C. Liu and Z.J. Haas, "Routing Protocol Design in Tag-to-Tag Networks with Capability-enhanced Passive Tags," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Montreal, QC, Canada, October 8-13, 2017

Routing Protocol Design in Tag-to-Tag Networks with Capability-enhanced Passive Tags

Chang Liu* and Zygmunt J. Haas*†
*Erik Jonsson School of Engineering and Computer Science, The University of Texas at Dallas, Richardson, TX 75080
†School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853
{chang.liu@enmu.edu, zhaas@cornell.edu}

***Abstract*—Radio frequency identification (RFID) is a technology that incorporates the use of electromagnetic fields to uniquely identify objects. Among different types of RFID tags, passive tags have some salient features such as light weight, low cost, small size, etc. However, the downside of passive RFID systems is very limited reading range due to lacking their own energy sources (passive RFID tags communicate solely by backscattering the reader's power). A novel concept of passive RFID tag-to-tag (T2T) communication has been recently proposed, via which passive tags in proximity (at centimeter level) can directly communicate with each other with the existence of an external energy source. Utilizing this concept, we proposed a *Network of Tags (NeTa)* that passive tags can connect with each other through multiple hops, using a the novel concept of turbo backscattering operation. This significantly enhances the scalability of such a T2T network. However, to implement the proposed *NeTa* architecture, one of the main issues is the inter-tag interference, which brings challenge to the routing protocol design. In our previous work [1], we introduced protocol design for both tag-to-reader routing and tag-to-tag routing, considering basic hardware capability of tags, i.e., tags cannot measure the strength of received signals. In this paper, we extend upon the results in [1] and focus on tag-to-tag routing for two distinct types of tags with different hardware capabilities – tags can measure and attenuate the received signal before backscattering. These functions can greatly reduce the inter-tag interference and therefore enhance the network throughput. The protocol design is based on solutions of two mixed integer non-linear programming (MINLP) problems, respectively. The performances of the proposed protocols are analyzed and the impacts of several network factors (e.g., tag density, the transmit power of the reader, etc.) are investigated.**

***Index Terms*—RFID; Tag-to-Tag Communication; Backscattering; Routing Protocols; Internet of Things;**

I. Introduction

RFID tags, are small-size and low-cost wireless devices that help identify objects and people ([2]). Each RFID tag has a unique identification code, which differentiate the tags as part of an RFID reader interrogation operation. RFID has applications in various sectors, such in retail, manufacturing, healthcare, agriculture, etc. We can generally divide RFID tags into three classes: active, passive, and semi-passive tags. Active tags are powered by batteries, while passive tags don't require on-board energy sources. Instead passive tags use the radiation of a reader as an energy source to power the electronics and for communication through backscattering. The operation principle of a typical passive RFID link between a tag and the reader is as follows: the reader sends an activation signal to a passive RFID tag in its coverage area, which energize the chip circuit of the RFID tag. The tag can then respond by backscattering the received waveform signal. Due to the salient features, such as low cost, small size, physical flexibility, theoretically infinite lifetime, and environmental safety, passive RFID tags are extremely attractive as an enabling technology of many novel applications.

978-1-5386-3531-5/17/$31.00 ©2017 IEEE

Tag-to-tag (T2T) communication ([2], [3]) has been recently proposed, via which passive tags can communicate with each other within close distance (at the centimeter level). With the introduction of a *Network of Tags (NeTa)* architecture proposed in our previous work [1], a tag which is too distant from another tag will attempt to reach the destination via relaying by a sequence of other tags. This is mainly achieved by the introduced novel mode of operation, which we refer to as *turbo backscattering,* and which relies on refreshing the backscattering energy at each hop in a sequence of tags that relay the information. The basic principle of the *turbo backscattering* is as follows: each tag in the sequence first receives and decodes the transmission, modulates the received signal with its own information, and then backscatters the "fresh" power waveform from the reader. To implement such a *NeTa* architecture, one of the main technical challenges is the routing protocol design, due to inter-tag interference and possibly complicated topology of the tags.

