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RFID-based smart parking management system

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ABSTRACT

In this paper, the adoption of passive Radio Frequency Identification (RFID) tag-to-tag communication paradigm within the context of a smart parking system is evangelised, in terms of achieving improved energy-efficiency and operational effectiveness. To demonstrate that the joint routing and RFID readers' transmission power minimisation problem is studied, considering tag-to-tag communication. The superiority of the proposed framework against conventional direct RFID reader-tag communication is demonstrated in terms of: (i) reduction of RFID readers' transmission power to the minimum required to guarantee connectivity, and (ii) expansion of RFID reader's coverage area towards communicating with more distant tags, otherwise unreachable through direct communication.

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1. Introduction

The Internet of Things (IoT) paradigm is gaining particular interest for industrial and commercial applications, as it enables connectivity among objects and persons, envisioning intelligent and context-aware environments like smart cities, smart monitoring and validation systems, etc. [1]. Radio Frequency Identification (RFID) technology supports the identification of objects and people, being one of the key enabling IoT technologies. RFID technology – under its various forms – presents high market penetration and has been utilised in numerous application areas, e.g. transportation and logistics management, smart parking systems (SPS), waste management, animal husbandry, patients monitoring, oil drilling, quality control, asset tracking, etc. [2,3].

The main components of an RFID network are: (a) the RFID reader, which emits electromagnetic waves and activates (b) the RFID tags, which backscatter signals with tags' unique related information to the reader. RFID tags are classified in

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active, passive and semi-passive tags. Active and semi-passive RFID tags embed a radio signal transceiver and an internal power source. Thus, they can be activated regardless of the presence of an RFID reader in proximity and provide greater operating range compared to passive RFID tags. However, they present high cost and important environmental limitations due to the presence of battery/capacitor, i.e. big size and their high transmission power. On the other hand, passive RFID tags emerge as the most energy-efficient, inexpensive and environmentally friendly solution, due to their low backscatter power, battery-free nature, low price and small and flat size [4].

The focus of this paper is on the design, analysis and evaluation of a passive RFID-based framework in the context of a SPS, where RFID technology is adopted for: (a) vehicles' validation while entering and exiting the parking area, (b) identification and localisation of vehicles while being parked and (c) smart parking space management. Most of the existing SPSs, either need expensive equipment, infrastructure and deployment or they are semi-autonomous asking for human actions [5,6]. The use of RFIDs has already been promoted as the most cost-effective solution with satisfactory achievements in SPSs [7]. RFID in SPS has been mainly used for check-ins and check-outs of the passing vehicle in the parking area, where vehicles are equipped with e-pass cards with active RFID tag [8]. Each vehicle entering the parking area has a unique identification number which can be paired with its number of license plates and the barriers open only if the vehicle is recognised as registered [9]. Moreover, the authors in [10] have combined RFID technology with wireless sensors towards collecting information about the occupancy state of parking spaces and directing the drivers to the nearest vacant parking lot. Except for vehicles' validation in the entrance and exit of a parking area, RFID technology has been utilised for vehicles' localisation while they are parked via exploiting the Time Difference of Arrival and Received Signal Strength measurements [11].

In the case of an infrastructure based on passive RFIDs to support smart parking management, a reader (or a set of readers in case of multiple readers) initiates communication via a radio signal, strong enough to enable the tag to 'answer' the reader with a return radio signal carrying information regarding the item to which it is attached. In such an environment, key research and engineering aspects are associated with the topology coverage and control, power management, interference mitigation and energy efficiency.

In this article, it is assumed that RFID readers have limited energy resources, while passive RFID tags are not equipped with battery at all. Both for energy efficiency and for interference management and control purposes, RFID reader's transmission power is considered as a limited resource that needs to be controlled [12,13], and as such is efficiently determined by the proposed framework, while passive RFID tags are assumed to reflect with their maximum feasible reflection power. Given the above setting and considerations, the problem of jointly selecting a communication route among a source – destination set of RFID readers while determining the minimum necessary RFID reader's/source's transmission power becomes of paramount importance. The latter becomes even more challenging while guaranteeing: (a) the connectivity of the communication route and (b) the fulfilment of nodes' QoS prerequisites (expressed via a minimum received power and target signal-to-noise ratio ((SNR)). This problem is considered and analysed in this paper under two different communication paradigms (a) single-hop communication, where each tag communicates directly with the RFID reader, and (b) multi-hop communication, where tag-to-tag communication is introduced for the intermediate nodes of a communication route. It should be noted that to the best of our knowledge, no prior work has been performed in the field of power control towards achieving energy-efficiency especially in multi-hop (i.e. tag-to-tag communication) passive RFID networks.

Specifically, the basic contributions of our proposed approach and framework in this paper are summarised as follows:

(1) The concept of tag-to-tag communication in a passive RFID network is introduced and applied in an SPS application towards collecting the information of the parked vehicles. The benefits of tag-to-tag communication are illustrated and compared to direct communication, in terms of RFID reader's power saving, ensuring connectivity among tags and expanding RFID reader's coverage area. Tag-to-tag communication in passive RFID networks differs fundamentally from traditional multi-hop networks due to the power reflection characteristic by the passive RFID tags and not retransmission of the original received power.
(2) The joint problem of routing and RFID reader's power minimisation is formulated and solved. The optimal communication route and RFID reader's transmission power is determined via adopting a shortest path algorithm. The proposed analysis shows the applicability of tag-to-tag communication in passive RFID networks, as well as its benefits.
(3) Detailed numerical results are provided that demonstrate the performance and operational effectiveness and efficiency of the proposed framework, along with its flexibility and adaptability under various scenarios. A detailed comparative evaluation among the tag-to-tag and direct communication is provided illustrating the superior performance of the first communication pattern in terms of RFID reader's power saving and coverage area expansion.

The outline of this paper is as follows: in Section 2 the architecture of the proposed SPS is presented and the usage of RFID technology within this context is explained. In Section 3, the two passive RFID network communications paradigms within the environment of a SPS are studied, i.e. direct reader to tag communication and passive tag-to-tag communication. The problem of routing and RFID reader's power minimisation is formulated in Section 4.1 and its corresponding solution is obtained. The routing and power minimisation (RPM) algorithm is introduced in Section 5. Detailed numerical results are presented in Section 6 towards evaluating the proposed framework, showing its energy-efficient attributes and RFID reader's battery life expansion capability, as well as indicating the benefits of adopting tag-to-tag communication in passive RFID networks. Finally, Section 7 concludes the paper.

