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Assessing the Performance of a Novel Tag-based Reader-to-Reader Communication Paradigm under Noisy Channel Conditions

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***Abstract*—The widespread deployment of Radio Frequency Identification (RFID) tags and readers paved the way for research activities focused on applications that go well beyond the mere identification of people and goods. In this context, the paper investigates an innovative paradigm, according to which the residual data storage capacity of passive RFID tags is used as a kind of "virtual" communication channel to exchange data in RFID ecosystems of the Internet of Things (IoT). The performance of the paradigm is assessed through the evaluation of a number of important communication parameters, such as goodput and delay. The analytical study, validated through simulations, evaluates the impact that the following key parameters have on the system performance: (i) radio channel errors, (ii) collisions, (iii) number of involved readers, (iv) memory block reading size under noisy channel conditions, and (v) heterogeneous storage capacity of available tags. This allows to obtain design directives for a well-performing implementation of the proposed communication paradigm. In particular, accounting for the negative effects of channel errors on the system goodput, in this paper we highlight the relationship between optimal memory reading block size and channel errors to maximize the communication performance.**

***Index Terms*—RFID virtual channel; Piconets; Anticollision; Bit Error Rate.**

I. INTRODUCTION

THE Radio Frequency Identification (RFID) technology is continuously gaining momentum in various R&D areas. An undoubted driving force in this direction is represented by the spread of the EPCglobal platform [1], promoting RFID tags as the favorite candidate for the replacement of widespread optical barcode in supply chain management and enhancing its value with a global integrated architecture. Besides, emerging paradigms, whose objectives go well beyond the mere identification, such as for example the Internet of Things (IoT), strongly rely on RFID [2]. This is also fuelled by the continuous progresses of RFID devices, which have recently driven to the development of enhanced tags like Wireless Identification and Sensing Platform (WISP) [3], i.e. small, RFID-based computing devices similar to RFID tags but augmented in their functionalities to perform environmental sensing. Moreover, research studies have proven the feasibility of unconventional applications of RFID technology to provide, for instance, indoor localization [4] - [5] or eHealth services [6]. All of these are evident indications that RFID will play a key role in the ubiquitous computing vision, which will characterize the future human lifestyle. To further support this idea, a sharp acceleration in the deployment process of RFID ecosystems in different areas of everyday life [7] has recently been observed.

When it comes to services that require the capability of transferring sensed and/or identification data to remote locations, a common approach is to couple the RFID system with other networking technologies. Although the amount of transferred information is rarely requiring high data-rates, still the use of an external communication technology is considered as unavoidable [8]. Our vision is that a real RFID ecosystem cannot come to a full implementation if the technology, thought to track and trace goods and persons, is not used also as a communication means to exchange information. The first steps towards this objective have brought to research studies in the literature that envisage the use of passive RFID tags as a virtual communication channel [9]. In particular, a group of RFID readers can exploit the available memory of surrounding tags to establish a local network, called RAN (RFID Area Network), and perform real-time data exchange in either a unicast or a broadcast modality [10]. This proposal is designed to keep full compatibility with the EPCglobal infrastructure and paves the way to several applications. To this aim, a thorough modelling of the communication paradigm is of utmost importance to support a comprehensive analysis of the performance potential in terms of goodput and delay, and provide design directives for a well-performing implementation of the proposed communication paradigm. However, this objective is very challenging since several parameters are to be considered simultaneously such as channel errors, collisions in the system, memory, storage capacity of the tags, reading/writing operations, and number of readers. To fill this gap, the objectives of this paper can be summarized as follows:

- we describe the main aspects of an RFID Area Network, by examining the background context which motivates its introduction; in particular, we clearly identify use cases where the novel communication paradigm can be considered as an added-valued;
- we investigate the key elements influencing the proposed paradigm and analytically study them by accounting for technology specific issues such as errors in transmission, collisions among readers, and RFID tag memory man-

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agement problems. The proposed analysis overcomes the limitations of the early model in [11] by accounting for the effects of errors occurring over the channel during the message exchange within the RAN;
- we provide an in-depth analysis of the RFID reading and writing operations during reader-tag interactions, under conditions of error prone channel and according to the EPCglobal UHF Class-1 Gen-2 protocol [12]. Moreover, we define the most appropriate size of the memory block to consider during reading operations as a function of the Bit Error Rate (BER) on the channel. To the best of the authors' knowledge, this study has not been investigated before and can provide useful indications also in other application scenarios, where operations on tag memory are required in a hostile interference environment;
- we conduct an extensive performance evaluation campaign, through an ad-hoc designed simulation tool, to validate the analytical results. This thorough analysis allows to identify the maximum size of a RAN that satisfies *goodput* and traffic delay constraints under given configurations. Besides, to account for a typical heterogeneous IoT ecosystem, we evaluate the overall performance in a scenario where available tags are equipped with different memory capacity.

The next section of the paper presents related works and motivations for the proposed paradigm with possible applications. In Sections III and IV details of the communication protocol are introduced, whereas in Section V the proposed analytical model is defined. Section VI presents a performance evaluation campaign, a discussion on practical implementation issues is provided in Section VII, whereas conclusions are drawn in the last Section.

II. Background and Use Cases

Several factors can be identified as a favorable background for the deployment of the proposed communication paradigm. First of all, the forthcoming Internet of Things (IoT) fosters a smarter world where billions of devices and objects are connected with each other through disparate network solutions. RFID systems will play a leading role thanks to their pervasiveness and to the expected massive presence of tagged objects and embedded readers in everyday life environments. Moreover, RFID technology is experiencing a continuous evolution process. On the one hand, engineering solutions are being developed to reduce complexity and size of mobile RFID readers, to encourage the technology transition from industry to home/educational environments [13]. On the other hand, RFID tags are being improved in their features to widen their potential application scope. In this regards, an aspect - extremely interesting for our scenario - is the development of new families of tag memories based on F-RAM (Ferroelectric Random Access Memory) technology allowing to reduce the write time intervals, increase the rewrite capability, and offer a greater data storage capability. This latter point is a key element for the tag-based communication paradigm we are addressing. In fact, the memory of the RFID tags available on the market, or still under study, has a data storage capacity that goes well beyond the one required for mere identification purposes. This gives a chance to look at the RFID tags as a sort of "virtual" communication channel already available in many environments, but not fully exploited yet. The proposed paradigm will enable low-cost and low-powered mobile readers to exchange data by relying only on the RFID interface, without any need for additional hardware and/or network interfaces.

The use of RFID technology for data exchange has attracted the interest of academia and industry, as witnessed by several recent research contributions. The Delay-Tolerant Network (DTN) using RFID tags proposed in [14] shows how information could be exchanged among remote RFID readers. Specifically, the authors propose an information network, made up of mobile passive tags and fixed readers, which exploits the tag movement to enable communications among completely isolated readers, while gathering both mobility information and sensed data. Further examples are given in [15] and [16], where respectively indoor navigation and distributed localization systems are addressed through the introduction of an RFID-based delay tolerant network. Both interesting examples of communications based on RFID tags neglect interference issues among readers. Differently, the communication channel proposed in this paper takes into account interference problems and is not limited to DTN networks, but also supports "real time" communications.

A feasibility study of an RFID tag-to-tag communication system is also presented in [17] and mathematically analyzed in [18]. Our approach differs from the cited papers, as the attention is on modeling reader-to-reader communication where the tag is used as a *means of data transmission* (thus, as *a sort of "virtual channel"*). In the vision of a networked RFID system, an interesting proposal is presented in [19], where computational RFID tags can exchange messages with one another and with external entities introducing opportune memory management abstractions. This solution foresees that readers operate as relays collecting packets from the tags and forwarding them to their destinations. Another approach to enable remote access of passive RFID tags via IPv6 addressing is described in [20]. In particular, RFID reader provides functionalities of IPv6 router and manages the communication for the tags in its operating range. Our tag-based channel is complementary to this strategy and might help mobile readers to exchange messages, in a multi-hop fashion, to reach a destination or a gateway to the Internet.