As a prerequisite for routing, the discovery and identification of tags in the coverage of a reader for a traditional RFID network has been widely investigated (e.g., [4] – [7]). However, there is inadequate existing literature on routing protocols specifically related to passive T2T networks. The design of routing protocol for T2T networks has unique challenges because of the significantly different connectivity/coverage requirements, which is due to the nature of backscattering communication. To the best of our knowledge, the only prior efforts on routing protocol design for T2T communication are [8] and [9]. In Ref. [8], an algorithm is designed to identify and define uplink paths in networked active tags. However, the proposed algorithm cannot be applied to *NeTa*, mainly due to the asymmetry between downlink (i.e., reader to tag) and uplink (i.e., tag to reader) communication. Ref. [9] develops a fully distributed optimal link cost multipath routing protocol in the network layer, as well as designs a MAC protocol for passive T2T communication. However, in [9] a tag's backscattered power is not considered as a strong function of the distance between the tag and the reader. We point out that this is the major difference and indeed a main challenge of the *NeTa* architecture, as compared with, for example, sensor networks.

In our prior publication ([1]), we proposed a routing protocol for a network of passive tags, when the tags have standard design. The research question that we focus on in this paper is the routing protocol design for the proposed *NeTa* architecture based on two additional new hardware capabilities of RFID tags. The considered RFID tags are able to: (1) measure the strength of the received signal, or (2) both measure and attenuate the strength of the received signal before backscattering. These functions, although brings more challenges in routing protocol design, can greatly reduce inter-tag interferences and therefore enhance the network throughput. We propose two tag-to-tag routing protocols to coordinate concurrent transmissions and to maximize the data throughput.

The main contribution of this paper is to facilitate the comparison of the performance of the routing protocol when the above two new hardware capabilities are incorporated into the tags' design. Furthermore, the result in this paper could be used to evaluate the significant improvement that could be achieved with the above two new hardware capabilities.

This paper is organized as follows. Section II describes the system model. Section III presents the tag-to-tag routing protocols for the two types of passive RFID tags. The simulation results follow. Finally, Section IV presents conclusions and proposes some future directions.

II. System Model

The passive RFID T2T network considered in this paper consists of a reader transmitting an RF waveform, which is referred to as *continuous wave (CW)*, and a number of passive RFID tags uniformly distributed in the coverage area.

According to FCC regulations (Part 15, section 15.247), the transmit power of an RFID reader cannot exceed 1 Watt. Due to the power limitation, only tags in proximity (within distance of centimeters) can directly communicate with each other using the regular T2T communication technique proposed in [3]. This is because when a tag backscatters the received CW from the reader to another tag, the backscattered signal undergoes two radiation operations, in addition to the backscattering loss. To address this issue, we proposed in [1] the *turbo backscattering operation* (TBO). For completeness of presentation, we demonstrate here again that through the use of multihop links, the inter-tag distances can be significantly enhanced.

The fundamental principle of TBO is as follows. The reader transmits a CW, which contains both power and commands. A tag that receives this CW will decode the transmissions and then backscatters a "fresh" power waveform from the reader, which is modulated with information of the tag. The concept of this operation is similar to that of the "decode and forward" ([10]), to be distinguished from "amplify and forward" ([11]). However, in TBO the new transmitted signal is modulated on a power waveform from the reader, rather than using a carrier signal locally generated by the transmitter. This, of course, affects how the TBO scheme is used and implemented. Although we consider standard tag operations in this paper – the tags do not have a traditional transmitter or energy storage – however, to accommodate the TBO scheme, tags are used in a different manner, so that a backscattered wave by one tag can be received and decoded by the next tag, as if it were transmitted by a reader.

