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Multi-Hop Routing Protocols for RFID Systems with Tag-to-Tag Communication

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Abstract**—Radio frequency identification (RFID) is a technology for automated identification of objects and people. RFID technology is expected to find extensive use in applications related to the *Internet of Things,* and in particular applications of *Internet of Battlefield Things.* Of particular interest are passive RFID tags due to a number of their salient advantages. Such tags, lacking energy sources of their own, use backscattering of the power of an RF source (a reader) to communicate. Recently, passive RFID tag-to-tag (T2T) communication has been demonstrated, via which tags can directly communicate with each other and share information. This opens the possibility of building a *Network of Tags (NeTa)*, in which the passive tags communicate among themselves to perform data processing functions. Among possible applications of *NeTa* are monitoring services in hard-to-reach locations. As an essential step toward implementation of *NeTa*, we consider a novel multi-hop network architecture; in particular, with the proposed novel turbo backscattering operation, inter-tag distances can be significantly increased. Due to the interference among tags' transmissions, one of the main technical challenges of implementing such the *NeTa* architecture is the routing protocol design. In this paper, we introduce a design of a routing protocol, which is based on a solution of a non-linear binary optimization problem. We study the performance of the proposed protocol and investigate impacts of several network factors, such as the tag density and the transmit power of the reader.**

I. INTRODUCTION

A radio frequency identification (RFID) system [1], which consists of a *reader* capable of interrogating tags, has become one of the most widely used platforms for automatic identification. RFID tags are classified into three major types: active, passive, and semi-passive. As the names imply, passive tags are battery-free; they are powered by radiation from the reader. A typical passive RFID tag-to-reader link operates as follows: when a passive RFID tag detects an activation signal from a reader, which "wakes up" the RFID chip, it can respond to the reader by backscattering the received waveform signal from the reader. As opposed to active tags, passive tags do not have traditional transmitters or energy storage. Among the advantages of passive tags are low cost, small dimensions, physical flexibility, (theoretically) infinite lifetime, and environmental safety.

In recent years, direct passive tag-to-tag (T2T) communication has been demonstrated between a pair of passive or semi-passive RFID tags (e.g., [2]). In such a communication system, tag-to-tag communications are enabled by backscattering. As the tags are passive, there is no need to charge or replace the batteries. Allowing tags to directly communicate with each other opens a new set of applications in areas such as smart spaces, medicine, and environmental monitoring. However, due to radio frequency (RF) signal attenuation, only short inter-tag distances on the order of centimeters ([2]) are feasible. To address this shortcoming, we introduce the notion of a *Network of Tags (NeTa)*, in which tags can directly communicate over extensive distances by multihop routing through intermediate tags. This is accomplished through the *turbo backscattering operation* for a sequence of relaying tags, in which each tag in the sequence first receives and decodes the transmission, and then backscatters the "fresh" power waveform from an RF source, such as a reader, after it is modulated with the tag's information. *NeTa,* together with the *turbo backscattering operation,* allows interconnecting relatively widely separated collection of tags.

Advanced RFID technology, in which the RFID chips are able to store and process information, is especially well suited for certain types of military applications, including sensing and monitoring. As one application, consider a flexible passive RFID tag attached to equipment or ammunition, where information such as manufacturing date, expiration date, service records, etc., could be stored on the RFID chip. Upon a temporary presence of a reader, the passive tags of *NeTa* can process the stored information to respond to global queries about the pool of equipment; e.g., the next date for needed maintenance operation. Because of the large span of *NeTa,* there is no need to individually scan each tag, an operation that would require significant manpower and time.

Routing is a key function in the operation of *NeTa*, with the initial requirements that the tags in the network have to be identified (e.g., [3]). However, existing literature on routing protocols for passive T2T networks is inadequate. Since passive RFID tags communicate by backscattering, routing protocol design for T2T networks is unique due to the significantly different connectivity/coverage requirements. To the best of our knowledge, [4] and [5] are the only prior efforts on routing protocol design for T2T communication. Reference [4] designed an algorithm to identify and define uplink paths in networked active tags. However, this work cannot be directly applied to passive tag networks due to the fact that the connectivity between two adjacent passive tags depends on the distance between the tags and the RF source. The authors in [5] developed a multipath routing protocol in the network layer and designed a MAC protocol which is suitable for passive tag-to-tag communication. However, [5] did not take into account that a tag's backscattered power is a strong function of the distance between the tag and the reader. Indeed, this is the main difference and a main challenge of the T2T communication compared with sensor networks.