An unconventional use of RFID systems is also investigated in [21], wherein the notion of RFID-Grid is introduced. The main difference with our proposal is that in [21] tags are used as a sort of distributed memory to store information to be accessed at a later time. Our proposal, instead, supports also "real time" communications, which may exploit the multitude of pre-existing standard tags. The potentialities of our paradigm are witnessed by the patent presented in [9] and by the papers [10] and [11]. In particular, in [10] we evaluated the performance of the tag-based channel by considering specific anti-collision protocols. The analysis proposed in this paper extends the model in [11], since here the effect of errors on the channel in terms of message exchange in the RAN is also

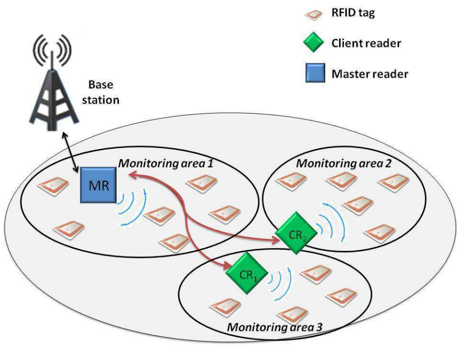


Fig. 1. Reference scenario.

modeled. Finally, further researches on the use of the tag as a means of communication brought to patenting activities such as [22] and [23].

Several applications, services, and systems could benefit from the tag-based virtual channel. A first possible application scenario can be a swarm of RFID-enabled mobile robots for monitoring, cleaning, exploration of large areas. The integration of RFID technology and robot swarms has been extensively investigated in the literature, which has demonstrated its benefits to several robot related issues, such as navigation [24], exploration [25], and distributed memory [26] problems. The proposed channel may exploit the already deployed tags also to enable massive communication exchange among mobile robots. In particular, we can consider a scenario (sketched in Fig. 1) where a base station dynamically assigns tasks to the robots for their monitoring areas, based on information about new user' requests, environmental changes, or node failure. Only a small subset of the available readers, called hereinafter master readers (MR), has the capability of communicating with the base station. The remaining readers, hereinafter referred to as client readers (CR), are very *simple*, *low-cost* and *low energy-consuming* devices. These can receive their allocated tasks and information about their monitoring areas from the MR through the tag-based channel communications. In this way, the mobile CRs can update their task either periodically or when they complete their jobs. This solution guarantees that the communication flow among readers is implemented with a single RFID technology without requiring additional and costly network interfaces in the client readers. Moreover, although in the literature some studies propose task coordination using RFID tags memory in a DTN approach [27] [28], they do not allow direct robot-to-robot communication for *delay-sensitive* applications. In [29] instead, a cooperative data gathering and energy recharging solution exploiting the tag-based channel was proposed for wide-area RFID Sensor Networks and the results demonstrated that lower data collection delay is obtained w.r.t. a DTN approach.

A second possible application may be the precise positioning and location tracking through the RFID technology. Several "reader oriented" solutions have been proposed in the literature that aim at locating mobile readers, which interact with RFID tags scattered in the surrounding environment. Their precision can be increased by enabling the continuous exchange of information among RFID mobile readers through the proposed paradigm and thus enabling cooperative positioning methods. The consequent attractive feature will be the possibility of implementing precise location mechanism *by only relying on the RFID technology*. Indeed, this would allow the use of simple and cheap (although more precise) mobile RFID readers, like those proposed in [13], for location purposes, without the need of additional technologies to support data exchanges. A further application can be envisaged in scenarios where sensing RFID tags (such as WISPs) are distributed for monitoring purposes in an everyday life environment. Low-cost miniaturized mobile readers can be used to gather the sensed information from the WISPs and can benefit from the tag-based channel to reach a more complex and enhanced RFID reader with communication capabilities. This costly reader will act as a "sink" for the collected data and as an "anchor" to the Internet. Several use-cases arise both for in-home automation, assisted living, telemedicine, eHealth (e.g., using RFID sensors like in [30]), energy consumption control leading to a remarkable breakthrough towards effective RFID sensor networks. Different from papers [31] [32] that investigated the integration of RFID systems and Wireless Sensor Networks, our proposed paradigm allows to establish a pure RFID ecosystem guaranteeing identification and sensing services.

The persistence of the identified transmission medium, i.e., the RFID tag memory, introduces further advantages and innovative solutions. By relying on classical short-range communication solutions, once a device temporarily falls out of the communication range, it may lose some data relevant to the current communication session that it cannot recover anymore. Differently, thanks to the persistence of the RFID memory, the data sent to a reader belonging to a RAN is maintained in the memory of one or more RFID tags; it will still be there and available for the "disappeared" reader if it again (in a short time) shows up within the communication range. The persistence of the distributed memory of the RFID tag can help also when small low-powered mobile readers use a sleeping mode for energy saving. In such a scenario, the presence of a proposed RFID Area Network can solve the well-known issue of synchronization between activity and sleeping phases, typical in sensor networks.

As a conclusive remark, we observe that the possible applications of the proposed tag-based virtual communication channel are manifold. It is *not to be considered as a competitor of existing wireless short range technologies*, but it represents an additional communication possibility in scenarios where RFID technology is already available and working.

III. The RFID Area Network

The key elements for an RFID Area Network (RAN) setup are here briefly recalled; for an extended description, the interested reader can refer to [9]. With reference to the scenario sketched in Fig. 1, a reader with a higher complexity level, the MR, assumes the role of creator and coordinator of the RAN. Several low-cost and simpler readers, the CRs, are only equipped with the RFID interface and can join the RAN to

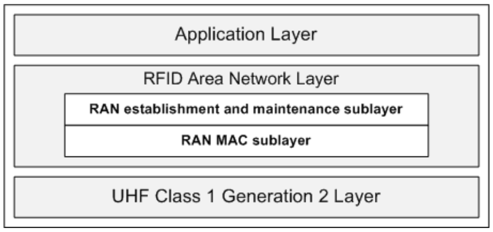


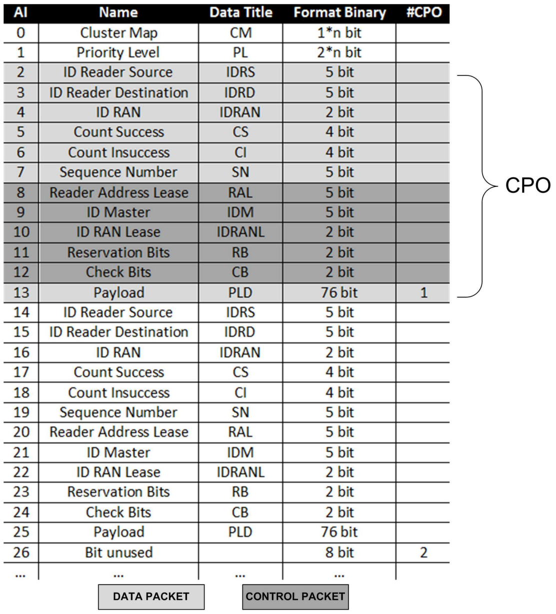
Fig. 2. RAN protocol stack.

exchange data with the MR and with other CRs. In the most general case, multiple RANs can be active simultaneously and a CR and an RFID tag can be simultaneously associated to different RANs, created either by the same MR or by different MRs. As already discussed, the data exchange between MR and CRs belonging to the same RAN is performed through the use of passive RFID tags (already existing in the environment, e.g., for tracing purposes) of type EPCglobal Class1 Gen2 [12] equipped with the User Memory Bank.

