part of this success was due to the concept of layered architecture design which allowed distribution of simplified tasks between semi-isolated layers and consequently manufacturer inter-operability. Wireless systems during the 80s and 90s were designed as extensions of their wireline counterparts, thereby reusing layered methodologies. Over the last few years, however, layered models have shown several drawbacks in achieving the data rates required by modern wireless applications (Dimic et al. (2004)). Reliable communication through wireless channels has been found to require, inherently, design across different layers, which has been coined cross-layer design.

Cross-layer design solutions can be generally classified as follows (Srivastaya & Montani (2005)): downward information flow, where information from an upper layer is used to tune the parameters of a lower layer; upward information flow, where the parameter exchange is in the opposite direction; back-and-forth, where the information flow is in both directions; design coupling, where one of the layers is fixed and another one is redesigned to cope with the fixed layer; vertical calibration, where parameters across different layers are simultaneously tuned; and merging of adjacent layers where two or more adjacent layers are completely jointly optimized.

Cross-layer solutions can adopt either only slight or tight interaction rules between layers. Tight cross-layer design can also be translated into a loss of architectural rules, which in the long term affects manufacturer inter-operability and increases the signaling bandwidth required for interaction between layers. Thus, cross-layer design must be accompanied by a careful evaluation of signaling loads and impact on architectural principles.

Typical examples of downward information flow are schedulers based on application layer priorities. In upward information flow we find channel-aware schedulers and transport adaptation schemes for wireless networks. Back-and-forth algorithms can be exemplified by schedulers with power control, while vertical calibration can be observed in solutions with error correction capabilities across different layers. Finally, the case of merging of adjacent layers represents the most attractive solution with examples given by joint design of scheduling, power control and link adaptation, as well as random access protocols jointly assisted by source separation and retransmission control.

Cross-layer design has been recognized as a key factor in achieving the stringent data rates required by future wireless networks. Therefore, wireless standards have adopted cross-layer design not only as a potential option but as mandatory for new schemes such as MIMO (multiple-input multiple-output) and distributed antenna systems. In the context of RFID, only context aware solutions and some multiple access protocols with tag estimation methods can be considered as early examples of cross-layer design. However, given the results of these few examples and the literature on cross-layer design it is envisioned a lot of potential improvement in RFID schemes by using this new paradigm, particularly at medium access control and physical layers.

5.1 MAC/PHY cross-layer design

Perhaps the best example of cross-layer design in wireless networks is the joint analysis of PHY and MAC layers. The physical layer is in charge of transmitting raw bits of information across a communication channel. It also defines modulation parameters, signal amplitudes, and mechanical and electrical specifications for reliable transmission of information. On the other hand, the MAC layer is in charge of scheduling the initially uncoordinated transmissions of a group of terminals who share the same medium, thus being in charge of avoiding or resolving the possible conflictive interactions between them.

Traditionally, MAC protocols were designed by considering the PHY layer as a "black box" with a behavior that was assumed to remain constant over long periods of time (as in a wire-line channel). However, the random phenomena that govern wireless environments (such as fading and multi-path transmission) create completely different conditions and thus other assumptions must be considered (Shakkotari et al. (2003)). Furthermore, the last two decades have witnessed the revolution of digital communications and the advent of faster and more reliable signal processors. This has made possible the implementation of complex signal processing techniques to cope more efficiently with harsh propagation conditions. The consequences of improved physical layer operations and the random behavior of wireless channels have not been appropriately modeled by conventional protocols at the MAC layer.

The first works that can be considered as cross-layer were the studies of the influence of wireless channels on ALOHA protocols (e.g., Abramson (1970; 1977)). Further investigations of throughput and stability of ALOHA under the power capture effect have been reported since then (e.g., Zorzi & Rao (1994)). The power capture effect allows the correct decoding of a packet if its power is much larger than the combined power of all the other contending packets. The power capture effect was used in channel aware stabilization schemes of ALOHA showing the direct relation between the maximum stable throughput (MST) and the roll-off parameter of the channel (Zorzi & Rao (1994)). Since most of the tag anti-collision algorithms in RFID (for tag and reader collision) are based on the ALOHA system, all these results can be potentially used to further optimize the operation of current solutions.