We use an example to demonstrate how TBO works, as shown in Fig.1. In the figure, *tag1* needs to transmit to *tag4.* Upon receiving the signal from tag 1, tag 2 decodes it,

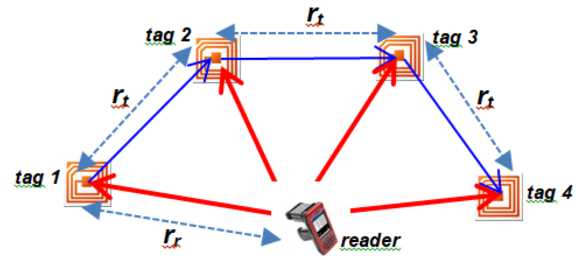

Fig.1: A simple example of *turbo backscattering.* Red links represent CW and blue directional links represent flow of information.

modulates it with its own information, and then backscatters a "fresh" power waveform from the reader to tag 3. This operation is then repeated from tag 3 to tag 4.

We make the following assumption: tags are not mounted on any surface; all antennas of tags and readers are isotropic radiators with 0 dBi; the T2T network is deployed in an open space, in other words, multi-path and shadowing phenomena are negligible; and the path loss coefficient is $\gamma = 2$. Then, according to a modified Friis formula ([14]), the received RF power at any tag outside the near-field zone in Fig.1 is:

$$P_p = P_t \cdot \left(\frac{\lambda}{4\pi r_r}\right)^2, \tag{1}$$

where P_t denotes the transmit power of the reader, λ denotes the operational wavelength, and r_r denotes the distance between the reader and the tag. This received signal is modulated by the tag's information, and then backscattered to the next tag. The received power at the next tag can then be calculated as:

$$P_r = P_p K \left(\frac{\lambda}{4\pi r_t}\right)^2 = P_t K \left(\frac{\lambda}{4\pi r_t}\right)^2 \left(\frac{\lambda}{4\pi r_r}\right)^2, \tag{2}$$

where r_t denotes the inter-tag distance, K denotes the backscattering coefficient, i.e., the factor that represents backscattering power losses, inclusive of the effect of impedance mismatch on the re-radiated power ([13]). Then according to eq. (2), we can conclude that the required condition for TBO is:

$$r_t \cdot r_r = \left(\frac{\lambda}{4\pi}\right)^2 \cdot \sqrt[2]{K \cdot \frac{P_t}{P_r^{tag}}}. \tag{3}$$

where P_r^{tag} denotes the sensitivity of a passive tag.

As calculated in our previous work ([1]), when $r_t = r_r = r, K = -10$ dB, the RF frequency $f = 1$ GHz), and $P_r^{tag} = -20\text{dBm}$ ([10]), a path between adjacent tags can be established as long as the density of the tags is such that the distance between adjacent tags on the route is smaller than 24 cm. With denser tags, the reader can be located further away from the network of tags. For example, with inter-tag distances up to 5 cm, the reader can be as far as 1.15 meter away.

Since the reader sensitivity is significantly larger (on the order of $P_r^{reader} = -80\text{dBm}$ ([14])), the reader can directly communicate (both uplink and downlink) with each tag in $NeTa$. The distances of uplink and the downlink of a reader $r_r^{uplink} = r_r^{downlink} \cong 7.5$ m. As a result, the reader is able to exercise direct control over each of the tags. Thanks to the global view of the *NeTa*'s tags, the reader can therefore better determine the best routes and the transmission scheduling times of the tags.

Since the reader acts as a central controller, one could question the need for *NeTa*, as in principle the reader acts as a central controller, which can serve as a "router" for information among the tags. However, it can be simply shown that in a network of large number (e.g., hundreds/thousands) of tags, such a reader acting as a central router would become a major "bottleneck" to the communications among tags, and thus to the overall operation or the network.

There are two stages in the proposed routing protocol. First of all, all the tags in its associated area (i.e., r_r) are identified. The corresponding protocol was presented in our previous work ([1]). Secondly, the neighbor tag information is established for the inter-tag route determination. To simplify the protocol operation, the coverage area is divided into annulus layers, where each layer represents "one hop" of the uplink path routing. For example, the reader will directly communicate with tags in the 1-hop layer on both directions (i.e., tag-to-reader and reader-to-tag). In an i-hop layer ($i \geq 2$), tags needs at least i hops to route back to the reader (although they can be directly reached from the reader on the downlink).