Suitable *Discovery Tables* are implemented in both the MR and CR to dynamically identify the RFID tags that each MR can use as a "communication channel" to transfer data towards a CR and vice-versa. To implement the whole set of procedures, the RFID User Memory Bank must be properly structured in compliance to the relevant ISO/IEC and EPCglobal data standard. More details about this aspect are given in Section VII. RFID Area Networks are designed to maintain full compatibility with EPCglobal platform and, in particular, with the radio interfaces defined by the EPCglobal UHF Class1 Gen2 standard. This means that the protocol stack is built on top of it, as shown in Fig. 2. The proposed functionalities are divided into two sublayers:

- RAN establishment and maintenance sublayer: defines the new data structures and formats to exploit the User Memory (UM) as a virtual communication channel; specifies the procedures to create and manage a RAN (Addressing and Control phases), and rules the message exchange (Communication phase); offers a high degree of flexibility in tag management so to optimize the memory capacity usage, according to any application request.
- RAN MAC sublayer: defines the radio channel access schemes accounting for the interference problems raised by the presence of MR and CRs within a given RAN. To this aim, in Section IV, we introduce a new anti-collision algorithm, Listen Before Talk (LBT) based protocol.

TABLE I
STRUCTURE OF USER MEMORY [9].



AI	Name	Data Title	Format Binary	#CPO
0	Cluster Map	CM	1*n bit	
1	Priority Level	PL	2*n bit	
2	ID Reader Source	IDRS	5 bit	
3	ID Reader Destination	IDRD	5 bit	
4	ID RAN	IDRAN	2 bit	
5	Count Success	CS	4 bit	
6	Count Insuccess	CI	4 bit	
7	Sequence Number	SN	5 bit	
8	Reader Address Lease	RAL	5 bit	
9	ID Master	IDM	5 bit	
10	ID RAN Lease	IDRANL	2 bit	
11	Reservation Bits	RB	2 bit	
12	Check Bits	CB	2 bit	
13	Payload	PLD	76 bit	1
14	ID Reader Source	IDRS	5 bit	
15	ID Reader Destination	IDRD	5 bit	
16	ID RAN	IDRAN	2 bit	
17	Count Success	CS	4 bit	
18	Count Insuccess	CI	4 bit	
19	Sequence Number	SN	5 bit	
20	Reader Address Lease	RAL	5 bit	
21	ID Master	IDM	5 bit	
22	ID RAN Lease	IDRANL	2 bit	
23	Reservation Bits	RB	2 bit	
24	Check Bits	CB	2 bit	
25	Payload	PLD	76 bit	
26	Bit unused		8 bit	2
...	...	...	...	

A. The three functioning phases (Addressing, Control, and Communications)

In the *Addressing* phase, an MR acquires an *ID Master address* from the so-called Master Control (MC) to establish an area network [9]. Then, the MR performs the inventory of the tags falling within its reading range to identify which of them can be used as an RFID communication channel. For each suitable tag, its UM is properly structured according to the scheme in Table I. In particular, the basic unit of data exchange is represented by the Cluster Packed Object (CPO), which contains a *Control Packet* and a *Data Packet*. The number of CPOs depends on the UM size and a specific field, the so-called ”Cluster Map”, is used to understand which CPOs are available for reading and writing operations. When a CR identifies a tag associated to a previously formed RAN, the CR can use it to join the RAN. In particular, through the exchange of Control Packets, each CR will obtain an address, which is stored into the Discovery Tables of the MR and the CR, and used during the Communication Phase.

In the *Control* phase, the Discovery Tables are updated. This phase can be started by either an MR or a CR to periodically check for the presence of a given MR/CR/tag within a RAN.

During the *Communication* phase, data exchange in the RAN can be unicast when an MR sends messages to a single CR, or *broadcast* when the MR sends messages to all the CRs over the same tag. In the *unicast* case, which is the communication modality considered in this paper, the involved CR must acknowledge each received message by updating the "Cluster Map" and, consequently, release the used memory resources on the tag (or on several tags when the message exchange involves more tags). A main peculiarity of the proposed communication protocol is that the tag memory (the memory of more tags, in general) is shared among the readers in the RAN since it is the ”repository” for the exchanged data. This poses some issues to handle an efficient sender-to-destination communication flow. Any reader in a RAN is not able to understand which of the other readers in the same RAN is currently transmitting and is not a priori aware of the presence of useful data in the UM of a tag. Consequently, it might happen that a given reader (either Master or Client) accesses the tag, but the stored information is already known or is not intended for the accessing reader. In any case, the readers shall continuously access the tag to be able to update their information. In the *unicast* communication modality, a CR has to verify the presence of new messages of interest and the MR has to check for the possibility to write the next message (only after the previous one has been read). Clearly, it might happen that a reader polls the tag, but the access is not useful causing a so-called *useless access*. This phenomenon strongly influences the final data transmission rate.

IV. REFERENCE PROTOCOLS FOR THE COMMUNICATION CHANNEL

The main factors influencing the communication over the tag-based virtual channel are identified and briefly described in this Section. The EPCglobal Gen2 standard [12] guidelines are considered to analyze reader-tag interactions finalized to read/write data from/into the UM of a tag. Readers in the RAN are assumed to operate in mutual proximity with overlapping tag communication areas. Consequently, the presence of an anti-collision protocol to avoid interferences is accounted for (the LBT-based approach proposed in [10] is assumed).

A. *EPCglobal Gen2 standard for reader-tag communication*

According to the EPCglobal Gen2 standard, before a reader can perform Reading or Writing operations on the UMs of the used tags, the singulation of the tag is required. When it successfully gains access to the radio channel, it can sequentially access all the relevant tags within its communication range through the Select command (we neglect tag-to-tag collisions). The Select command allows to singulate the tag to use as a virtual channel. After the Electronic Product Code (EPC) reception, a reader requests a 16-bit Handle to be included in the subsequent Read or Write commands. In the remainder of the paper, we will denote this phase as *Singulation*. In particular, the *Singulation* duration is considered as a necessary overhead delay to perform operations on the tag memory. Once the Handle is obtained from the tag, a reader has to check the tag channel status by reading the UM. A *Reading* operation consists of a Read command, which allows to read the whole content of the UM. Based on the status of the memory, a reader in the RAN can send new messages or acknowledge received messages. This involves a *Writing* operation, whereby the memory of the tag is updated. In particular, a Write command allows to write a single 16-bit word at a time; therefore, to update the UM, this command is likely to be repeated several times. Differently from the reader commands which foresee a fixed time interval T_1 between the reader message and the subsequent tag reply (*immediate reply*), the Write command allows for a temporal window lasting for a maximum of $T_{5(max)}$=20ms (*delayed reply*). During this window, the reader energizes the tag to enable the memory writing. Under noisy channel conditions, messages could be received corrupted and retransmissions are necessary. Like the analysis reported in [33], [34], [35], we consider only the possibility of errors in tag-to-reader transmissions. The time wasting due to an error depends on the specific message sent by the tag in response to a reader command. If the preamble of a message is corrupted, then the reader will not detect the tag response. Therefore, for messages requiring an *immediate reply* we assume that the time needed to detect a channel error affecting the preamble of a tag message is $T_{ReaderCommand} + T_1 + T_{TagPreamble}$. The value for T_1 can be computed according to the standard, $T_{ReaderCommand}$ is the time required by the reader to send the specific command, and $T_{TagPreamble}$ is the time required by the tag to transmit the message preamble. If, instead, the reader performs a Write command and a delayed reply is foreseen, then any corrupted preamble of the tag reply implies that the reader will wait for a time interval lasting up to $T_{5(max)}$ as defined by the standard. When the error occurs on the tag message itself, then it is detected in the time $T_{ReaderCommand} + T_{WaitTagResponse} + T_{TagResponse}$, where $T_{TagResponse}$ is the time the tag needs to respond to the message, $T_{WaitTagResponse}$ is equal to T_1 for the commands requiring an immediate reply and to T_5 for those followed by a *delayed reply*.