Another relevant work in MAC/PHY cross-layer design was presented in (Ghez et al. (1988)). The authors analyzed the stability properties of ALOHA with multi-packet reception under symmetrical and infinite user scenarios. The novelty brought by this approach was a stochastic multi-packet reception matrix that represents in an accurate way the impairments of wireless channels and signal processing schemes with multiple antenna diversity. A further improvement was presented in (Naware et al. (2005)), where the authors extended the model to the asymmetrical user scenario and proposed a stochastic reception model based on conditional reception probabilities. The relevance of these works for RFID systems is that random access protocols with multiple antennas can be used to improve tag reading rates in the uplink. Readers can implement modified ALOHA protocols with multi-packet reception and considerably reduce tag collisions. Thus, the tools developed in these works can be used directly in the analysis of advanced cross-layer features for RFID including the signal processing schemes and impairments discussed in previous subsections.

A different approach to achieve diversity in multiple access protocols was presented in (Tsatsanis et al. (2000)), where packet collisions are resolved by means of protocol-induced retransmissions. In NDMA, a MIMO system is created by collecting consecutive packet retransmissions. The packets are then recovered using conventional multiuser detection schemes. NDMA has been proposed for RFID applications in (Samano & Gameiro (2008)). NDMA is particularly attractive for RFID applications since it allows using signal processing tools to combine several tag readings received at different times.

5.1.1 Context-aware solutions

Context aware solutions are employed in RFID applications to enhance security/privacy features and to improve reading reliability levels. Security/privacy enhanced features are based on the concept that some tags will follow a given trajectory inside a business process or factory. Therefore, tags will be read with higher probability by some readers rather than others. Middleware applications can easily detect unauthorized attempts to read a tag by a reader which is not supposed to do that, and vice versa to detect unauthorized tags that attempt sending information from unauthorized location. Therefore correlation between tags and physical locations has been found useful in improving security and privacy features.

A similar approach can be used to improve reading reliability figures. For example, tags that move across a supply chain follow known paths and locations. Therefore, their movements can be predicted with certain accuracy. Whenever a false negative occurs, the middleware can perform a modified decision based on previous outcomes to infer that the tag is in the vicinity of a reader with high probability and that perhaps a reading error caused the tag not being detected. Outcomes from different readers can be stored to provide a historical record to infer the real trajectory of the tag and thus eliminate both false negative and false positive readings. For example, a middleware approach to security is given by the authors in (Du et al. (2009)) where they use an access control scheme as a security layer of a reconfigurable middleware platform. The middleware platform is especially designed to provide security in ubiquitous environments. Security issues are also tackled by the security-enhanced RFID middleware platform proposed in (Song & Kim (2006)). This platform deploys a novel context aware access control service. The access control scheme prevents unauthorized users from having access to consolidated data provided by the middleware server.

Physical access control policies for captured RFID data has been addressed by the work in (Kriplean et al. (2007)), where a visibility metric is used to control access to data captured by authorized readers. Another work is given by the data cleaning model used by the authors in (Song et al. (2009)). The authors propose a virtual spatial granularity concept and a Bayesian estimation algorithm to cope with false positives and false negatives. The virtual spatial granularity concept exploits the fact that tags across a supply chain follow similar movements and spatial locations. The algorithm classifies tags according to their spatial movements and thus improves their probability of correct detection by estimating their next movement.

Another approach to improve reliability in RFID systems is given in (Ahmed et al. (2007)). The authors have proposed a middleware architecture called RF^2ID which is based on the concept of context aware design assisted by virtual reader and path abstraction models. Additionally, their design is oriented to organize queries in an efficient manner and provide high levels of reliability and scalability. The concept consists of creating virtual readers, which consider the unreliable nature of each interrogator, and virtual paths, which serve as a higher level abstraction that can identify and follow a tag moving across the environment. A virtual path can cope with false negative and false positive reads of a tag moving across different virtual readers. Another work on data cleaning models is reported in (Peng et al. (2009)), where the authors propose a P2P (Peer to Peer) collaborative model. The model exploits redundancy information that is exchanged between the different nodes across the path of a tag.

5.2 Cross-layer framework for optimization

Consider a set $\mathcal{R}$ of R readers $\mathcal{R} = \{r_1, r_2, \ldots, r_R\}$ and a set $\mathcal{T}$ of J tags $\mathcal{T} = \{t_1, t_2, \ldots, t_J\}$. We consider that a subset of tags $\mathcal{T}_A \subset \mathcal{T}$ appears in the vicinity of the area under analysis with probability $\Pr\{\mathcal{T}_A\}$. For context-aware purposes we further define the conditional probability of inter-tag arrival as $\Pr\{t_j \in \mathcal{T}_A | t_l \in \mathcal{T}_A\}$ for tag-to-tag correlation, $\Pr\{t_j \in \mathcal{T}_A | \mathcal{S} \in \mathcal{T}_A\}$ for correlation between a single tag t_j and a group $\mathcal{S}$ of tags, and $\Pr\{\mathcal{U} \in \mathcal{T}_A | \mathcal{S} \in \mathcal{T}_A\}$ for correlation between two groups of tags ($\mathcal{U}$ and $\mathcal{S}$). The transmit power level of reader r_k will be denoted by $P_k^{(r)}$ and the subset of scheduled readers can be denoted by $\mathcal{R}_t \subset \mathcal{R}$. The probability of transmission of reader r_k will be denoted by $p_k^{(r)}$. Additionally, the transmit power level of tag t_j will de denoted by $P_j^{(t)}$, the set of activated tags will be $\mathcal{T}_P$ and the subset of tags that transmit their ID once they have been activated, also called contending tags, will be denoted by $\mathcal{T}_t$.