III. TAG-TO-TAG ROUTING PROTOCOLS

For tag-to-tag routing protocol design, we consider two types of tags with different hardware capabilities: (1) tags with ability to measure the received power (referred to as *scenario A*), and (2) tags with abilities to both measure the received power and attenuate the backscattered power (referred to as *scenario B*).

The main technical issue of tag-to-tag routing design is the inter-tag interferences. When interfered by other transmissions, the existence of a link can be difficult to establish due to the degraded link quality by summation of such other transmissions. In other words, although tag i may not be able to decode the transmission of tag j (and thus, the link between i and j may be considered as non-existent), the transmission from tag j may still create interference at tag i. Furthermore, with sufficient total amount of interference coming from other nodes, tag i may not be able to receive from otherwise existing link. Therefore, we aim to propose a protocol to coordinate tag transmissions as to reduce the effect of interference and to maximize the number of concurrent transmissions.

To this extent, we propose two routing protocols for the two types of tags (1) and (2) discussed above. These protocols are presented in Sections III-A and III-B, respectively. Simulation results are provided as well. In scenario A, tags are able to discover all interference patterns in the neighbor discovery process and make optimal decisions based on this information. In scenario B, tags can further reduce the interference by attenuating backscattering power of a tag to the minimum power that a tag needs to transmit to its destination.

A. Tag-to-Tag Routing Protocol for Tags with Ability to Measure the Received Power

We assume that all the tags in the associated area of the reader have been identified and that their uplink routing paths have been determined. Such a tag discovery could be implemented, for example, based on the Gen-2 protocol ([15]) or its modification. The routing protocol starts with neighbor discovery to discover the transmission links and interfering links. The reader transmits with its maximum power P_{max}, so that all possible links can be discovered. (Note that although the reader operates at P_{max} for neighbor discovery, it may transmit at a lower power level for actual T2T communications.) By measuring the power that a tag receives from backscattering by another tag, it is possible to determine the minimum power the reader needs to transmit for that link to exist. For instance, when the reader transmits at its maximum power P_{max} the backscattered power from tag i is received by tag j with power P_1, we can calculate that the link from tag i to tag j exists as long as the reader's transmit power is at least:

$$P_{ij} = P_{max} - (P_1 - P_r^{tag}). \tag{4}$$

From (4) we can build a power matrix for scenario A, $\mathbf{P^A} = \{P_{ij}^A\}$ where each element P_{ij}^A represents the minimum reader's power needed for the link from tag i to tag j to exist.

Furthermore, if a tag can measure the received power, it can determine the residual interference even if a tag cannot fully receive on the link. For example, if when the reader operates at P_{max}, the backscattered power from tag i is received by tag j with strength P_1, we can calculate that when the reader transmits at an arbitrary power P_R ($P_R \leq P_{max}$), the received power at tag j from tag i, P_{ij}^r, is $P_{ij}^r = P_1 - (P_{max} - P_R)$. From (4), knowing P_{ij}^A (which is included in matrix $\mathbf{P^A}$), P_{ij}^r can be calculated as:

$$P_{ij}^r = P_R - P_{ij}^A + P_r^{tag}. \tag{5}$$

The power matrix, $\mathbf{P^A}$, obtained from (4), and the residual interference of one link on another, obtained by (5), will allow us to maximize the concurrent transmission opportunities by the various network tags as part of the routing protocol.

The operation of the routing protocol includes two cycles: *Message Discovery (MD) Cycle* and *Message Routing (MR) Cycle*. During the *MD* cycle, the reader queries all its associated tags so that the identities of newly generated messages are reported to the reader. In each MR, a tag can transmit at most one message (a tag can store more than one messages, though). When a *MR* starts, the reader selects a subset of tags to transmit in this *MR* and instructs those nodes to transmit by sending a command. After the transmission from the selected nodes, the reader updates its list for pending messages of each tag accordingly.