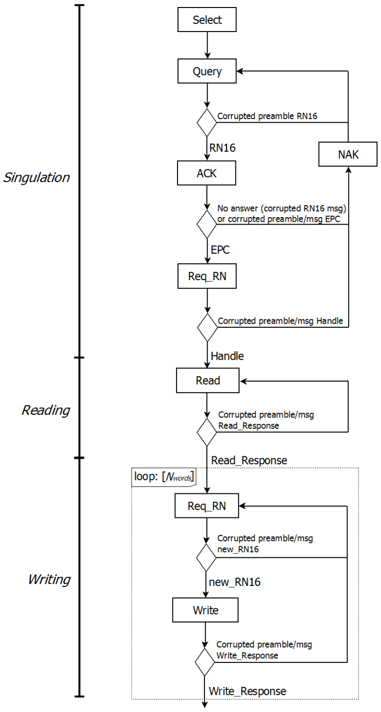


Fig. 3. Messages flow chart for the reader.

A complete reader-tag communication involves three subsequent phases, namely *Singulation*, *Reading*, and *Writing*, as shown in Fig. 3 by pointing out all messages exchanged between reader and tag. Reader messages are within squares and the flow chart accounts for either correct or incorrect tag replies. Any phase of the reader-tag communication is successfully completed if and only if all the relevant tag-to-reader messages are successfully received. Whenever an error occurs in any of the messages of a given phase, the whole phase restarts from its first message.

Two particular cases exist in the *Singulation* phase. The *first* case concerns the RN16 message, sent by the tag after a Query command, which does not contain a CRC field in its preamble. This implies that the reader has no means for evaluating the message correctness and thus it can just send an ACK including the received RN16 value “as it stands”. If the RN16 was corrupted by errors, then the tag is unable to recognize it and will not reply to the reader. The *second* case refers to an error occurring on the reply sent by the tag upon reception of either an ACK or a Req_RN message from the

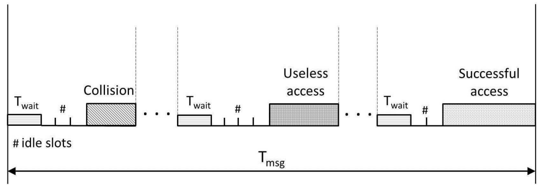


Fig. 4. Scheme of contributions for T_{msg}.

reader. In both cases, the reader must send a NAK message and wait for a time T_4, defined by the standard, before sending a new Query command and restarting the *Singulation*. The NAK allows resetting the state of the selected tag before a new inventory phase.

B. LBT-based anti-collision protocol

To handle Reader-to-Reader and Multiple-Reader-to-Tag interferences, we consider an algorithm of the CSMA family, derived from the LBT (Listen Before Talk) [36] standard modality. All readers in the RAN are assumed to operate over the same radio channel and continuously contend for the channel access. Before starting any transmission, each reader monitors the channel for a 5ms time interval T_{wait} plus a random time (called backoff time in the remainder of the paper) uniformly distributed in the [0, 5] ms interval (11 slots with a time slot duration $T_{SlotTime}$=0.5ms) to detect possible ongoing transmissions. If the channel is busy, then the reader continues to sense it until it becomes idle and a new access procedure can start.

We assume RFID readers equipped with omnidirectional antennas and with the same transmission power. Thus, within a RAN, each reader can listen to any other reader and the hidden terminal problem can be excluded, as discussed in [37]. Interferences among readers occur when they try to simultaneously singulate a tag used as a communication channel and this latter is unable to decode the received commands and to reply to the readers. Thus, in a static RAN, whenever a reader sends a Query command to access the selected tag, but it does not receive the RN16 reply message, it assumes that another reader is transmitting and identifies this event as a *collision*. When a *collision* event is identified, the reader releases the channel and attempts a later new channel access. Noteworthy, when a channel error occurs on the preamble transmission of the first RN16 message (i.e., when a reader attempts to interact with the selected tag), the reader will erroneously consider the lack of a tag reply as a collision. We refer to this case as *false collision*. Our model takes into account both true collisions (due to interference among readers) and false collisions (due to errors on the *first* RN16 message).

V. ANALYTIC MODEL FOR THE TAG-BASED CHANNEL

We model the proposed communication channel by focusing on a single RAN, where one MR sends data to multiple CRs, over a single tag, in saturation conditions. For saturation conditions we intend that the MR has always data to send. Let N be the number of readers involved in the RAN (one MR and $N-1$ CRs). Every MR-to-CR unicast communication must be acknowledged. Therefore, the destination CR, after correctly reading the message from the tag memory, writes the relative ack message. When the MR again accesses the tag and reads the ack, then it will write on the tag a new message for the next CR in a Round Robin fashion. In every MR-to-CR transmission the whole tag memory is used. Thus, a tag is either *ready to be written* by the MR (if the previous message is acknowledged) or *ready to be read* by a specific CR. Objective of the proposed model is to evaluate the channel *goodput* for the RAN. To this aim we define *TimeCycle* as the average time interval required to complete a successful message exchange between the MR and a CR.

We can thus define the *goodput* for the RAN as follows:

$$goodput = \frac{NumberCPO \cdot BitPayload}{TimeCycle} \tag{1}$$

where *BitPayload* is the payload of 76 bits included in each CPO and *NumberCPO* is the number of CPOs which depends on the size of UM. The *TimeCycle* term includes an average time required for the MR to send a message, hereafter called T_{msg}, and a time T_{ack} in which the destination CR acknowledges the correct reception of the message. As reported in Fig. 4, the correct modeling of the T_{msg} and T_{ack} terms requires to take into account: (i) the time wasted due to collisions, (ii) the time wasted due to the so-called useless accesses (see Section III), and (iii) the time for the reading and writing operations on the tag memory. The idle time periods before a channel attempt is performed are also to be considered. We can define T_{msg} and T_{ack} as:

$$T_{msg} = E[N_c]T_c + E[N_u]T_u + Tx_{msg} \tag{2}$$

$$T_{ack} = E[N_c]T_c + E[N_u]T_u + Tx_{ack} \tag{3}$$

where $E[N_c]T_c$ is the expected number of collisions multiplied by the time wasted due to a single collision; $E[N_u]T_u$ is a similar term referred to useless accesses; and Tx_{msg} and Tx_{ack} are the times for successfully transmitting the data and the ack message over the tag-based channel. The exact definition of all terms in equations (2) and (3) is given in the following subsections.

A. Contributions from the channel contention

Let us first compute the term $E[N_c]T_c$ in equations (2) and (3). T_c includes both the variable idle time before a collision and some terms with standard values in Table III:

$$T_c = T_{idle} + T_{TagPower-Up} + T_{Select} + T_4 + T_{Query} + T_1 + T_3 \tag{4}$$

where T_{Select} and T_{Query} are the time spent by the reader to respectively send the Select and the Query messages and T_{idle} is the average time the channel remains idle before a radio channel access. This latter includes both the initial waiting time T_{wait} and a time corresponding to the average number of slots during which none of the readers accesses the channel. More precisely:

$$T_{idle} = T_{wait} + Nslots_{idle}(N) \cdot T_{SlotTime} \tag{5}$$

The value of $Nslots_{idle}$ depends on N and its exact definition is the result of the probabilistic analysis reported in Appendix A. As for the definition of the average number of collisions $E[N_c]$ per successful access in equations (2) and (3), we introduce the probability of collisions P_c. In particular, P_c is given by the sum of the probability of *true collision* P_{LBT}, relevant to the LBT-based protocol for radio channel access, and the probability of *false collision* P_{fc}. The exact definition of P_{LBT} is given in Appendix A. Whereas, P_{fc} is simply computed as the probability of an error occurring on the preamble of the tag RN16 message (under the assumption of independent bit errors on the channel) when no collision happens: $P_{fc} = (1 - P_{LBT})(1 - (1 - BER)^{Preamble})$, where *Preamble* is the number of bits in the tag message preamble and *BER* stands for the bit error rate. The average number of collisions $E[N_c]$ is thus computed as:

$$E[N_c] = P_c \sum_{k=1}^{\infty} k(P_c)^{k-1}(1 - P_c) = \frac{P_c}{1 - P_c} \tag{6}$$

Larger values for the $E[N_c]T_c$ product correspond to longer time intervals to gain access to the tag and, consequently, to a final reduced *goodput*. As observed from the formulations, the parameters influencing this value are the number of readers N and the BER in the system.