Now consider that the instantaneous channel between reader r_k and tag t_j is given by $h_{k,j}^{(rt)}$ for the main multi-path component and $g_{k,j}^{(rt)}$ for the combined effect of additional multi-path components. Similarly, the channel experienced between reader r_k and reader r_m is given by $h^{(rr)}_{k,m}$ for the main component and $g^{(rr)}_{k,m}$ for additional multipath components. Finally, the channel experienced between tag t_n and tag t_j is given by $h^{(tt)}_{n,j}$ for the dominant multipath component and $g^{(tt)}_{n,j}$ for the combined effect of the remaining multi-path components. All channels may include both fast- and slow-fading distributions, as well as path loss and radiation patterns as the result of using, for example, smart antennas or beamforming algorithms. The signal-to-interference-plus-noise ratio (SINR) experienced by tag t_j due to a transmission from reader r_k will be denoted by $\gamma^{(rt)}_{k,j}$ and can be mathematically expressed as follows:

$$\gamma^{(rt)}_{k,j} = \frac{P^{(r)}_k |h^{(rt)}_{k,j}|^2}{I^{(s)}_{k,j} + I^{(r)}_{k,j} + I_{t,j} + \sigma^2_{v,j}}, \qquad r_k \in \mathcal{R}_t \tag{1}$$

where $I^{(s)}_{k,j} = P^{(r)}_k |g^{(rt)}_{k,j}|^2$ is the inter-symbol interference due to multi-path distortion, $I^{(r)}_{k,j} = \sum_{m \in \mathcal{R}_t, m \neq k} P^{(r)}_m (|h^{(rt)}_{m,j}|^2 + |g^{(rt)}_{m,j}|^2)$ is the interference created by other active readers, $I_{t,j} = \sum_{n \in \mathcal{T}_t, n \neq j} P^{(t)}_n (|h^{(tt)}_{j,n}|^2 + |g^{(tt)}_{j,n}|^2)$ is the interference created by other tags, and $\sigma^2_{v,j}$ is the noise component. The SINR expression in eq.(1) can be also modified to represent multiple antenna schemes or other diversity mechanism by considering the contributions from different diversity sources.

If the SINR experienced by tag t_j is above the tag sensitivity threshold $\widehat{\gamma}^{(t)}_j$, then the tag is considered as active. The probability of tag t_j being activated is given by $\Pr\{t_j \in \mathcal{T}_P\} = \Pr\{\max_k \gamma^{(rt)}_{k,j} > \widehat{\gamma}^{(t)}_j\}$. In the strict sense the set of active tags should be a subset of the set of available tags, i.e., $\mathcal{T}_P \subset \mathcal{T}_A$. However, in some cases another tag which does not belong to the set of targeted tags $t_n \notin \mathcal{T}_A$ can also be activated by mistake, i.e.,$t_n \in \mathcal{T}_P$, thus being considered as a potential false positive. Tags are also considered to start a random transmission process once they have been activated, which will prevent collisions with other actives tags. This random transmission control will be characterized as a Bernoulli process with parameter p_j.

Now consider the backscattering factor function $\beta_j(\gamma^{(rt)}_{k,j})$ and the transmission power of tag t_j which can be calculated as $P^t_j = \beta_j(\gamma^{(rt)}_{k_{opt},j}) P^{(r)}_{k_{opt}} |h^{(rt)}_{k_{opt},j}|^2$. The term $r_{k_{opt}}$ (where $k_{opt} = \arg\max_k \gamma^{(rt)}_{k,j}$) denotes the reader that has activated the tag. Thus, the SINR of the backscattered signal from tag t_j upon reader r_k can be written as:

$$\gamma^{(tr)}_{j,k} = \frac{P^t_j |h^{(tr)}_{j,k}|^2}{I^{(s)}_{j,k} + I_{r,k} + I^{(t)}_{j,k} + P^{(r)}_k \eta_k + \sigma^2_{v,k}}, \qquad t_j \in \mathcal{T}_t \tag{2}$$