2. SPS's architecture

In this section, the architecture of an automated unmanned SPS is described. The SPS consists of: RFID readers, passive RFID tags, barriers, retractable bollards, Wi-Fi spots and a database. An RFID reader controls the entrance and exit of the vehicles from the parking area. The considered parking areas can be an open parking space of an airport or a campus, etc. Parking users can be divided into (a) registered users that have already acquired a parking license card and (b) temporary users, who get parking license cards from the card recycling machine at the entrance of the parking. Both types of cards are equipped with a passive RFID tag.

At the entrance and exit of the parking area, an RFID reader activates the passive RFID tag on the card of the driver entering or exiting the area and reads the tag's information, which contains a unique identification number for verification purposes. If the passive RFID tag's identification number is verified, then the barrier opens. Considering the entrance procedure, the parking space which is assigned the same identification number with the passive RFID tag, will be distributed to the entering vehicle and the entry time will be saved. The barrier opens and the vehicle is directed to each assigned parking lot.

RFID readers are placed at the two sides of each parking array, in order to constantly monitor the vehicles and report the occupancy of the parking lot and the identity of the vehicle. The collected information from the passive RFID tags is reported by the RFID readers via Wi-Fi connection to the database for further exploitation, i.e. parking space management, automated tickets to offender drivers, vehicles validation, parking area security, etc. However, the latter is beyond the scope and analysis of this paper. The constant monitoring of the vehicles in the parking area is of great importance mainly due to security related issues, as well as for parking space management purposes.

Currently, the main technique that it is commercially used for vehicles' monitoring is the usage of Optical Character Recognition (OCR) cameras [14]. Specifically, employees of the parking company patrol with parking company's private cars the whole parking area and take pictures of parked vehicles' license plates with an OCR camera. The number plate is converted in text format and act as input to the database. If the vehicle is not verified, the employee gives a penalty ticket to the driver. However, this approach is not automated and it is very expensive due to the necessary equipment, i.e. cameras, private vehicles, etc., the salaries of the employees and the gas that is spent for patrolling. Therefore, the usage of RFID

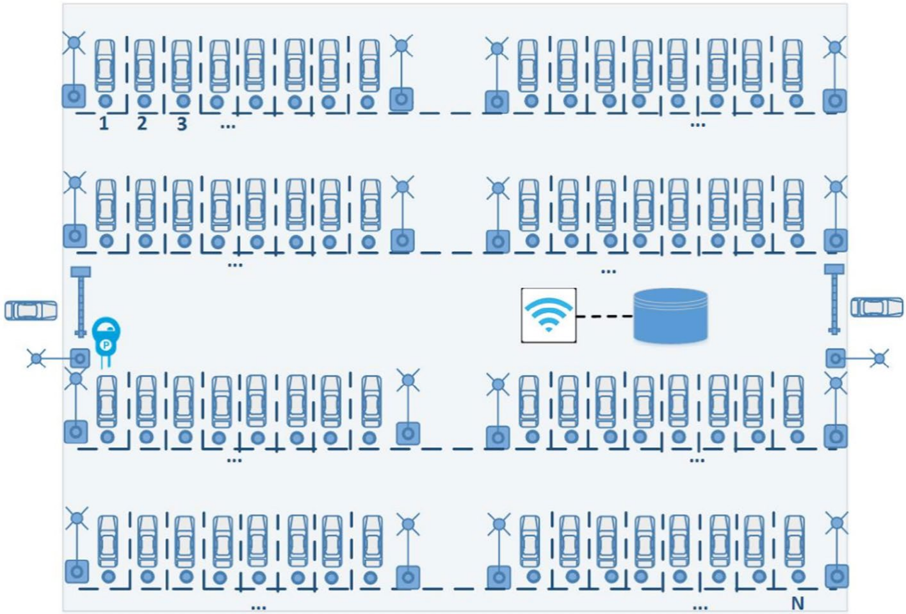

Figure 1. SPS's architecture.

technology will reduce significantly the operation cost. The overall SPS architecture is presented in Figure 1.

As mentioned before, our goal in this paper is that given the above-described SPS architecture to propose a routing and RFID readers' power minimisation approach towards (a) extending the battery life of the RFID readers in the sides of the parking area and (b) guaranteeing the constant monitoring of the parked cars via their attached passive RFID tags.

3. Communication paradigms in Passive RFID Networks

In this section, the two communication paradigms that may emerge in a passive RFID network are discussed in more detail. Let us denote the set of RFID readers established at the two sides of each parking array being responsible for continuous vehicles' monitoring as: $R = \{R_1, R_2, \ldots, R_r, \ldots, R_{|R|}\}$. The set of passive RFID tags in the parked vehicles is denoted as: $T = \{T_1, T_2, \ldots, T_t, \ldots, T_{|T|}\}$. The overall set of RFID nodes – readers and tags – within the RFID network in the parking area is $N = R \cup T$. Each node is equipped with a directional antenna that can provide various beamwidth, i.e. horizontal angular variations θ_{beam}, translated to different coverage areas. Let G_{R_r} and G_{T_t} denote RFID reader's R_r and passive RFID tag's T_t directional antenna's gain, respectively. Directional antenna's gain depends on the beamwidth θ_{beam}, while for various values of θ_{beam} the corresponding specific values of G_{R_r} and G_{T_t} are empirically determined based on antenna's technical characteristics [15]. Let $\mathcal{P}_{R_r} = [0, P_{R_r}^{Max}]$ denote the feasible set of RFID reader's transmission power P_{R_r}, where the upper bound of RFID reader's transmission power $P_{R_r}^{\mathrm{Max}}$ depends on physical and technical limitations. Furthermore, let $\mathcal{P}_{T_t} = [0, P_{T_t}^{\mathrm{Max}}]$ denote the set of passive RFID tag's reflection power P_{T_t}, where the upper bound is determined based on the previous hop(s) transmitted/reflected power.