B. The useless access contribution

The $E[N_u]T_u$ term in equations (2) and (3), represents the time wasted due to useless accesses in the RAN. The average number of useless accesses $E[N_u]$ can be defined as:

$$E[N_u] = P_u \sum_{k=1}^{\infty} k(P_u)^{k-1}(1 - P_u) = \frac{P_u}{1 - P_u} \tag{7}$$

where P_u is the probability of a *useless access* occurring on the channel. To model this term, we consider the possible states of the UM in a tag. Saturation conditions are assumed in transmission. Thus, the only two possible states correspond to: (1) *tag memory containing a "message to a generic n-th CR"*, or (2) *tag memory containing an "ACK to the MR"*. If the tag is in state (1), then a useful access happens only if the destination CR accesses the tag. In this case it reads the message sent by the MR and acknowledges it. According to the LBT-based protocol, every reader, either an MR or a CR, gains access to the radio resource (and, thus, to the tag-based virtual channel) with the same probability $1/N$. With the tag in state (2), the access is useful only if the MR accesses the tag and writes into the UM a new message for the next CR; also this event has probability $1/N$. The useless access probability in both states is thus $P_u = 1 - 1/N$.

The T_u term is the time wasted for a single useless access, i.e., the average time required by a reader to check the content of the tag memory without having the possibility to perform any change to the memory due to the unsuitable state of UM. T_u is given by the sum of the expected time spent to contend for the radio channel and the time to read the UM:

$$T_u = E[N_c]T_c + T_{idle} + E[T_S] + E[T_R(N_{words})] \tag{8}$$

where $E[T_S]$ is the expected time for the *Singulation* and $E[T_R(N_{words})]$ is the expected time for *Reading* N_{words} from the tag memory (N_{words} depends on the UM size). These terms will be defined in the next subsection, as they also contribute to define Tx_{msg}. The influencing parameters are not only the BER and the number of readers N, but also the N_{words} term.

C. The reader-tag interaction contribution

As described in Section IV-A, to send data or an ack over the tag memory a reader needs to sequentially perform a *Singulation* phase, a *Reading* phase and a *Writing* phase. Thus, we define the average time Tx_{msg} requested by the MR to transfer data into the UM of the tag:

$$Tx_{msg} = T_{idle} + E[T_S] + E[T_R(N_{words})] + E[T_W(N_{words})] \tag{9}$$

where, besides the already cited T_{idle}, $E[T_S]$, and, $E[T_R(N_{words})]$ terms, we have also the additional term $E[T_W(N_{words})]$, which represents the expected time spent for *Writing* N_{words} into the memory of the tag. The computation of any single term has to account for errors occurring on the channel. To this aim, we define the error probability for the messages exchanged during each single phase and the channel time wasted due to the retransmission(s) of any corrupted message. Let us denote with $P_{E,p,m}$ the error probability for message m in phase p (where $p = S$ stands for *Singulation*, $p = R$ stands for *Reading* and $p = W$ stands for *Writing*), and let M_p be the total number of messages for a specific phase p. Under the assumption of independent bit errors on the channel, $P_{E,p,m}$ can be computed as $1-(1-BER)^{L_{p,m}}$, where BER is the bit error rate and $L_{p,m}$ indicates the number of involved bits, as specified in Table II for any single message. Let $T_{E,p,m}$ be the time lost due to an error occurrence in phase p on message m. The definition of all $T_{E,p,m}$ values includes waiting time values defined by the standard [12] and the retransmission of the corrupted messages. The exact values of these terms are given in Table II (errors on the message and on its preamble are separately considered, being the associated wasted channel time different).

Let us focus on a generic phase p and a generic message m in this phase to evaluate the time wasted due to errors on the channel $TimeLost_{p,m}$. Whenever an error occurs in any message of a given phase, the whole phase is restarted. Therefore, for each message m, we consider the sum of the relevant deterministic time $T_{E,p,m}$ plus a stochastic time that accounts for the average number of transmissions associated to the messages that precede message m in phase p:

$$TimeLost_{p,m} = T_{E,p,m} + \sum_{i=1}^{m-1} T_{E,p,i} \frac{P_{E,p,i}}{1 - P_{E,p,i}} \tag{10}$$

TABLE II
Errors on Tag Messages

Message	Time lost for an error	Bits
Preamble RN16	$T_{E,S,1} = T_{Query} + T_1 + T_{TagPreamble}$	$L_{S,1} = 18$
RN16	$T_{E,S,2} = T_{Query} + T_1 + T_{RN16} + T_2 + T_{ACK} + T_1 + T_{TagPreamble} + T_{NAK} + T_4$	$L_{S,2} = 16$
Preamble EPC	$T_{E,S,3} = T_{Query} + T_1 + T_{RN16} + T_2 + T_{ACK} + T_1 + T_{TagPreamble} + T_{NAK} + T_4$	$L_{S,3} = 18$
EPC	$T_{E,S,4} = T_{Query} + T_1 + T_{RN16} + T_2 + T_{ACK} + T_1 + T_{EPC} + T_2 + T_{NAK} + T_4$	$L_{S,4} = 128$
Preamble Handle	$T_{E,S,5} = T_{Query} + T_1 + T_{RN16} + T_2 + T_{ACK} + T_1 + T_{EPC} + T_2 + T_{Req\_RN} + T_1 +$ $+ T_{TagPreamble} + T_{NAK} + T_4$	$L_{S,5} = 18$
Handle	$T_{E,S,6} = T_{Query} + T_1 + T_{RN16} + T_2 + T_{ACK} + T_1 + T_{EPC} + T_2 + T_{Req\_RN} + T_1 +$ $+ T_{Handle} + T_2 + T_{NAK} + T_4$	$L_{S,6} = 32$
Preamble Read_Response	$T_{E,R,1} = T_{Read} + T_1 + T_{TagPreamble}$	$L_{R,1} = 18$
Read_Response	$T_{E,R,2}(N_{words}) = T_{Read} + T_1 + T_{Read\_Response}(N_{words}) + T_2$	$L_{R,2} = 33 + 16N_{words}$
Preamble new_RN16	$T_{E,W,1} = T_{Req\_RN} + T_1 + T_{TagPreamble}$	$L_{W,1} = 18$
new_RN16	$T_{E,W,2} = T_{Req\_RN} + T_1 + T_{new\_RN16} + T_2$	$L_{W,2} = 32$
Preamble Write_Response	$T_{E,W,3} = T_{Req\_RN} + T_1 + T_{new\_RN16} + T_2 + T_{Write} + T_{5(max)}$	$L_{W,3} = 18$
Write_Response	$T_{E,W,4} = T_{Req\_RN} + T_1 + T_{new\_RN16} + T_2 + T_{Write} + T_5 + T_{Write\_Response} + T_2$	$L_{W,4} = 33$

The definition in equation (10) is valid for any of the messages in the three different phases. Thus we can define the expected total time for a generic phase p as in equation (11):

$$E[T_p] = T_p + \sum_{i=1}^{M_p} TimeLost_{p,m} \frac{P_{E,p,m}}{1 - P_{E,p,m}} \tag{11}$$

where T_p is the time to correctly send all messages in phase p and the second term accounts for the time wasted due to corrupted messages in phase p. In particular, the time T_p can be simply computed summing the time contributions specified by the standard for each message in each phase p. Based on this formulation, the exact values for the three possible phases are derived. Thus, it is possible to compute the $E[T_S]$, $E[T_R(N_{words}]$, and $E[T_W(N_{words})]$ terms required in equations (8) and (9) to define T_u and Tx_{msg} respectively. A similar analysis can be performed to define Tx_{ack} where only the number of words involved in the *Writing* operation changes and depends on the Cluster Map size, as specified in Section III. For the dependencies on N_{words} please refer to Appendix B where the explicit computation of the expected time for the *Reading* and *Writing* phases is reported.