where $I^{(s)}_{j,k} = P^{(t)}_j |g^{(tr)}_{j,k}|^2$ is the inter-symbol interference due to multi-path distortion, $I_{r,k} = \sum_{m \neq k} P^{(r)}_m (|h^{(tr)}_{m,k}|^2 + |g^{(tr)}_{m,k}|^2)$ is the interference created by other active readers, $I^{(t)}_{j,k} = \sum_{n \neq j} P^{(t)}_n (|h^{(tr)}_{n,k}|^2 + |g^{(tr)}_{n,k}|^2)$ is the interference created by other active tags and $\sigma^2_{v,k}$ is the noise component at the reader side. Interference cancelation schemes or multiple access protocols based on diversity can help in reducing the interference terms in the denominator, thus improving the SINR received at the reader side. Furthermore, the backscattering function works as an abstraction model of all tag physical layer schemes. New electromagnetic antenna or chip designs with reduced power consumption can be easily abstracted into this function. Let us now consider that tag t_j can be detected by reader r_k if the received SINR is above a threshold denoted by $\widehat{\gamma}_k^{(r)}$. The set of detected tags by reader r_k will be denoted by $\mathcal{T}_D^{(k)}$, hence the probability of tag t_j being in $\mathcal{T}_D^{(k)}$ will be given by $\Pr\{t_j \in \mathcal{T}_D^{(k)} | t_j \in \mathcal{T}_P\} = \Pr\{\gamma_{j,k}^{(tr)} > \widehat{\gamma}_k^{(r)}\}$. For context aware purposes we can also consider correlation between different readers (spatial correlation) $\Pr\{t_j \in \mathcal{T}_D^{(k)} | t_j \in \mathcal{T}_D^{(m)}\}$, which can be further extended along the time domain as $\Pr\{t_j \in \mathcal{T}_D^{(k)}(\Delta) | t_j \in \mathcal{T}_D^{(m)}(\Delta + \delta)\}$.

5.2.1 Optimization

The parameters to be optimized are the set of scheduled readers $\mathcal{R}_t \subset \mathcal{R}$ (or the vector of transmission probabilities $\mathbf{p}^{(r)} = [p_1^{(r)}, \ldots p_R^{(r)}]^T$), the vector of transmit powers $\mathbf{P}^{(r)}$ whose elements are the transmit power levels $P_m^{(r)}$ of $r_m \in \mathcal{R}_t$, and the transmission probabilities of the active tags $\mathbf{p}^{(t)}$ whose elements are the transmission probabilities $p_j^{(t)}$ of $t_n \in \mathcal{T}_P$. The main target of the optimization will be the maximization of the number of correctly detected tags per reader ($|\mathcal{T}_D^{(k)} \cap \mathcal{T}_A|$ where $|\cdot|$ is the cardinality operator) and optionally the minimization of the number of false positives readings ($|\mathcal{T}_D^{(k)} \cap \overline{\mathcal{T}}_A|$, where $\overline{(\cdot)}$ denotes the complement set operator). There are several ways to express the optimization problem. A straightforward option can be optimizing the summation of all the correctly detected tags per reader as follows:

$$\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}_{opt} = \arg \max_{\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}} \sum_{r_k \in \mathcal{R}} |\mathcal{T}_D^{(k)} \cap \mathcal{T}_A| \tag{3}$$

However, this type of optimization, which is similar to a sum-rate optimization problem, leads to unfairness by giving too much weight to readers with good conditions. To counteract this problem it is possible to use a transmit power constraint as follows:

$$\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}_{opt} = \arg \max_{\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}} \sum_{r_k \in \mathcal{R}} |\mathcal{T}_D^{(k)} \cap \mathcal{T}_A| \quad \text{s.t.} \quad \mathbf{P}^{(r)} < \mathbf{P}_0^{(r)} \tag{4}$$

Or by optimizing one individual reader subject to the throughput of all the other readers being constant:

$$\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}_{opt} = \arg \max_{\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}} |\mathcal{T}_D^{(k)} \cap \mathcal{T}_A| \quad \text{s.t.} \quad \mathbf{P}^{(r)} < \mathbf{P}_0^{(r)}, \quad |\mathcal{T}_D^{(m)} \cap \mathcal{T}_A| = \theta_m, m \neq k \tag{5}$$