The choice of the subset of tags to transmit in each *MR* is based on the following algorithm which assigns a weight to each pending message. A message with larger weight is generally more likely to be selected for transmission. Such weight of a message from tag i to tag j w_{ij} is defined as:

$$w_{ij} = p_{ij}\,(1 + d_{ij}\,\alpha)(1 + h_{ij}\,\beta), \tag{6}$$

where p_{ij} denotes a parameter indicating the priority of this message. The term $(1 + d_{ij}\,\alpha)$ is used to avoid "starving" messages, where d_{ij} denotes the total number of *MRs* that the message has been waiting (delayed), and α denotes the relative importance of the delay. In other words, each time the transmission of a message is inhibited, the reader increases the message's accordingly. The term $(1 + h_{ij}\,\beta)$ is used to speed up messages that travel across longer paths, where h_{ij} denotes the minimum path length (in number of hops) of the message, and β denotes the relative importance of the path length.

The algorithm uses the binary variables x_i to signify the state of the tag i (i.e., transmits when $x_i = 1$, or holds when $x_i = 0$) and c_{ij} to signify the state of a message from tag i to tag j (i.e., transmitted when $c_{ij} = 1$, or withheld when $c_{ij} = 0$). Since tag i may have more than one message to tag j, the index of the message, k, is added to the following variables, c_{ijk}, w_{ijk}, d_{ijk}, p_{ijk}, and h_{ij}.To select messages for transmission in the current *MR* such that the transmissions do not interfere with each other, we emphasize that the algorithm is performed centrally at the reader, so there is no need to share any parameters among the tags. The problem can be formulated as a mixed-integer optimization problem; i.e., select the set of transmitting nodes (**x**), their respective messages (**c**), and the power of the reader, P_R, such that the sum of all the weights of the transmitted messages is maximized. In other words (c' represents the negation of c, i.e., $c' = 1 - c$):

<u>Maximize:</u> $F(P_R, \mathbf{x}, \mathbf{c}) = \sum x_i c_{ijk} I\left(P_{ij}^A\right) w_{ijk}$,

<u>Subject to:</u>

C1: $x_i \in \{0,1\}, c_{ijk} \in \{0,1\}$,

C2: $c_{ijk}\, I\left(P_{ij}^A\right) + c'_{ijk}\, I'\left(P_{ij}^A\right) = 1, k \in \{1, \dots, n_{ij}\}$,

C3: $x_i \sum_j \left(c_{ijk} \prod_{l \neq k} c'_{ijl} \prod_{m \neq j} c'_{imq}\right) + x'_i \prod c'_{ijk} = 1$,
$j, m \in \Psi_i, k, l \in \{1, \dots, n_{ij}\}$ and $q \in \{1, \dots, n_{im}\}$

C4: $c_{ijk} = 0$ if $P_{ij}^r / \sum_{l \neq i}\left(P_{lj}^r x_l\right) \leq \eta$.

where $x = [x_1, x_2, \dots, x_n]$ and $c = \{c_{ijk}\}$. $I(P_{ij}^A)$ denotes an indicator function that $I(P_{ij}^A) = 1$ if $P_R \geq P_{ij}^A$, and otherwise $I(P_{ij}^A) = 0$. c_{ijk} denotes the k^{th} message from tag i to tag j. η is the minimum required signal-to-interference ratio (SIR) for reception. Note that here tag j is the next-hop destination rather than the final destination of this message. The weight of the k^{th} message from tag i to tag j w_{ijk} is redefined (based on eq. (6)) as $w_{ijk} = p_{ijk}\,(1 + d_{ijk}\,\alpha)(1 + h_{ij}\,\beta)$, where p_{ijk} denotes a priority parameter and d_{ijk} denotes the accumulative delay of the k^{th} message from tag i to tag j since the message was originally generated. n_{ij} denotes the number of messages from tag i to tag j. Ψ_i denotes the set of the next-hop destinations of the message copies at tag i.

In the proposed problem stated above, constraint C2 represents that a message copy cannot be transmitted unless the transmit power of the reader is sufficient. Constraint C3 represents that at a time slot each tag can transmit at most one message. Also, a node transmits if and only if it has one message being transmitted. Otherwise the node does not transmit. Constraint C4 represents interference constraints that a message copy cannot be transmitted when the total received power from neighbor tags is large enough to interfere; i.e., where the SIR is smaller than the threshold SIR η. This formulated mixed integer nonlinear programming (MINLP) problem can be solved by methods such as branch and bound, genetic and evolution algorithms ([16]).