3.1. Reader to tag communication case

In the single hop scenario or equivalently the direct type of communication, the RFID reader activates directly each one of the passive RFID tags that reside within its coverage area. The RFID reader R_r transmits with power P_{R_r} and the passive RFID tag answers with reflection power $P_{T_t}^{\mathrm{Max}}$.

$$P_{T_t}^{\mathrm{Max}} = P_{R_r} \cdot G_{R_r} \cdot G_{T_t} \cdot K_{T_t} \left(\frac{\lambda}{4\pi d} \right)^2 \quad (1)$$

where K_{T_t} is the backscatter gain of passive RFID tag T_t and the factor $\left(\frac{\lambda}{4\pi d} \right)^2$ determines the free space path loss [16]. In the direct reader to tag communication case, the maximum distance of the reader for reading tags is predetermined given the hardware characteristics of the reader and the passive RFID tags, as well as the maximum RFID reader's transmission power $P_{R_r}^{\mathrm{Max}}$ and cannot be further extended.

3.2. Tag-to-tag communication case

Towards ensuring the connectivity and feasibility of a passive RFID network, in an energy-efficient and effective manner, the paradigm of passive tag-to-tag communication has been introduced in [17]. The authors in [17] demonstrated in hardware the feasibility of a system where passive tags communicate with each other. A multi-hop passive RFID network of objects, i.e. readers and passive RFID tags, where passive tags may also communicate with each other, is emerging as a promising energy-efficient alternative. The authors in [18] propose an optimal link cost multipath routing protocol for passive RFID tag-to-tag networks by using modulation depth as the link cost. To the best of our knowledge, no prior work has been performed in the field of power control towards achieving energy-efficiency in multi-hop (i.e. tag-to-tag communication) passive RFID networks.

In this subsection, the passive tag-to-tag communication paradigm is introduced and compared to the direct type of communication case, among RFID nodes in terms of RFID reader's power saving and correspondingly the prolongation of its battery life. Tag-to-tag communication in passive RFID networks essentially differs from traditional multi-hop networks, e.g. ad-hoc or sensor networks, due to the power reflection by the passive RFID tags and not retransmission of the original received power, which in turn results in additional power attenuation within a multi-hop communication route. Therefore, topology control and routing algorithms proposed in ad-hoc or sensor networks cannot be easily extended and/

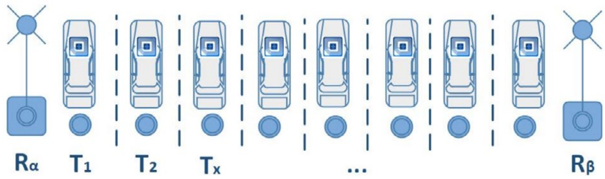

Figure 2. RFID-connected parking array topology.

or adapted in passive RFID networks. As it is shown in the rest of this article, the main benefits of adopting tag-to-tag communication in the passive RFID network deployed in the examined parking area include: (i) the reduction of RFID readers' transmission power P_{R_r} to the minimum required transmission power to guarantee connectivity and collection of information through specific/targeted tags assigned to each parked vehicle, and (ii) expansion of RFID reader's coverage area towards reaching and communicating with more distant passive RFID tags/vehicles, otherwise unreachable through single hop (direct) communication.

In the following, a specific use case scenario is examined towards obtaining an intuitive understanding of the main factors that influence reader's/source's transmission power and its corresponding power savings under the different types of communication, i.e. direct and multi-hop. A simplified passive RFID network topology is considered as presented in Figure 2.

Let us consider that passive RFID tag T_x is attached to the parking license card assigned to the parked vehicle and reader R_a activates T_x. The passive RFID tag T_x reflects its information to the destination reader R_β, which accumulates information also from other tags in the rest of the parked vehicles in the parking area to be reported via Wi-Fi connection to the database for further processing. Therefore, the communication route is $R_a \to T_x \to R_\beta$. At this point, it should be noted that each passive RFID tag and RFID reader is characterised by a power threshold P_{TH}, which denotes the minimum power required for the passive RFID tag to be activated and reflect the signal to the next passive RFID tag, or to the destination RFID reader. Similarly, for simplicity and without loss of generality, P_{TH} is also considered as the minimum power in order the receiver RFID reader to decode the signal of an RFID tag.

3.3. Direct versus multi-hop communication analysis

For simplicity in the presentation, the first part, i.e. $R_\alpha \to T_x$, of the complete communication route ($R_a \to T_x \to R_\beta$) is studied in the following analysis. In the case that there exist additional passive RFID tags (e.g. T_1, T_2 as in Figure 2) from other parked vehicles in the parking array $R_\alpha \to T_x$, the following question arises:

Which type of communication, i.e. direct or multi-hop, among $R_\alpha \to T_x$ results in lower transmission power P_{R_α}, while in both cases the received power at passive RFID tag T_x is at least equal to P_{TH}?

Towards addressing and answering the aforementioned question, each type of communication (i.e. direct versus multi-hop) is separately studied and then they are compared against each other.

Considering the multi-hop communication scenario between reader R_α and passive RFID tag T_x, the communication route $R_\alpha \to T_1 \to T_2 \to T_x$ is examined, where for simplicity in this example, equal distance hops are assumed, i.e. $D/3$, where D is the distance between R_α and T_x. The assumption of hops of equal distance stems from the topology presented in Fig. 2, i.e. the vehicles in a parking array are parked in approximately equal distance among each other. The attenuation of the power with respect to the distance in the communication route $R_\alpha \to T_1 \to T_2 \to T_x$ is presented in Figure 3. Based on Equation (1), which can be applied for the three hops (i.e. $R_\alpha \to T_1$, $T_1 \to T_2$, $T_2 \to T_x$) and considering that the desired received power at T_x is P_{TH}, then the transmission power of reader R_a is given as follows:

$$P_{R_{\alpha_{multi-hop}}} = \frac{P_{TH}}{G^6K^3} \cdot \left(\frac{4\pi \frac{D}{3}}{\lambda}\right)^6 \qquad (2)$$

On the other hand, considering the direct communication among R_α and T_x, the corresponding reader's R_α transmission power is:

$$P_{R_{\alpha_{direct}}} = \frac{P_{TH}}{G^2K} \cdot \left(\frac{4\pi D}{\lambda}\right)^2 \qquad (3)$$

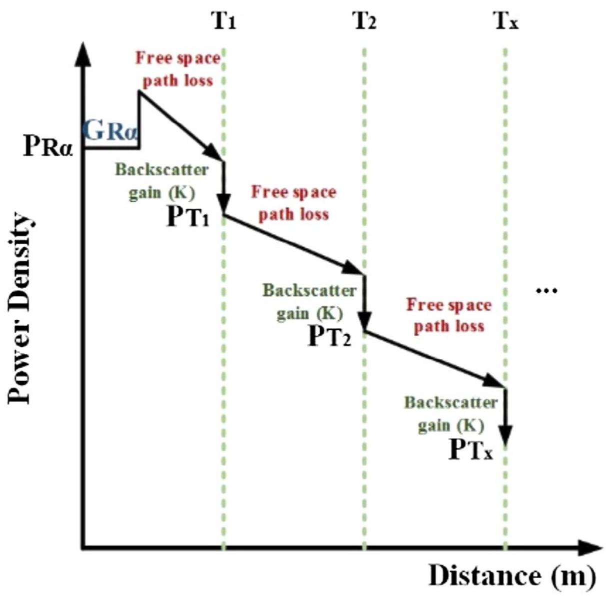

Figure 3. Attenuation of RFID readers' transmission power & passive RFID tags' reflection power.