This particular optimization can be modified to cope complexity-constrained environments. Defining a complexity measure of the reader as a function of the tag reading rate, i.e. $C_k = f_{ck}(|\mathcal{T}_D^{(m)} \cap \mathcal{T}_A|)$, then the expression $|\mathcal{T}_D^{(m)} \cap \mathcal{T}_A| = \theta_m$ or $|\mathcal{T}_D^{(m)} \cap \mathcal{T}_A| < \theta_m$, represents a complexity constraint. Another approach is to minimize the total power of the readers subject to a constant level of successful tag readings per reader:

$$\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}_{opt} = \arg \min_{\{\mathbf{P}^{(r)}, \mathbf{p}^{(t)}, \mathcal{R}_t\}} \sum_k P_k^{(r)} \quad \text{s.t.} \quad |\mathcal{T}_D^{(m)} \cap \mathcal{T}_A| = \theta_m, \tag{6}$$

The above optimization problems assume perfect knowledge of channels between readers and tags, which is an unrealistic assumption. However, the optimization problem can be modified to use average channel values instead of instantaneous values. These average channel values can be defined over a given optimization area for each reader.

5.2.2 Reader and tag ALOHA protocols: joint optimization

Consider a symmetrical system where all devices of the same kind (readers or tags) are statistically equivalent and with fixed transmit power. Slotted ALOHA protocol will be used as contention mechanism both in the reader and tag sides including incorrect detection and activation probabilities. Two main assumptions will be used: one in which readers and tags do not interfere with each other except for the powering-up process, and another one in which they have close interaction.

Scenario without reader-tag interference. In this subsection we consider that the activation process of tags from readers and tag transmissions toward readers do not interfere with each other. The probability of a group of u tags being activated, denoted here by p_u, assuming ALOHA operation will be given by the probability that only one reader transmits in a time-slot and that its signal strength is high enough to power-up the tag, which occurs with probability $P_{dt} = \Pr\{\gamma_{rt} > \widehat{\gamma}_t\}$. Therefore p_u can be written as:

$$p_u = \binom{J}{u} P_{dt}^{u}(1-P_{dt})^{J-u} R p_r (1-p_r)^{R-1}. \tag{7}$$

The tag throughput (T) of all the readers can thus be expressed as the modified formula of ALOHA for each possible number of active tags u:

$$T = \sum_u u p_u (1-P_{dr})^R p_t (1-p_t)^{u-1}, \tag{8}$$

where P_{dr} is the probability that a single tag transmission is correctly detected by any of the readers, and which can be written as $P_{dr} = \Pr\{\gamma_{tr} > \widehat{\gamma}_r\}$. Results for a scenario with 15 tags and 5 readers with power-up probability $P_{dt} = 0.7$ and probability of detection at the reader of $P_{dr} = 0.95$ are displayed in Fig. 2a. It can be observed that optimum probabilities of the reader and tag anti-collision components are independent (no need of joint optimization).

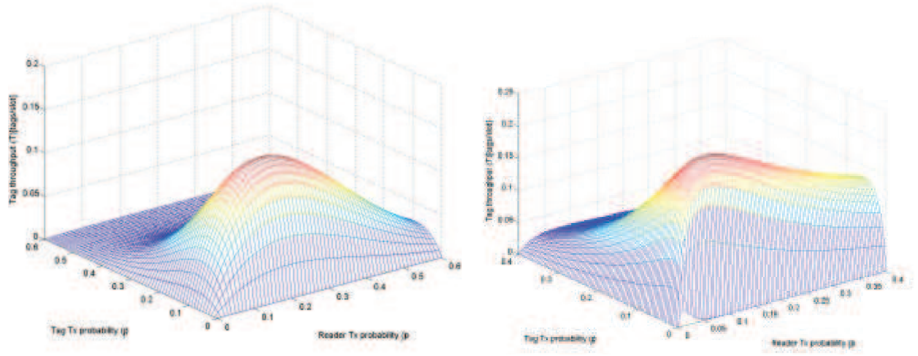
Scenario with full reader-tag interference. Consider now that activation of tags from readers and tag transmissions toward readers interfere with each other. The state of the system is defined as the number of powered-up tags. The transition probability between state m and state n is given by

$$p_{mn} = \begin{cases} \binom{m}{m-n} p_t^{m-n}(1-p_t)^n & n < m \\ \binom{J-m}{n-m} P_{dt}^{n-m}(1-P_{dt})^{J-n} R p_r (1-p_r)^{R-1}(1-p_t)^m & n > m \\ (1-p_t)^m & m = n = J \\ (1 - R P_{dt} p_r (1-p_r)^{R-1})(1-p_t)^m & m = n, n \neq J \end{cases} \tag{9}$$

The transition probabilities define a Markov chain that can be solved using standard tools. Throughput can be finally assessed using

$$T = \sum_u u p_u (1-(1-P_{dr})^R) p_t (1-p_t)^{u-1} (1-p_r)^R. \tag{10}$$

Results for the same scenario as in the previous example are displayed in Fig. 2b. It can be observed that probabilities of the reader and tag anti-collision components are now dependent on each other. This means that, unlike the previous example, joint optimization of reader and tag algorithms is now justified.