To further improve the above algorithm , we allow nodes that overhear a transmitted message to retain the message copy and try to route it on a *non-preferred path* (i.e., a path that is not the shortest among all feasible paths). Accommodating this modification, the reader continues to select messages for transmission on their preferred routes, but sequentially checks each of the other copies of the messages to see if they could still be transmitted after the optimization. This is achieved by substituting the values of variables that were already chosen to transmit or not to the constraints, and checking if transmitting a copy violates the constraints. The order of messages being checked is as follow: (1) copies of all the non-transmitted messages in this *MR* (from the shortest path to the longest path), (2) copies of all the messages transmitted in this *MR* (each message being transmitted by a node other than the node that hold the copy), from the shortest path to the longest. Once a message or its copy reaches its destination, all its copies are erased from the nodes that hold such copies.

B. Tag-to-Tag Routing Protocol for Tags with Ability to Measure and Attenuate Received Power

In scenario B, we consider tags with ability to measure the received power and attenuate the power that a tag backscatters to the next tag. The main advantage of such a tag design is that each tag can limit the backscattering power to the minimum required for reception by the next tag, thus limiting the interference on other communications. The main difference in the neighbor discovery process from that of scenario A (as presented in Section III-A) is that now the reader always operates at its maximum power P_{max}. Then the maximum backscattering power of tag i can be calculated as

$$P_{imax} = P_{Ri}\, K, \tag{7}$$

where P_{Ri} denotes the received power at tag i from the reader.

By measuring P_{ij} (the power received at tag j when tag i backscatters), the reader builds a power matrix $\mathbf{P^B}$ in which each element P_{ij}^B represents the needed backscattering power of the tag i for the link from tag i to tag j to exist.

$$P_{ij}^B = \frac{P_{imax} P_r^{tag}}{P_{ij}}. \tag{8}$$

In scenario B, the reader always transmits at its maximum power, so that all the possible links could be illuminated. On one hand, this may increase the number of links, but, on the other hand, it may also disable some links due to interference conditions. Since the tags have abilities to selectively reduce the backscattering power of some nodes (without affecting other nodes), this will allow the transmissions to affect only some nodes. In other words, if a node i is chosen to transmit to tag j, it can transmit at the minimum required power P_{ij}^B (as long as $P_{ij}^B \le P_{imax}$). When tag i transmits to tag j at power P_{ij}^B, the received power at tag j is P_r^{tag}, while the reduced power received at tag k ($j \neq k$) P_{ik}^r, is determined as

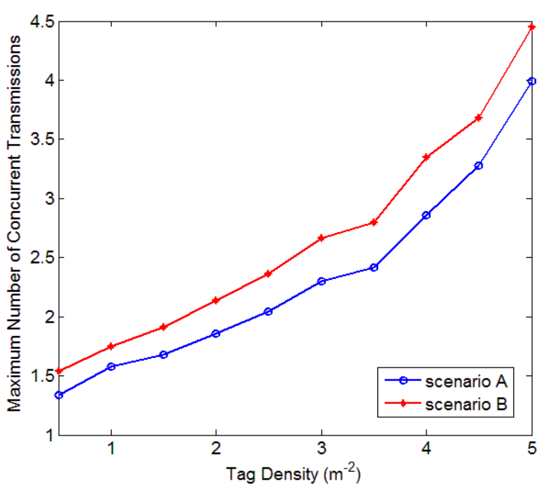

Fig. 2: Data Throughput vs. Tag Density in Scenario A and B

$$P_{ik}^r = {P_{ij}^B P_{ik}}\Big/{P_{imax}}. \tag{9}$$

where P_{ik} denotes the received power at tag k when tag i transmits without reducing its backscattered power.