Comparing reader's R_α transmission power P_{R_α} under the two different types of communication, it is concluded that the examined multi-hop scenario is better than the direct communication, i.e. $P_{R_{\alpha_{multi-hop}}} \prec P_{R_{\alpha_{direct}}}$, if and only if $D \prec \frac{\lambda G \sqrt{K3}\sqrt{3}}{4\pi}$.

Based on the above-presented use case scenario, it is observed that there exists a correlation of the distance between two RFID nodes and the number of hops in their interconnecting communication route. Based on this correlation, the optimal communication route among two RFID nodes, in terms of reader's/source's power saving and optimal number of hops in the interconnecting straight-line, can be determined, as it will be shown later in Section 4.

In a nutshell it is noted that power control combined with tag-to-tag communication in passive RFID systems can contribute to:

(1) maintain the connectivity among passive RFID tags, even if they reside in areas non-covered directly by the RFID readers' range,
(2) reduce RFID readers' transmission power, thus extending their battery life and concluding to a 'green' passive RFID system,
(3) mitigate the reader-to-reader interference and eliminate reader-to-tag interference within the overall RFID system, thus concluding to a more energy-efficient solution.

4. Routing and RFID Reader's Power Minimisation Problem

In this section, our goal is to propose an energy-efficient framework in order to guarantee the collection of information by the side RFID readers from the passive RFID tags in the parked vehicles in each parking array. A routing and RFID reader's power minimisation problem is formulated (Section 4.1).

4.1. Problem formulation and solution

Let us consider the passive RFID network deployed in one parking array consisting of the two side RFID readers, i.e. R_α (source) and R_β (destination) and the intermediate passive RFID tags of the parked vehicles $T_1, T_2, ..., T_x, ...$, as presented in Figure 1. The multi-hop passive RFID network is modelled as a graph $G = (V, E)$, where V is the set of nodes (vertices), i.e. RFID readers and passive RFID tags, and E denotes the set of links $i \in E$ between two nodes in the passive RFID network. Assume a communication route $\mathcal{R}: R_\alpha \rightarrow T_x \rightarrow R_\beta$ between a source RFID reader R_α and a destination RFID reader R_β collecting information from a specific passive RFID tag T_x, which possibly consists of multiple links (hops) i among the intermediate passive RFID tags. The communication route $\mathcal{R}$ can be written as a directed path, i.e. $\mathcal{R} = \{j = R_\alpha, T_1, T_2, \ldots, T_x, \ldots, R_\beta\}, \mathcal{R} \in \mathcal{R}_{\alpha x \beta}$, where $\mathcal{R}_{\alpha x \beta}$ is the set of all feasible paths $\mathcal{R}$ connecting R_α, T_x, R_β triple of RFID nodes. It should be noted that for simplicity in the presentation it is assumed that all nodes share a common channel using TDMA without spatial reuse/interference. Thus, each node transmits in its own unique time slot. As part of our future work, the proposed approach can be extended towards considering interference within the RFID system. In the latter case, allowing spatial reuse/interference to the communication routes of the RFID system can conclude to further improvement of system's energy-efficiency, while the need for power control at the RFID tags may arise as well.

For a link $i \in E$, the SNR measured at the destination node R_β is given by:

$$\gamma_\beta = \frac{P_{rec.,\beta}}{N_0 B} = f\left(P_{R_\alpha}\right) \tag{4}$$

where N_0 is the power spectral density of the Additive White Gaussian Noise and B denotes the system's bandwidth. The received power at the destination RFID reader R_β is denoted as $P_{rec.,\beta}$ and based on Equation (1) is given as follows.

$$P_{rec.,\beta} = P_{R_\alpha} \prod_{j=R_\alpha}^{R_\beta} \left[G^2 K \left(\frac{\lambda}{4\pi d_{j,j+1}} \right)^2 \right] \tag{5}$$

where P_{R_α} denotes the transmission power of the source R_α, G is the directional antenna's gain of an RFID node (either tag or reader) in the communication route $\mathcal{R} = \left\{ j = R_a, T_1, T_2, ..., T_x, ..., R_\beta \right\}$, $\mathcal{R} \in \mathcal{R}_{\alpha x \beta}$, K is the backscatter gain of each RFID tag/reader and $d_{j,j+1}$ denotes the distance between two successive nodes, i.e. $j, j+1$, in the communication route $\mathcal{R} \in \mathcal{R}_{\alpha x \beta}$.

The problem of jointly selecting a communication route and determining the minimum necessary transmission power of the source RFID reader towards reading the information of T_x passive RFID tag of the parked vehicle in the corresponding parking lot, can be expressed as follows.

$$\min_{P_{R_\alpha} \in \left[0, P_{R_\alpha}^{Max}\right]} P_{R_\alpha} \tag{6a}$$

$$s.t. \frac{P_{rec.,\beta}}{N_0 B} \geq \gamma_{target} \tag{6b}$$

$$\mathcal{R} \in \mathcal{R}_{\alpha\beta} \tag{6c}$$

$$P_{rec.,\beta} \geq P_{TH} \tag{6d}$$

The constraint (6b) represents the QoS prerequisites of the receiver RFID reader R_β, within the communication route $\mathcal{R} = \left\{ j = R_a, T_1, T_2, \ldots, T_t, \ldots, R_\beta \right\}$. It should be noted that if the SNR measured at the destination RFID reader R_β is above the targeted value γ_{target} (i.e. constraint (6b) holds true) and due to the attenuation of the power within the communication route $\mathcal{R} \in \mathcal{R}_{\alpha\beta}$, it is ensured that the QoS prerequisites of all intermediate nodes (i.e. passive RFID tags) j will also be fulfilled (assuming that all intermediate nodes have the same targeted value γ_{target}). The constraint (6c) states that the selected communication route $\mathcal{R}$ connects source RFID reader R_α and destination RFID reader R_β, while constraint (6d) ensures that the received power at the destination RFID reader R_β is above threshold P_{TH}, thus the received signal can be decoded at the receiver and not considered as interference.