(a) ALOHA model 1

(b) ALOHA model 2

Fig. 2. Joint evaluation of ALOHA reader and tag anti-collision algorithms optimization

5.2.3 ALOHA tag protocol with imperfect tag detection

We now address an asymmetrical ALOHA tag protocol with incorrect tag detection and false alarm. We define the probability of correct detection of tag t_j as $P_{D,j}$ and the false alarm as $P_{F,j}$. The throughput of ALOHA can thus be expressed as the probability that only one tag transmits provided it has been correctly detected and that the remaining tags either do not transmit or do not experience a false alarm:

$$T_j = p_j P_{D,j} \prod_{n=1;n\neq j} (1 - p_n)(1 - P_{F,n}) \tag{11}$$

Note that this expression is only for tag t_j and it belongs to the observations made by only one reader. Since probabilities of detection and false alarm are related to each other via the activation threshold of the tag, the joint optimization problem for calculation of the throughput region can thus be written as follows:

$$\{\mathbf{p}, \mathbf{P}_F\}_{opt} = \arg \max_{\{\mathbf{p},\mathbf{P}_F\}} T_j, \quad T_m = \theta_m, m \neq j \tag{12}$$

where $\mathbf{p} = [p_1, \ldots, p_J]^T$ and $\mathbf{P}_F = [P_{F,1}, \ldots, P_{F,J}]^T$. The optimization problem in the previous expression can be solved using the technique of Lagrange multipliers as follows:

$$\partial T_n / \partial p_j - \sum_{l\neq j} \nu_l \partial T_l / \partial p_j = 0 \qquad \partial T_n / \partial P_{F,j} - \sum_{l\neq j} \partial T_l / \partial P_{F,j} = 0 \tag{13}$$

where ν_l is the Lagrange multiplier associated to the l-th throughput constraint. Solving this system of simultaneous equations for different throughput constraints results in the derivation of the boundaries of the throughput region. An alternate approach consists of obtaining from the previous expression $J - 1$ expressions that are independent from the

Lagrange multipliers and then solve the problem for the remaining variables and equations. For each one of these $J-1$ expressions, it is necessary to select J out of the $2J$ equations in the previous expression. Since each one of the selected combinations involves a different selection of variables either from $\mathbf{p}$ or $\mathbf{P}_F$, we will denote the m-th combination by the dummy vector variable $\mathbf{x}^m = [x_1^m, \ldots, x_J^m]^T$, where x_j^m denotes any of the probabilities of transmission or false alarm from the m-th combination. The derivation of the desired expression for the m-th combination is equivalent to solving the following equation:

$$det(\mathbf{Ja}^m) = 0$$

where $det(\cdot)$ denotes the determinant operator and $\mathbf{Ja}^m$ is the Jacobian matrix with elements given by $Ja_{k,j}^m = \frac{\partial T_k}{\partial x_j^m}$. Some simplifications of the expressions yield the following equations for the optimum transmission and detection probabilities, respectively:

$$\sum_{j=1}^{J} p_j = 1 \qquad \sum_{j=1}^{J} \left\{ \frac{P_{D,j}/(1-P_{F,j})}{\partial P_{D,j}/\partial P_{F,j} - P_{D,j}/(1-P_{F,j})} \right\} = 1. \tag{14}$$

The term $\frac{\partial P_{D,j}}{\partial P_{F,j}}$ describes the operational curve of the tag detector and it depends on the adopted reader collision algorithm, interference and noise. ALOHA performances using different SNR values with Rayleigh fading channels are displayed in Figure 3(a).

5.2.4 Retransmission diversity multiple access

The performance analysis and optimization of NDMA for RFID is similar to the ALOHA protocol in the previous subsection. The throughput of NDMA can be expressed as follows(see Samano et al. (2009) and references therein):