Therefore, the problem can be formulated as:

Maximize: $F(x,c) = \sum x_i\, c_{ijk}\, w_{ijk}$,
Subject to:

C1: $x_i \in \{0,1\}, c_{ijk} \in \{0,1\}$,
C2: $x_i(\sum_k c_{ijk}) \prod_{m\neq j} c'_{imq} + x'_i \prod c'_{ijk} = 1,\ j,m \in \Psi_i, k,l \in \{1,\dots,n_{ij}\}$ and $q \in \{1,\dots,n_{im}\}$,
C3: $c_{ijk} = 0$ if $P_{ij}^r / \sum_{l\neq i}(P_{lj}^r x_l) \le \eta$,
C4: $P_i = \sum_j (P_{ij}^B \sum_k c_{ijk})$.

Here the constraint C2 represents that each tag can transmit at most one message copy at a time slot. Also, if a message is transmitted, the node needs to transmit. Constraint C3 represents interference constraints that a message copy cannot be transmitted when it receives backscattering power from neighbor tags is large enough to interfere i.e., where the SIR is larger than the threshold η. Constraint C4 can also be written as:

$$P_i = \begin{cases} 0, & if\ c_{ijk} = 0, \forall j \in \Psi_i, \forall k \in \{1,\dots,n_{ij}\} \\ P_{ij}^B, & if\ \exists j \in \Psi_i, k \in \{1,\dots,n_{ij}\}, c_{ijk} = 1 \end{cases}.$$

It represents that the transmit power of tag i is the minimum power needed to transmit to its destination tag, or zero if no message copy at tag i is selected to transmit.

Similarly, this formulated problem is an integer programming problem with nonlinear constraints, which can be solved by methods such as branch and bound, genetic and evolution algorithms. After obtaining the solutions, the following procedure is the same as those in the routing protocol for scenario A as presented in Section III-A.

C. Simulation Results

In the simulation, we consider a reader in the center of the range of interest, and a number of tags uniformly distributed in a 5 m × 5 m area. We assume that the operational wavelength $\lambda = 0.3$ m, backscattering loss $K = -10$ dB, the maximum transmit power of the reader $P_{max} = 1$ Watt, the required minimum reception signal at the tags $P_r^{tag} = -20$ dB, and the SIR threshold $\eta = 0$ dB. For tags in scenario A, we set the transmit power of the reader to be $0 \le P_R \le 1$ Watt. For tags in scenario B, the reader transmits at power level $P_R = 1$ Watt.

We first investigated data throughput, i.e., the maximum number of concurrent transmissions. In Fig. 2, we set the number of message copies that need to be transmitted equal to the number of available links, to investigate the maximum achievable number of concurrent transmissions. It is shown that the data throughput in both scenario A and scenario B monotonically increases with the tag density. This is intuitive, since the number of available links increases as both the number of tags increases and the inter-tag distances decrease. The data throughput of tags in scenario B is larger than tags in scenario A. This is because the interference is minimized when tags can attenuate their backscattered power.

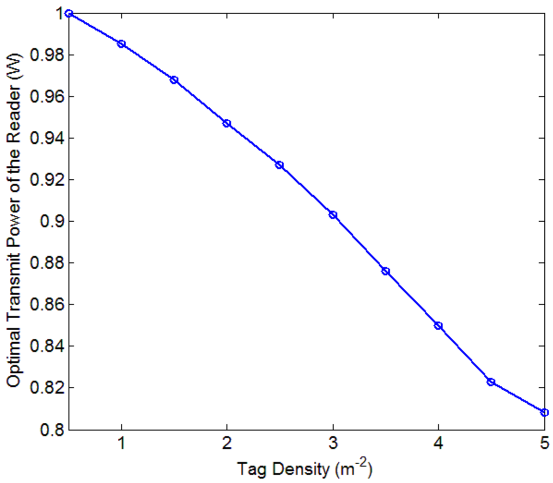

Fig. 3 Optimal Transmit Power vs. Tag Density

We also investigated the optimal transmit power of the reader for tags with varying tag density in scenario A. As shown in Fig. 3, the optimal transmit power of the reader monotonically decreases with the tag density. This is because the denser the tags are, the less power they generally need for links to exist, and the more sensitive the tags are to interference due to shorter inter-tag distances.