D. Analysis for a general heterogeneous multi-tag case

Although the model presented so far focused on a single-tag scenario, it can be easily extended to the case of multiple tags where also different UM sizes are considered. In particular, in a multi-tag scenario, once a reader has successfully occupied the radio channel, it can transfer data by sequentially accessing the UMs of the available tags adopted as communication channel, and thus avoiding possible tag-to-tag collisions. According to the scheme defined earlier in this Section and given the saturation conditions, we assume that in each round the MR uses all the available tags to transfer data towards a specific CR. To account for the heterogeneous UM sizes of the available tags belonging to set $\mathcal{M} = \{t_1, t_2, ..., t_M\}$, the computation of the total system goodput in equation (1) must be modified as follows:

$$goodput(\mathcal{M}) = \frac{\sum_{m \in \mathcal{M}} (NumberCPO_m \cdot BitPayload)}{\sum_{m \in \mathcal{M}} TimeCycle_m} \tag{12}$$

VI. Performance Evaluation

TABLE III
Simulation Parameters

Category	Parameter	Value
EPCglobal UHF Gen2 protocol	Reader-to-Tag Data Rate	54.23 kbps
	Tag-to-Reader Data Rate	256 kbps
	Encoding	FM0
	TRext (Extended Preamble)	1
	T_1	39 μs
	T_2	39 μs
	T_3 (equal to $T_{TagPreamble}$)	70.2 μs
	T_4	73.75 μs
	T_5	39 μs
	$T_{TagPower-Up}$	1500 μs
LBT-based protocol	$T_{SlotTime}$	500 μs
	T_{wait}	5000 μs
	CW	11

The proposed analytical model is validated through an extensive simulation campaign by using an ad-hoc discrete event simulator. The main performance metric of interest is the goodput for a single CR, defined as:

$$goodput\_single\_CR = \frac{goodput}{N - 1} \tag{13}$$

We compare the results for different RAN configurations, by varying the main influencing parameters in the model: (i) number of CRs in the RAN, (ii) BER on the channel, and (iii) size of the UM for the single tag used in this analysis. As for this latter parameter, we consider commercially available tags having a UM size of 128, 256, 512, 1024, 2048, and 4096 bits. Data rates and link timing settings are derived from the EPCglobal Gen2 physical layer specifications (values in Table III). In particular, depending on the coding, the downlink rates (reader-to-tag data rate) range from 27 kbps to 128 kbps, while the uplink data rates (tag-to-reader data rate) are between 5 kbps and 640 kbps.

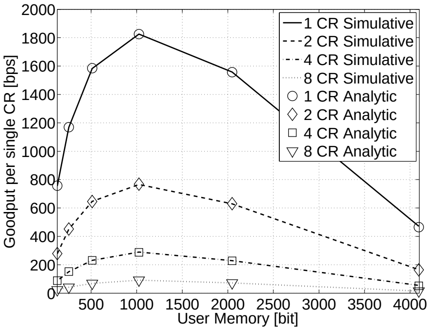


Fig. 5. *Goodput* per CR with BER=10^{-3}: analytic vs. simulative (*whole* UM reading in a single Read command).

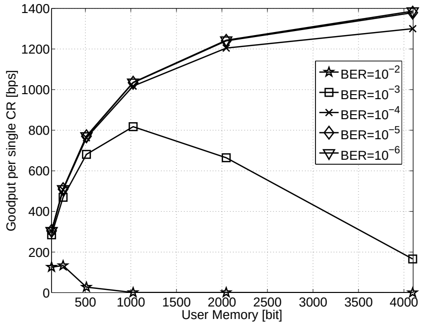


Fig. 6. *Goodput* per CR with variable BER and 2 CRs in the RAN (*whole* UM reading in a single Read command).

To best show the close match between analytic and simulative results, Fig. 5 depicts the sample case where a high BER is considered (i.e., BER=10^{-3}), in saturation conditions. The plots show that the *goodput* for the single CR decreases with the number of CRs in the RAN, whereas it increases for tag UM capacity between 128 and 1024 bits and then it begins to decrease. In fact, the performance is strictly related to the system behavior during the Reading phase. In particular, the overall time duration of this phase is made of two terms: (i) a first fixed term relevant to the transmission of the request message (Read command) and to the reception of the control bits in the tag response message, i.e., CRC field; (ii) a second term associated to the reception of the tag response message payload, which is variable and can span over the whole UM. In an ideal error-free environment, the best solution would be to request the content of the UM in a single operation because this would reduce the overhead caused by the first term cited above. Contrarily, under noisy channel conditions, the error probability intrinsically increases for longer payloads and the tested solution where the *whole* UM is read/written at every access is not the best choice, especially for large UM sizes. This is the reason for the peak in the goodput corresponding to 1024 bits in Fig. 5 with BER=10^{-3}.

This aspect is further investigated in Fig. 6, which shows the achievable system performance for BER values ranging from 10^{-2} to 10^{-6}, in the sample case of 2 CRs (same trends are obtained for different numbers of CRs in the RAN). Given the close match of analytic and simulative results, only analytic results are presented in the remainder of the paper. For lower values of BER the goodput increases, whereas for very high values of BER the goodput goes to zero in almost all cases. Although this behavior is largely expected, observing the impact of the tag UM size gives interesting indications. In particular, for low BER values the goodput increases with the UM size and the best performing UM size is not always 1024 bits. We expect that by splitting a long Reading phase into a number of shorter operations could be advantageous, as under noisy channel conditions the probability of a successful reception of a message decreases with the message size. To investigate on this aspect, we study the optimal number of bits per Reading operation, hereafter called *reading block size*, under different BER conditions. To do this, we consider a tag with UM = 4096 bits, and compute the time for the Reading phase when varying the reading block size. As reported in the Table IV, we observe that for each BER value an optimal reading block size can be found so that a minimum in the corresponding transmission time is obtained. For instance, for BER=10^{-3} the best strategy is to read the UM in consecutive blocks of 512 bits. This gives insightful indications for a well performing RAN design. In fact, adopting the optimal reading block size under different BER conditions significantly improves the goodput per CR. This is observed in Fig. 7 where the goodput is computed under the same conditions of Fig. 6 and the optimal reading block size is used during the Reading phase. The performance improvement is manifest for all values of BER.

TABLE IV

Reading Time [ms] by varying the number of bits per Read operations, for different BER values in a tag with UM size of 4096 bits. The optimal memory block reading sizes for all values of BER are highlighted in grey.