$$T_j = (1/L)p_j P_{D,j} \prod_{n=1, n\neq j}^{J} P_{U,n} \tag{15}$$

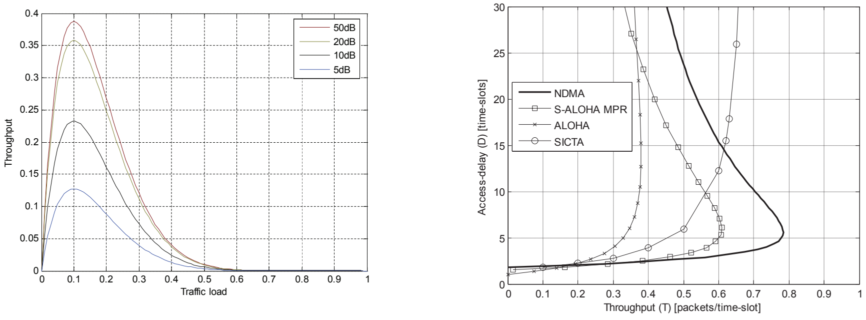
Where $P_{U,j} = p_j P_{D,j} + (1-p_j)(1-P_{F,j})$, $L = \sum_{j=1}^{J} P_{A,j} + \prod_{j=1}^{J}(1-P_{A,j})$ and $P_{A,j} = p_j P_{D,j} + (1-p_j)P_{F,j}$. The optimization, using the previous subsection, gives(Samano et al. (2009)):

$$\sum_{j=1}^{J} \left\{ \frac{(\partial P_{U,j}/\partial x_j^m)(L/P_{U,j}) - (\partial L/\partial x_j^m)}{(\partial P_{U,j}/\partial x_j^m)(1/P_{U,j}) - \partial(p_j P_{D,j})/\partial x_j^m (1/p_j P_{D,j})} \right\} = L \tag{16}$$

Figure 3(b) shows the benefits of the NDMA protocol as compared to other multiple access protocols, thus being amongst the most attractive for RFID solutions (Samano et al. (2009)).

5.2.5 Two-user ALOHA protocol with context aware analysis

Let us now analyze an ALOHA protocol in the case where we have knowledge of the joint tag-arrival distribution, which is called here context information. Using this joint distribution we can infer the presence of another tag that due to imperfect channel conditions was not correctly detected. For convenience we analyze a system with only two tags. The probability space for tag arrival is given by $\Pr\{1\}$, which indicates the arrival of tag 1 only; $\Pr\{2\}$, which indicates the arrival of tag 2 only; $\Pr\{1,2\}$ which indicates the joint arrival of tags 1 and 2; and $\Pr\{\emptyset\}$ which indicates the probability that none of the tags are available. To denote the



(a) ALOHA with imperfect tag activation (b) NDMA vs. other multiple access protocols

Fig. 3. Performance of MAC algorithms with cross-layer optimization

imperfect detection of tags we will use P_{D1} and P_{D2} as the correct detection probabilities of tag 1 and 2, respectively, and P_{F1} and P_{F2} as the false detection probabilities of tag 1 and 2, respectively. The throughput of user one can be written as follows:

$$T_1 = \Pr\{1\}P_{D1}\overline{P}_{F2} + \Pr\{1,2\}P_{D1}\overline{P}_{D2} + x(\Pr\{1,2\}P_{D2}\overline{P}_{D1}), \tag{17}$$

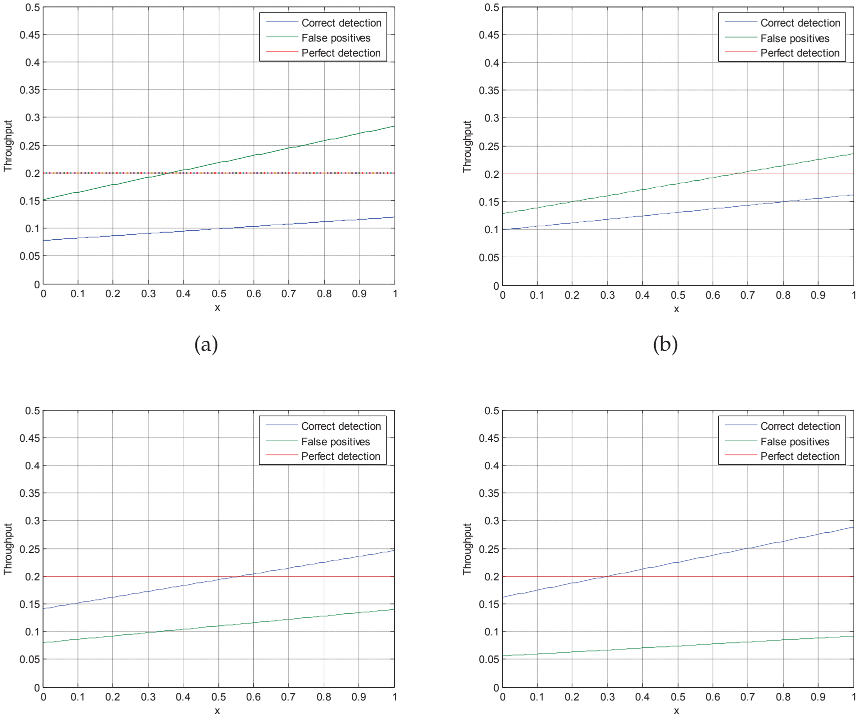
where $\overline{(\cdot)} = 1 - (\cdot)$ and the parameter x is used to regulate the average probability of false positives. Note that the throughput with perfect tag detection is simply given by $T_1^0 = \Pr\{1\}$. Now the false positives of tag 1 are given by