Via observing constraint (6b) of the optimisation problem (6a)–(6d), the following proposition is stated.

Proposition 1: The strict equality of constraint (6b) is always satisfied by the optimal solution of optimisation problem (6a)–(6d).

Proof: Towards proving the above proposition, the reductio ad absurdum method is adopted. Let $\mathcal{R}^*$ be the optimal communication route between source RFID reader R_α and destination RFID reader R_β and $P^*_{R_\alpha}$ be the optimal transmission power of source RFID reader R_α. Assume that the inequality $\frac{P_{rec.,\beta}}{N_0 B} \succ \gamma_{target}$ holds true. Due to the monotonicity of the linear function $f\left(P_{R_\alpha}\right)$ and based on Equation (4), the transmission power $P^*_{R_\alpha}$ can be reduced so that the equality of constraint (6b) holds true, i.e. $\frac{P_{rec.,\beta}}{N_0 B} = \gamma_{target}$. Via reducing the transmission power $P^*_{R_\alpha}$, this corresponds to reducing the objective function of optimisation problem (6a)–(6d), while constraints (6b)–(6d) still hold true. It is ensured that the constraint (6d) holds true after decreasing the transmission power $P^*_{R_\alpha}$, due to the fact that achieving γ_{target} with the received power $P_{rec.,\beta}$ at destination node R_β guarantees that $P_{rec.,\beta}$ is at least equal to the threshold P_{TH}, otherwise receiver's QoS prerequisites expressed via γ_{target} could not be fulfilled. Based on the above, $\mathcal{R}^*$ and $P^*_{R_\alpha}$ are not the optimal communication route and source's R_α transmission power of (6a)–(6d), respectively. □

Based on Proposition 1, the optimisation problem (6a)–(6d) can be rewritten as follows.

$$\min_{R \in R_{\alpha\beta}} \left\{ \gamma_{target} \cdot N_0 \cdot B \cdot \left(\frac{4\pi}{\lambda}\right)^2 \frac{1}{\prod_{j=R_\alpha}^{R_\beta} \left[G_j G_{j+1} K_j \left(\frac{1}{d_{j,j+1}}\right)^2\right]} \right\} \tag{7}$$

The optimisation problem (7) reduces to a pure routing problem towards determining the optimal communication route $\mathcal{R}^*$ among source RFID reader R_α and destination RFID reader R_β, where $\mathcal{R}^* \in \mathcal{R}_{\alpha\beta}$. Considering the optimal communication route $\mathcal{R}^*$ determined in optimisation problem (7), the corresponding optimal transmission power $P^*_{R_\alpha}$ of the source RFID reader R_α is determined based on Proposition 1 and Equation (4), as follows:

$$P^*_{R_\alpha} = \gamma_{target} \cdot N_0 \cdot B \cdot \left(\frac{4\pi}{\lambda}\right)^2 \frac{1}{\prod_{j=R_\alpha}^{R_\beta} \left[G_j G_{j+1} K_j \left(\frac{1}{d_{j,j+1}}\right)^2\right]} \tag{8}$$

Towards solving optimisation problem (7), it is observed that the goal of minimising its objective function $\gamma_{target} \cdot N_0 \cdot B \cdot \left(\frac{4\pi}{\lambda}\right)^2 \frac{1}{\prod_{j=R_\alpha}^{R_\beta}\left[G_j G_{j+1} K_j \left(\frac{1}{d_{j,j+1}}\right)^2\right]}$ is equivalent to minimising $\prod_{j=R_\alpha}^{R_\beta}\left(\frac{d_{j,j+1}^2}{G_j G_{j+1} K_j}\right)$, $\mathcal{R} \in \mathcal{R}_{\alpha\beta}$, as follows:

$$\min_{\mathcal{R}\in\mathcal{R}_{\alpha\beta}} \left\{ \prod_{j=R_\alpha}^{R_\beta} \left(\frac{d_{j,j+1}^2}{G_j G_{j+1} K_j} \right) \right\} \tag{9}$$

due to the fact that γ_{target}, N_0, B and λ are constant values for the optimisation problem (7). Moreover, the considered RFID system has $|N|$ number of nodes, i.e. RFID readers and passive RFID tags, thus the total number of links in an optimal communication route $\mathcal{R}^* \in \mathcal{R}_{\alpha\beta}$ can be at most $|N| - 1$. Therefore, the optimisation problem (9) can be addressed via examining in the worst case all possible values of $|R^*|$, i.e. $2, \ldots, |N|$. At this point, it should be noted that the complexity of the above search can be reduced due to the usage of directional antennas by the nodes, as well as nodes' limited coverage area. Therefore, given a source RFID reader R_α and destination RFID reader R_β, a smaller number of links than $|N| - 1$, will be feasible to create a communication route $\mathcal{R}^* \in \mathcal{R}_{\alpha\beta}$, as presented in the example coloured area of Figure 4, including feasible links for R_α, R_β communication.

The optimisation problem (9) can be solved via adopting the concept of shortest path algorithm [19] after appropriately rewriting the problem, as follows.

$$\min_{\mathcal{R}\in\mathcal{R}_{\alpha\beta}} \left\{ \sum_{j=R_\alpha}^{R_\beta} \log \left(\frac{d_{j,j+1}^2}{G_j G_{j+1} K_j} \right) \right\} \tag{10}$$

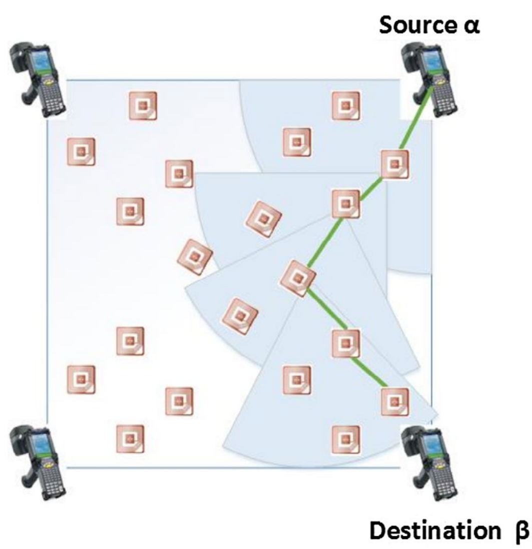

Figure 4. Communication route R among source node α and destination node β via utilising directional antennas.