IV. Conclusions and Future Work

In this paper, we proposed a multi-hop passive RFID T2T network with turbo backscattering operation. The proposed scheme increases the inter-tag distances and the interrogation ranges of readers by orders of magnitudes. We presented the routing problem as an optimization problem and developed two protocols based on the available hardware features of the tags. Computer simulations verify that the presented routing protocol designs can effectively coordinate concurrent transmissions to enhance data throughput. Our future work will include routing protocol design of passive RFID T2T networks in a multiple-reader scenario, which involves additional technical challenges, such as new interference scenarios.

Acknowledgment

This work has been funded in part by the NSF grant number ECSS-1533282.

References

[1] C. Liu, and Z. J. Haas, "Multi-Hop Routing Protocols for RFID Systems with Tag-to-Tag Communication", 36th IEEE Military Communications Conference, Baltimore, MD, October 23-25, 2017.

[2] P. V. Nikitin, K. V. S. Rao, and S. Lam, "RFID paperclip tags," in 2011 IEEE International Conference on RFID, April 2011, pp. 162–169.

[3] P. V. Nikitin, S. Ramamurthy, R. Martinez, and K. V. S. Rao, "Passive tag-to-tag communication," in 2012 IEEE International Conference on RFID (RFID), April 2012, pp. 177–184.

[4] X. Jia, Q. Feng, and L. Yu, "Stability analysis of an efficient anticollision protocol for RFID tag identification," IEEE Transactions on Communications, vol. 60, no. 8, pp. 2285–2294, August 2012.

[5] M. Shahzad and A. X. Liu, "Probabilistic optimal tree hopping for RFID identification," IEEE/ACM Transactions on Networking, vol. 23, no. 3, pp. 796–809, June 2015.

[6] B. A. Alsaify, D. R. Thompson, and J. Di, "Identifying passive UHF RFID tags using signal features at different Tari durations," in 2012 IEEE International Conference on RFID (RFID), April 2012, pp. 40–46.

[7] Y. Jiang, R. Zhang, W. Cheng, B. Li, and W. Sun, "A group-based ternary query splitting protocol for tag identification in RFID systems," in 2016 International Conference on Networking and Network Applications (NaNA), July 2016, pp. 267–272.

[8] M. Chen and S. Chen, "Identifying state-free networked tags," in 2015 IEEE 23rd International Conference on Network Protocols (ICNP), Nov 2015, pp. 302–312.

[9] H. Niu and S. Jagannathan, "A cross layer routing scheme for passive RFID tag-to-tag communication," in 39th Annual IEEE Conference on Local Computer Networks, Sept 2014, pp. 438–441.

[10] G. Kramer, M. Gastpar and P. Gupta, "Cooperative Strategies and Capacity Theorems for Relay Networks," in IEEE Transactions on Information Theory, vol. 51, no. 9, pp. 3037-3063, Sept. 2005.

[11] R. U. Nabar, H. Bolcskei and F. W. Kneubuhler, "Fading relay channels: performance limits and space-time signal design," in IEEE Journal on Selected Areas in Comm., vol. 22, no. 6, pp. 1099-1109, Aug. 2004.

[12] A. P. P. L., J. J. Pantoja, E. Neira, and F. Vega, "On the backscattering from RFID tags installed on objects," in 2016 10th European Conference on Antennas and Propagation (EuCAP), April 2016, pp. 1–5.

[13] P. V. Nikitin and K. V. S. Rao, "Theory and measurement of backscattering from RFID tags," IEEE Antennas and Propagation Magazine, vol. 48, no. 6, pp. 212–218, Dec 2006.

[14] D. M. Dobkin, "UHF RFID tags," in The RF in RFID, 2008, pp. 195–239.

[15] EPCglobal, G. S. "EPC Radio-Frequency Identity Protocols Generation-2 UHF RFID; Specification for RFID Air Interface Protocol for Communications at 860 MHz-960 MHz." EPCglobal Inc., Nov. 2013.

[16] P. Belotti, C. Kirches, S. Leyffer, J. Linderoth, J. Luedtke, and A. Mahajan. Mixed-integer nonlinear optimization. Acta Numerica, 22, 1-131, 2013.