$$F_1 = \Pr\{\varnothing\}P_{F1}\overline{P}_{F2} + \Pr\{2\}P_{F1}\overline{P}_{D2} + x(\Pr\{\varnothing\}P_{F2}\overline{P}_{F1} + \Pr\{2\}P_{D2}\overline{P}_{F1}) \tag{18}$$

The previous expressions indicate that we can increase the throughput of correct tag detections as much as we want by using the parameter x, which is an indication of how many correct tag detections we can infer of tag 1 from the observations of tag 2 being detected. Let us now illustrate an example with the following values: $\Pr\{1\} = 0.2$, $\Pr\{2\} = 0.2$, $\Pr\{1,2\} = 0.2$, $\Pr\{\varnothing\} = 0.4$, $P_{D1} = 0.3$,$P_{D2} = 0.3$,$P_{F1} = 0.4$,and $P_{F2} = 0.4$, which can be found in Figure 4(a) for several values of x. Note that the throughput of correctly detected tags lies below the throughput with perfect detection and the number of false positives. If we now use $\Pr\{1,2\} = 0.3$, $\Pr\{\varnothing\} = 0.3$ we obtain the graph in Figure 4(b). Similarly, we study the system for $\Pr\{1,2\} = 0.5$, $\Pr\{\varnothing\} = 0.1$ and $\Pr\{1,2\} = 0.6$, $\Pr\{\varnothing\} = 0$ in Figure 4(c) and Figure 4(d), respectively. Note that the higher the joint arrival probability the higher the throughput of correctly detected tags and the lower the number of false positives. Note that the throughput can surpass the one with perfect detection of tags. Therefore, context aware detection can improve the number correctly detected tags and false positives.

5.2.6 Complexity optimization

Consider the reader complexity C and the occupied bandwidth B as functions of the tag traffic λ: $C = f_c(\lambda)$ and $B = f_b(\lambda)$. As discussed in Section 2 reduction in complexity can be translated into an increase of traffic due to extra signaling procedures. On the contrary, an increase of signaling traffic is also translated into an increase of complexity to handle remote commands. The optimization problem can be thus be tackled in two different ways: to optimize complexity subject to bandwidth constraints ($\min C, \text{s.t.} B < B_0$) or to optimize



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

Fig. 4. Performance of ALOHA with context aware analysis

bandwidth subject to complexity constraints ($\min B, \text{s.t.} C < C_0$). Since complexity and bandwidth functions are difficult to express in analytical form, these optimization problems could be solved by exhaustive search in tables mapping hardware complexity figures and bandwidth requirements. Performance figures can also be included using the cross-layer framework proposed in this subsection.

6. Conclusions

Cross-layer design has been identified in this chapter as an attractive tool in the optimization of RFID platforms. After a thorough investigation of different impairments that affect RFID, as well as a review of existing algorithms and technologies across different layers of RFID architectures, it has been found that cross-layer methodologies can provide additional useful gains, particularly at the MAC and PHY layers. A general framework for MAC/PHY cross-layer optimization has been proposed for the design of RFID platforms. The framework can be potentially used for a wide variety of PHY and MAC algorithms, thereby paving the way for interesting research topics. Particular examples of MAC/PHY optimized algorithms with imperfect tag detection, reader collision, retransmission diversity and context aware mechanisms have shown the benefits of joint optimization of algorithms across different layers and its importance for future RFID applications. Future work includes to adopt security/privacy parameters and different signal processing schemes with multiple antenna diversity, beam-forming, and smart-antennas in the cross-layer framework proposed in this chapter.

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With the increased adoption of RFID (Radio Frequency Identification) across multiple industries, new research opportunities have arisen among many academic and engineering communities who are currently interested in maximizing the practice potential of this technology and in minimizing all its potential risks. Aiming at providing an outstanding survey of recent advances in RFID technology, this book brings together interesting research results and innovative ideas from scholars and researchers worldwide. Current Trends and Challenges in RFID offers important insights into: RF/RFID Background, RFID Tag/Antennas, RFID Readers, RFID Protocols and Algorithms, RFID Applications and Solutions. Comprehensive enough, the present book is invaluable to engineers, scholars, graduate students, industrial and technology insiders, as well as engineering and technology aficionados.

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