It should be noted that the above alternative expression (10) is equivalent to the optimisation problem (9), due to the fact that $log(\cdot)$ is a strictly increasing function.

5. RPM Algorithm

In this section, a RPM algorithm is presented towards determining the optimal communication route $\mathcal{R}^* \in \mathcal{R}_{\alpha\beta}$ and source RFID reader's R_α transmission power $P^*_{R_\alpha}$ of optimisation problem (10). The concept of finding the shortest path among source RFID reader R_α and destination RFID reader R_β is adopted via utilising $w(j, j+1) = \log\left(\frac{d^2_{j,j+1}}{G_j G_{j+1} K_j}\right)$ as link label, i.e. weight. However, the use of the logarithmic function may produce negative values, thus Bellman-Ford's shortest path algorithm [19], dealing also with negative link labels, is adopted as follows.

Routing & Power Minimization (RPM) Algorithm

A. Routing Part (G, w, R_α)

1. Initialization

For each vertex $v \in G.V$, where $G.V = R \cup T$

$v.d = \infty$

$v.\pi = None$

$R_\alpha.d = 0$

2. Relaxation for each adjacent vertex

Relax(u,v,w)

For each vertex $v \in G.Adj[u]$

If $v.d \succ u.d + w(u,v)$

$v.d = u.d + w(u,v)$

$v.\pi = u$

3. Report negative-weight cycle existence

For (u,v) in E

If $v.d \succ u.d + w(u,v)$

Return FALSE

Return $\mathcal{R}^*$

B. Power Minimization Part ($\mathcal{R}^*$)

Given the optimal communication route $\mathcal{R}^*$, determine the optimal power $P_{R_\alpha}^*$ based on equation (8).

It is well known that the complexity of the Bellman-Ford is $O\left(|N|^3\right)$, where $|N|$ is the number of nodes (i.e. RFID readers and passive RFID tags). An improved version of the Bellman–Ford algorithm for large-scale topologies is proposed in [19] with a worst-case complexity of $O\left(|N|^3 / \log |N|^3\right)$. The algorithm proposed in [19] is adopted also for implementing the RPM algorithm, which further implies that RPM algorithm's computational complexity is $O\left(|N|^3 / \log |N|^3\right)$.

6. Numerical results

In this section, we provide some numerical results illustrating the operation, features and benefits of the proposed framework and the RPM algorithm. Initially, in

Section 6.1, we focus on the operational performance achievements of our proposed approach by providing a detailed comparative evaluation between the multi-hop and single-hop communication [8–11] approach in a passive RFID-enabled SPS, with respect to the metric of RFID reader's transmission power. Then, in Section 6.2, we demonstrate the potential expansion of RFID reader's coverage area that can be obtained via adopting tag-to-tag communication, without incurring the cost associated with increasing the max power of the reader or provisioning additional readers. Based on the obtained results, it is clearly demonstrated that the RFID reader is able to reach and communicate with more distant passive RFID tags/vehicles, which would be unreachable through single-hop (i.e. direct) communication.

Throughout our study, we consider an SPS as presented in Figure 1, deployed in a *300* m × *90* m two-dimensional area. Based on the typical dimensions of a vehicle, a total number of $|T| = 840$ vehicles can potentially reside within the examined parking area. The maximum available power of each RFID reader is $P_{R_r}^{Max} = 10$ W, where $R_r \in R$. The RFID reader's R_r, $R_r \in R$ and passive RFID tag's T_t, $T_t \in T$ directional antenna's gain, i.e. G_{R_r} and G_{T_t}, respectively, range in the interval [10,15] dBi based on the device's different hardware and technical characteristics. The range of the backscatter gain values K_{T_t} of each passive RFID tag T_t, $T_t \in T$ is 11–25% [20]. We consider an HF (High Frequency) passive RFID network, where $f = 13.56$ MHz. The minimum power in order the receiver RFID reader to decode the signal of an RFID tag is $P_{TH} = -15$ dBm. Moreover, we performed a detailed Monte Carlo analysis over 10,000 different topologies both in the case of multi-hop and single-hop communication for all the presented scenarios and numerical results.

6.1. Power efficient multi-hop communication

In this subsection, as explained before, the main goal is to discuss and quantify the benefits, in terms of RFID reader's power saving, obtained by tag-to-tag

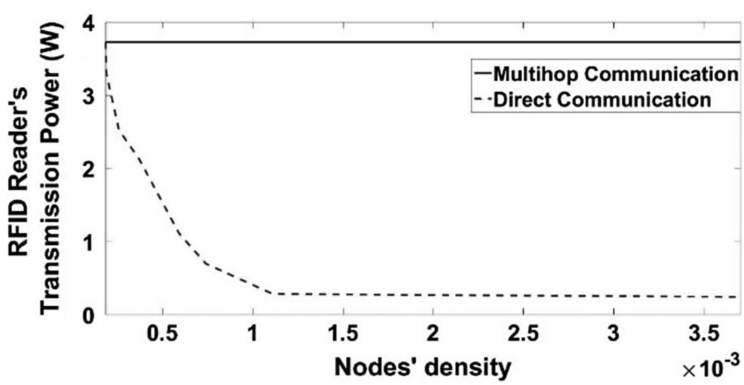

Figure 5. RFID reader's transmission power as a function of the nodes' density for the multi-hop and direct communication.

communication through a comparative performance evaluation against the direct communication paradigm.

Figure 5 presents RFID reader's transmission power as a function of nodes' density within the examined SPS, considering multi-hop and direct communication. Specifically, a communication path R_α, T_x, R_β is considered, where the RFID reader R_α transmits with P_{R_α} transmission power, activates the passive RFID tag T_x and tag's T_x information is collected by the RFID reader R_β. The results clearly reveal the superiority of the multi-hop communication versus direct communication in terms of RFID reader's power saving. The average percentage of multi-hop communication's power saving is 52.9% compared to the direct communication. Furthermore, as the nodes' density increases, the RFID reader's power saving also increases, due to the fact that the RPM algorithm is able to exploit the multiple tags/vehicles, and thus determine a more power efficient communication path. As noticed from the corresponding results, the RFID reader's power saving increases up to a point with respect to nodes' density and then it stabilises. The latter observation stems from the fact that the RPM algorithm after a certain value regarding the tags' density has already determined the most energy-efficient communication path, while guaranteeing the decoding of the received signal. Thus, a further increase in nodes' density will not contribute to further RFID reader's power savings. In a nutshell, the above results show the ability of tag-to-tag communication to reduce RFID readers' transmission powers, thus extending their battery life and concluding to an autonomous and unmanned SPS.