BER	Number bit per Read Operation								
	16	32	64	128	256	512	1024	2048	4096
10^{-2}	720,89	438,57	323,68	348,26	776,40	7000,67	929638,7	2,34E+10	Inf
10^{-3}	402,63	213,03	118,79	72,72	52,012	47,39	62,58	151,34	1085,19
10^{-4}	380,02	198,30	107,54	62,24	39,76	28,84	24,07	23,18	26,31
10^{-5}	377,84	196,89	106,48	61,28	38,70	27,44	21,87	19,22	18,14
10^{-6}	377,62	196,75	106,37	61,19	38,60	27,31	21,67	18,86	17,48
0	377,60	196,73	106,36	61,184	38,59	27,29	21,64	18,82	17,41

As a final observation, a correct RAN design should take into consideration that in real scenarios the network topology and the channel conditions may vary over time. Therefore, a periodic RAN configuration update should be triggered to best configure the communication and adapt the network operations to environmental changes. In particular, the period of time for the update should be chosen depending on how rapidly the environment is changing. In a further analysis we obtained that the optimized Read operation shows good robustness features to BER estimation errors (plots not reported due to length constraints). An initial estimated BER=10^{-3} has been assumed, while variations between BER=$10^{-2.5}$ and BER=$10^{-3.5}$ have been actually considered. In particular, we evaluated the goodput loss per single CR w.r.t. the ideal case where the reading block size is perfectly tuned to the BER variations. The observed goodput loss when the reading block size is set according to the initial estimation of BER=10^{-3} is very low and respectively around 1% and 15%.

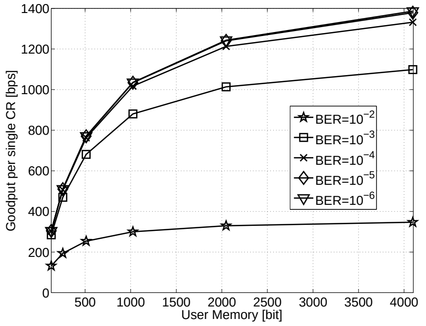


Fig. 7. *Goodput* per CR with variable BER and 2 CRs in the RAN (optimized Read operation).

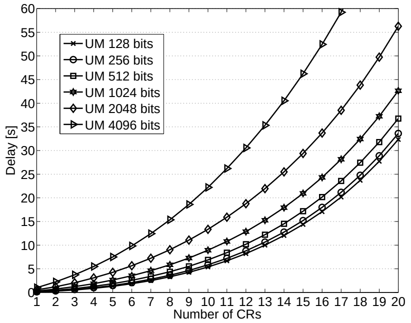


Fig. 8. Optimized *delay* between two consecutive data transmissions from the MR to a CR when BER=10^{-3}.

A. Time interval between two consecutive transmissions

A further result of interest is the evaluation of how the presence of channel errors influences the time interval between two consecutive transmissions correctly received by a CR, hereafter simply called *delay*. This parameter shows the minimum time required for a CR to receive a useful transmission from the MR. This information is especially useful in cases of *Non-delay Tolerant* services. In particular, this parameter, expressed in seconds on the y-axis, is plotted for a number of CRs in the RAN ranging from 1 to 20 and BER=10^{-3}. Fig. 8 shows an increasing delay with the UM size of the tag (optimal settings per Read operation for the considered memory sizes in Table IV are used). The delay trend is an expected result since when sending a message, the whole memory is used; consequently, read and write operations take a longer time. By referring to Fig. 8 the designer can easily determine the *maximum number of CRs to accept in the RAN*, given a tag type and a value of the maximum allowed traffic delay. Noteworthy, these results can be extremely useful to the MR to implement admission policies during the phase of establishment of a RAN. Based on the evaluation of the data storage capacity of the available tags and the type of service to guarantee, the MR can decide to accept only a reduced number of CRs and select the most appropriate modality of data exchange.

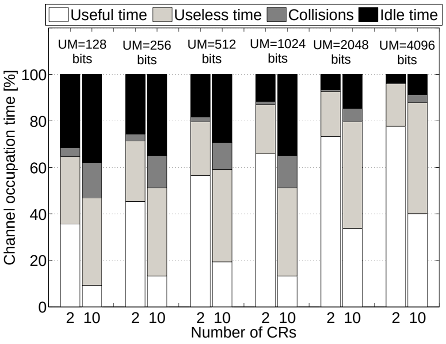


Fig. 9. Channel occupation time for communication contributions in the RAN. Variable UM size and BER=10^{-3}.

B. Channel occupation time contributions

This further analysis provides an in-depth study on the channel occupation time to understand the impact of each term contributing to the overall performance of the tag-based channel. We focus on sample scenarios with BER=10^{-3}. Fig. 9 shows the percentage of time the channel is occupied during the following events: *useful communications, useless accesses, collisions, channel idle time*. Scenarios with low and high numbers of CRs in the RAN (i.e., respectively with 2 or 10 CRs) are compared when varying the UM size (always the optimal size of the memory blocks is considered). From the plots in Fig. 9 one can observe that: (1) for larger values of the UM size, the time the channel is occupied for useful transmissions increases and the time the channel remains idle decreases; (2) the time relevant to useless accesses plays an important role both for low and high number of CRs; (3) the time wasted for collisions is, as expected, higher with 10 CRs, but it does not represent the most ”time consuming” phenomenon. In particular, the useful channel time reaches over 77% and 40% of the total time for 2 and 10 CRs respectively, when UM=4096 bits.

C. Analysis of a multi-tag case with different storage capacity

The last part of our analysis focuses on a RAN with 2 CRs, a population of tags whose maximum storage capacity is 4096 bits, and BER=0. To evaluate, the impact of different memory sizes, according to the scheme defined in Section V.D, the percentage of tags with UM size of either 128, 512, or 1024 bits is varied. In Fig. 10, as expected, the overall goodput per single CR decreases by increasing the number of tags with the smallest UM and for smaller UM sizes of these tags. In case of homogeneous UM sizes (0% case), the goodput is equal to the single tag scenario due to the sequential tag access under saturation conditions. In all other cases, a goodput reduction is caused by the greater impact of the overhead in terms of tag singulation and memory operations. Thus, in a dense reader scenario, with heterogeneous tags, the MRs should carefully select the tags to exploit as virtual communication channel to increase the overall goodput.

VII. DISCUSSION ON PRACTICAL IMPLEMENTATION

The proposed tag-based communications channel is designed to be complaint with the specifications of the standard-

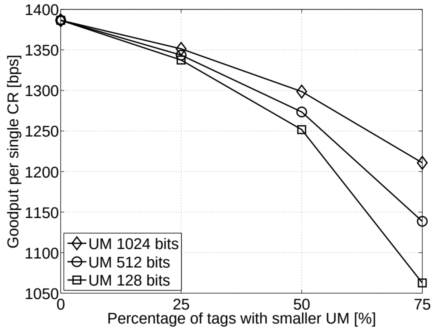


Fig. 10. *Goodput* per CR with a variable number of tags with the smallest UM. The basic scenarios foresee tags with 4096 bits as maximum UM size, 2 CRs and BER=0.

ization bodies addressing the RFID technology. In particular, when considering schemes for the storage of data in RFID tags, the ISO/IEC 15962 and EPCglobal Tag Data Standard specify methods for encoding the User Bank contents. To meet these specifications, the first eight bits of the UM must contain a Data Storage Format Identifier (DSFID) with control information about the used encoding scheme. In particular, the Data Format field indicates the predominating data system in the memory contents. An appropriate Data Format for our proposed tag-based communication channel must be registered under the procedures of ISO/IEC 15961 to guarantee compatibility with other RFID systems.