Figure 6 illustrates the number of hops towards realising the optimal communication R_α, T_x, R_β as a function of the nodes' density considering the multi-hop communication. The results reveal and confirm that as the nodes' density increases, the RPM algorithm exploits the existence of the additional passive RFID tags/vehicles in order to determine a more energy-efficient communication path. Thus, the number of hops increases, respectively. The above conclusion is mainly based

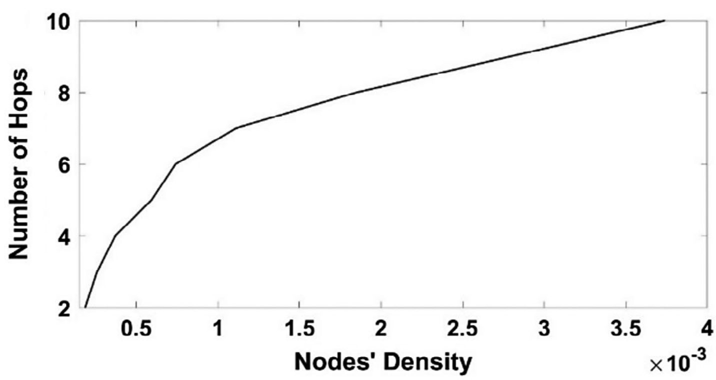

Figure 6. Number of hops realising the multi-hop communication as a function of the nodes' density.

on Equation (1), where it is observed that via splitting the same communication distance in smaller steps, contributes to greater power savings for the RFID reader.

Figure 7 presents the total distance of the R_α, T_x, R_β communication path as a function of the nodes' density for the multi-hop and direct communication scenarios. It is observed that the total distance in the multi-hop communication scenario is slightly larger than the direct communication case (by approximately 12.26% on average), however, due to the fact that it is split in smaller steps, it concludes to significant RFID reader's power savings (as observed by Figure 5).

Figure 8 illustrates the running time of RPM algorithm towards determining the energy efficient multi-hop communication path as a function of the nodes' density. The proposed framework was tested and evaluated in an Intel(R) Core(TM) i5-42104 CPU @ 1.70 GHz laptop with 8.00 Gb available RAM. The results show that as the nodes' density increases, the running time of the RPM algorithm also increases. However, the increase of the running time is relatively low and definitely of the order of magnitude of seconds, thus the proposed approach is applicable for all practical purposes, i.e. a realistic SPS.

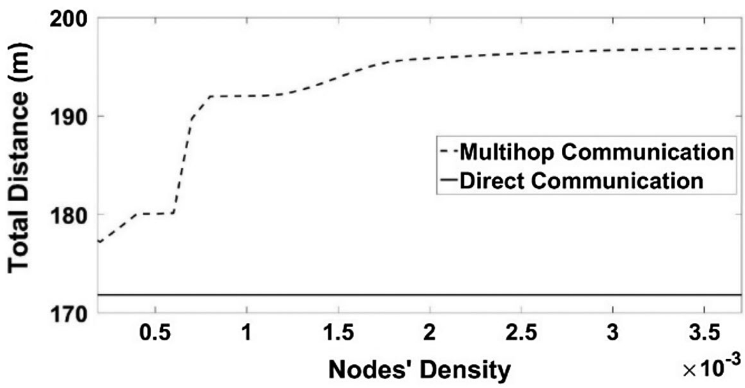

Figure 7. Total distance of the communication path for multi-hop and direct communication as a function of the nodes' density.

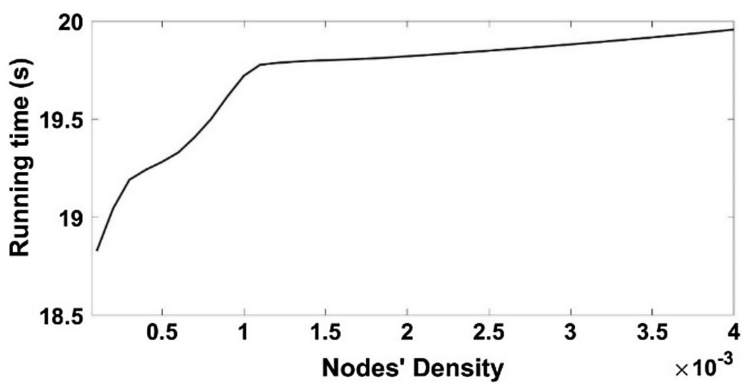

Figure 8. Running time of RPM algorithm as a function of nodes' density.

6.2. RFID reader's coverage area expansion

In this subsection, we study the RFID reader's coverage area expansion achieved via adopting tag-to-tag communication, when compared to the direct type of communication between the reader and the passive RFID tags. In a nutshell, the following analysis demonstrates that less RFID reader's transmission power is required in order to reach more distant passive RFID tags from the reader via adopting tag-to-tag communication, or equivalently for a given reader and RFID transmission power greater area can be covered when adopting tag-to-tag communication. Specifically, Figure 9 illustrates the percentage of reachable passive RFID tags by one RFID reader in SPS area as a function of the RFID reader's transmission power considering the multi-hop and direct communication patterns. The average percentage increase of reachable vehicles via adopting tag-to-tag communication is quite impressive reaching up to 219.35% in the considered scenario. The results reveal simply that less RFID reader's transmission power is needed in the multi-hop communication scenario in order to reach a larger number of passive RFID tags. This observation stems from the fact that the multi-hop communication scenario can exploit the existence of multiple passive RFID tags, thus determining a more energy-efficient communication path.

Figure 10 presents the farthest distance in the SPS area that can be covered either by the multi-hop or direct communication, as a function of RFID reader's transmission power. The results clearly reveal that multi-hop communication can contribute to significant RFID reader's coverage area expansion with less power consumption compared to the direct communication by an average percentage increase of 127.68%. This observation is of great practical importance due to the following reasons: (a) the RFID reader is able to extend its battery life in the multi-hop communication scenario and (b) the RFID reader's transmission power is

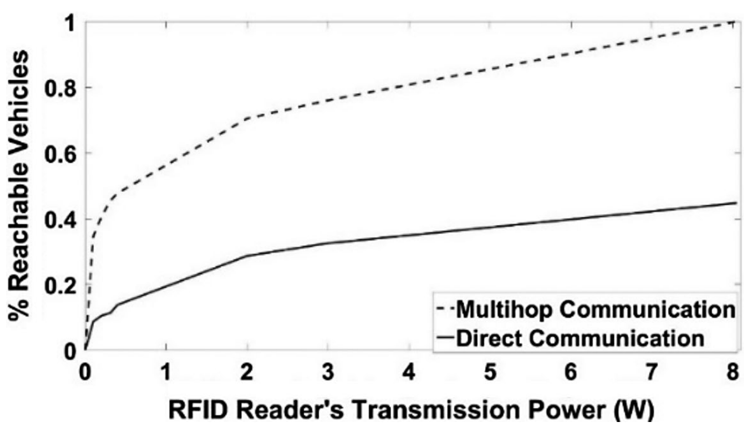

Figure 9. Percentage of reachable vehicles for multi-hop and direct communication as a function of the RFID reader's transmission power.

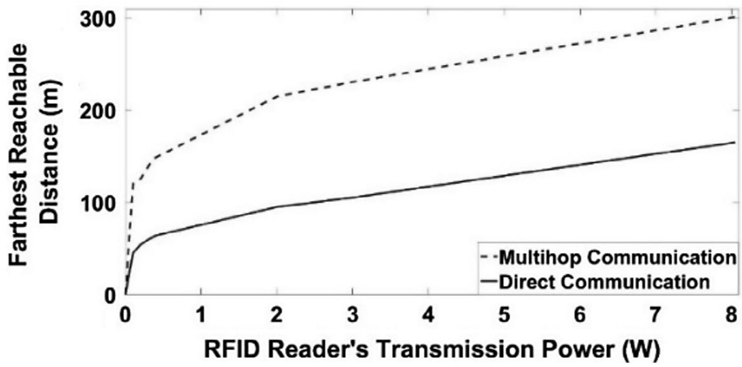

Figure 10. Farthest reachable vehicle (distance) for multi-hop and direct communication as a function of the RFID reader's transmission power.

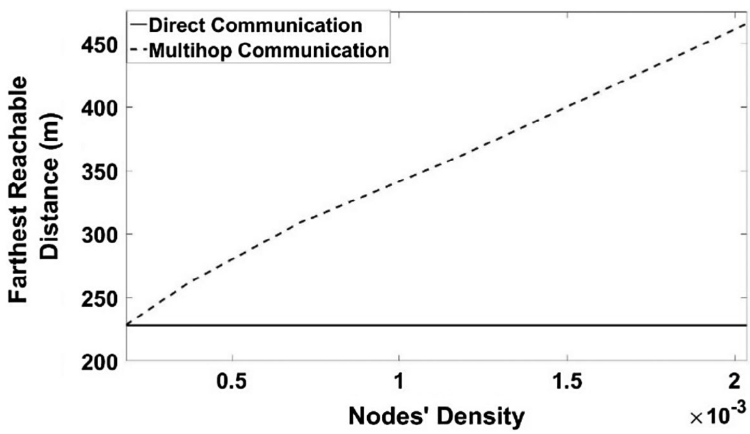

Figure 11. Farthest reachable vehicle (distance) for multi-hop and direct communication as a function of the nodes' density.

upper bounded, thus it could be the case that its maximum transmission power would not be sufficient to reach the most distant vehicles in the parking area, if the direct communication was adopted.

Complimentary to the previous results, Figure 11 shows the farthest reachable passive RFID tag within the parking area as a function of the nodes' density for fixed RFID reader's transmission power $P_{R_r} = 4$ W. The results illustrate that multi-hop communication is able to exploit the existence of multiple tags and reach more distant vehicles, while consuming the same amount of transmission power as in direct communication, where the coverage area of the RFID reader is fixed for its given transmission power. The average percentage increase of the farthest reachable distance by the multi-hop communication is 42.70% compared to the direct communication.

7. Concluding remarks

In this paper, the problem of jointly selecting a communication route among a source-destination set of RFID readers, while determining the minimum necessary RFID reader's transmission power towards guaranteeing the connectivity of the communication route, as well as the fulfilment of RFID tags' QoS prerequisites, is studied. The main novelty of the proposed framework is the adoption of RFID tag-to-tag communication, which can support a more energy-efficient collection of information from the RFID tags compared to the conventional direct type of communication. The overall framework is considered and examined within a SPS use case scenario, targeting at the prolongation of the RFID readers' battery life and the constant and uninterrupted monitoring of the vehicles via the attached RFID tags. Within the context of an RFID-based SPS architecture, the joint RPM problem of RFID reader's/source's transmission power is studied under the constraints of guaranteeing the connectivity between the tags, as well as the fulfilment of their QoS demands. A RPM algorithm is proposed towards determining the optimal communication route to collect the information from the RFID tags, and the optimal RFID reader's transmission power. The presented numerical results clearly demonstrate RFID reader's power savings and coverage area expansion achieved via adopting tag-to-tag communication.

The analysis provided in this paper assumes that all nodes share a common channel and interference is appropriately mitigated, either using TDMA without spatial reuse or by the use of several orthogonal channels appropriately allocated. Thus, each node transmits in its own unique slot (i.e. either time slot or frequency slot). However, allowing spatial reuse/interference to the communication routes of the RFID system can conclude to further improvement of system's energy-efficiency, while the need for power control at the RFID tags may arise as well, a topic which is of high research and practical importance.

Part of our current and future work is also to identify and confront the security issues that arise via adopting the proposed framework. Specifically, the problem of mitigating the interference/jamming imposed by potential intruder RFID tags within the SPS towards disrupting the RFID network's proper operation is of great interest. In addition, the problem where a team of intruders is strategically placing themselves and acting so as to induce maximum damage in the network via exploiting the tag-to-tag communication is of high research interest as well. Finally, given the distributed nature of the emerging IoT paradigm, additional types of attacks may be considered including localised ones that mainly aim at damaging a specific subset of RFID tags.

Disclosure statement

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