As for the RFID radio interface, our proposal is fully compliant to the EPCglobal Gen2 protocol [12] and can be seen as an overlay protocol over the legacy reader-tag interaction. Furthermore, to reduce interference among readers, an LBT-based approach is designed so that only very minor variations in the reader firmware are needed to adopt the envisaged anti-collision protocol in legacy systems. Nevertheless, the functions offered by commercial off-the-shelf readers suffer from scarce flexibility and all the capabilities defined by the worldwide adopted EPCglobal LLRP protocol are not supported yet. For instance, the so-called "RF Survey" operation allows to scan the power level on a predefined set of frequencies. The resulting information would allow the reader to evaluate the occupancy of the selected RF channel and, thus, could be exploited to implement the anti-collision procedures as defined by the proposed LBT-based protocol. Unfortunately, this extremely useful function is not implemented by commercial readers of the major RFID manufacturers. Nonetheless, the practical realization of our protocol would just need a firmware update for the readers and absolutely no hardware modification for readers and tags. Off-the-shelf RFID tags, equipped with User Memory of sufficient size, can be exploited to enable the proposed communication channel. Software Defined Radio (SDR) can also be used to prove the feasibility of our solution. Recent RFID literature, e.g., [38] , and [39] have exploited low cost SDR platforms to emulate UHF RFID readers implementing the EPCglobal Gen2 standard. Therefore, objective of our future works will be focused on implementing a real testbed on SDR platforms operating as EPCglobal Gen2 readers and implementing the LBT-based anti-collision protocol as well as the foreseen "RAN establishment and maintenance" functionalities.

VIII. Conclusion

In this paper the behavior of a tag-based "virtual" communication channel that allows RFID readers to communicate in real-time modality by simply using the UM of RFID tags already available on the surrounding objects is analytically studied. In particular, the attention has been put on the achievable goodput and the delay between consecutive data transmissions. A further result obtained is the definition of the optimal *reading block size*, which maximizes the performance and reduces the negative impact of errors on the communication process. Efforts are still required to model the effect of varying traffic patterns. Moreover, CRs-to-MR communications and simultaneous bi-directional communications deserve more attention. Finally, the implementation of a prototype would help in assessing the effectiveness of the proposed solution through real experiments.

Appendix A

Proposition 1 defines the exact collision probability for the LBT-based protocol. It is important to underline that no solutions from the literature (e.g., for 802.11 standard [40]) can be used to model the collision probability for the reference problem. In particular, two main aspects make the specific problem particularly novel: (i) the *backoff time* for a reader is not frozen when the channel is occupied, (ii) a new *backoff time* is extracted by *each* reader every time the channel becomes free again, (iii) we are not interested in the probability of a collision relevant to a single generic slot, but we need to determine the collision probability in a whole contention window.

Proposition 1: The collision probability P_{LBT} for the LBT-based protocol can be expressed as the weighted average of its conditional probabilities $P(C|S_i)$ of a collision event C occurring in slot $i \in [0, CW-1]$ where the weights S_i are the probabilities of each condition occurring, that is the probability of reaching slot i during a channel access:

$$P_{LBT} = \sum_{i=0}^{CW-1} P(C|S_i)P(S_i)$$

Proof: In the LBT-based protocol the backoff counter is not frozen and consequently, every time the channel becomes free, each of the N readers extracts a new random value in the range [0,CW-1]. Given the event S_i of reaching the $i-th$ slot out of the possible CW slots, the collision probability $P(C|S_i)$ in every slot i in the range [0,CW-1] must be computed. One observes that a collision occurs if at least two out of the N readers simultaneously access the considered slot i.

Let us define p_i the conditional probability that a reader accesses the channel in slot i given the event S_i of reaching the $i-th$ slot. Let event A be the case that a node extracted slot i as its backoff and event B be the case that a node did not extract a value among the $i-1$ previous slots. The probability p_i can be computed as $P(A|B) = \frac{P(A \cap B)}{P(B)}$. Considering that event A is actually a subset of B, we have that $P(A \cap B) = P(A)$.

In particular we have $P(A) = \frac{1}{CW}$, as the probability to extract a value out of the CW slots is always constant. Differently, the probability of event B of a node not extracting a value in $i-1$ previous slots is given by the probability that the extracted value is equal to one of the $CW-i$ remaining slots: $P(B) = \frac{CW-i}{CW}$. By substituting the so-defined terms, we obtain that $p_i = P(A|B) = \frac{1}{CW-i}$. We are now ready to define the collision probability in slot i as the probability that at least two out of the N readers access slot i:

$$P(C|S_i) = \sum_{k=2}^{N} \binom{N}{k} p_i^k (1-p_i)^{N-k}$$

To compute the general collision probability in the contention window, we also need to determine the probability of reaching slot i, $P(S_i)$. This is given by the probability of all previous slots being idle. Noteworthy, slot zero is always reached, thus we obtain:

$$P(S_i) = \begin{cases} 1 & i = 0 \\ \prod_{j=o}^{i-1} (1-p_j)^N & i > 0 \end{cases}$$

Finally, the collision probability P_{LBT} in the channel access can be computed as the weighted average of the conditional probabilities $P(C|S_i)$ of a collision event C occurring in slot $i \in [0, CW-1]$, with weights S_i being the probabilities of each condition occurring, that is the probability of reaching slot i during a channel access:

$$P_{LBT} = \sum_{i=0}^{CW-1} P(C|S_i) P(S_i)$$

■

Proposition 2: The average number of slots the channel remains idle during a channel access contention can be determined as the weighted average of the probability that a slot is idle, where the weights are the probability $P(S_i)$ of reaching slot i for the LBT-based protocol as defined in the proof of Proposition 1:

$$Nslots_{idle}(N) = \sum_{i=0}^{CW-1} (1-p_i)^N P(S_i)$$

Appendix B

To better highlight the dependencies on N_{words} we report the explicit computation for the expected time for the Reading and Writing phases. The average time required by the Reading phase can be estimated as: $E[T_R(N_{words})] = T_R(N_{words}) + TimeLost_{R,1} \frac{P_{E,R,1}}{1-P_{E,R,1}} + TimeLost_{R,2}(N_{words}) \frac{P_{E,R,2}}{1-P_{E,R,2}}$ where $P_{E,R,1}$ and $P_{E,R,2}$ are computed as $1-(1-BER)^{L_{p,m}}$ with $L_{p,m}$ being equal to the number of bits reported in Table II for any single message. The other terms are defined as:

$$T_R(N_{words}) = T_{Read} + T_1 + T_{Read\_Response}(N_{words}) + T_2$$

$$TimeLost_{R,1} = T_{E,R,1}$$

$$TimeLost_{R,2}(N_{words}) = T_{E,R,2}(N_{words}) + T_{E,R,1} \frac{P_{E,R,1}}{1-P_{E,R,1}}$$

Note that N_{words} influences the size of the tag *Read_Response* message, whose length is equal to $33 + 16 \cdot N_{words}$ bits, according to the standard [12]. Based on the size of the *Read_Response* message, also $T_{E,R,2}(N_{words})$ is determined (see Table II). Concerning the *Writing* phase, we recall that a reader can update the UM writing a single 16-bit word at a time. Thus, we define with $T_{WriteOperation}$ the time required to write a single 16-bit word:

$$T_{WriteOperation} = T_{Req\_RN} + T_1 + T_{new\_RN16} + T_2 + T_{Write} + T_5 + \\ + T_{Write\_Response} + T_2$$

To write N_{words} on the UM of a tag, the average time for the overall Writing phase is:

$$E[T_W(N_{words})] = N_{words} \cdot E[T_{WriteOperation}]$$

where the expected time $E[T_{WriteOperation}]$ can be computed by means of equation (11):

$$E[T_{WriteOperation}] = T_{WriteOperation} + TimeLost_{W,1} \frac{P_{E,W,1}}{1-P_{E,W,1}} + \\ + TimeLost_{W,2} \frac{P_{E,W,2}}{1-P_{E,W,2}} + TimeLost_{W,3} \frac{P_{E,W,3}}{1-P_{E,W,3}} + \\ + TimeLost_{W,4} \frac{P_{E,W,4}}{1-P_{E,W,4}}$$

where the single $TimeLost$ terms are computed through equation (10), and the error probability terms again are computed as $1-(1-BER)^{L_{p,m}}$ with $L_{p,m}$ equal to the bit values reported in Table II for any single message.

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