II. SYSTEM MODEL

In this paper, we consider a reader transmitting an RF waveform (referred to as *continuous wave (CW)*), which contains power (and possibly data/commands). Upon receiving this CW, an RFID tag modulates the received waveform with its own information and backscatters the modulated CW to another tag (or back to the reader). The tag operations are standard, however, by employing the *turbo backscattering*, we use the tags in a different manner than a traditional RFID system does.

When a tag backscatters the received constant wave from the reader to another tag, the backscattered signal undergoes two radiation operations in addition to the backscattering loss at the transmitting tag. With regular multi-hop tag-to-tag links, the backscattered signal would undergo multiple radiation operations as well as backscattering loss at the relaying tags. In practical applications, due to power limitations (according to FCC regulations (Part 15, section 15.247), the maximum allowable transmit power of an RFID reader is 1 Watt), the backscattered signal after one hop is far from sufficient to meet the minimum required received power for another tag. In the following, we demonstrate that through the use of the *turbo backscattering operation* (TBO), multihop chain of relaying tags can be enabled.

An example of TBO is shown in Fig. 1, in which *tag1* wants to communicate with *tag4*. When a tag receives a transmission, it decodes it and then backscatters a "fresh" power waveform from the reader, after the waveform is modulated with the tag's information. This operation is repeated in the next hop (i.e., to the following tag). The TBO is conceptually similar to "decode and forward" ([6]), to be distinguished from "amplify and forward" ([7]). However, the main difference between the "turbo backscattering" and the "decode and forward" scheme is in the fact that, in the former, the new transmitted signal is modulated on a power waveform received from the reader (i.e., backscattered), rather than using the transmitter's own generated carrier signal.

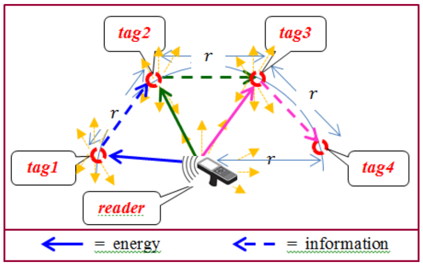

Fig.1: Simple example of *turbo backscattering*

For simplicity, we assume that: (i) all antennas (tags and readers) are isotropic radiators with 0 dBi, (ii) tags are not mounted on any surface, (iii) the T2T network is deployed in an open space, so that multi-path and shadowing phenomena could be neglected, and (iv) the propagation attenuation exponent $\gamma = 2$. Then based on a modified Friis formula ([8]), for distances larger than the near-field zone, the received RF power at any tag in Fig.1 is:

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

where P_t is the transmit power of the reader, λ is the operational wavelength, and r_r is the distance between the reader and the tag. This RF power is then backscattered to the next tag, after being modulated by the tag's information. Assuming that the inter-tag distance is $r_{t,}$ the received power at the next tag is:

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

where K (the *backscattering coefficient*) is the factor that represents backscattering power losses, inclusive of the effect of impedance mismatch on the re-radiated power ([9]). If the sensitivity of a passive tag is P_r^{tag}, then we conclude from (2) that for TBO to work, the following condition is required:

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

As an example, assuming that $r_t = r_r = r$ (as in Fig.1), that $K = -10$dB, that $\lambda = 0.3$m (corresponding to RF frequency of about 1 GHz), and that P_r^{tag} is -20dBm ([10]), then the maximum distance, r, between any of the tags has to be smaller than 0.24 meter. In other words, as long as the density of the tags is such that the distance between adjacent tags on the route is smaller than 24 cm, the path can be established. If the tags' density is larger, the reader can be located further away from the tags. For example, if the inter-tag distances are no larger than 5 cm, the reader can be as far as 1.15 meter away. In general, based on (3), if a reader is placed "in the middle" of a uniformly distributed tags with maximum inter-tag distance r_t, the reader can power tags in the area defined by r_r. Due to the significantly higher sensitivity of a reader (on the order of $P_r^{reader} = -80$dBm ([10]), the reader can directly communicate (both uplink and downlink) with each tag in *NeTa*. The downlink of a reader is $r_r^{downlink} = \frac{\lambda}{4\pi} \cdot \sqrt[2]{\frac{P_t}{P_r^{tag}}}$ and the uplink is $r_r^{uplink} = \frac{\lambda}{4\pi} \cdot \sqrt[4]{K \cdot \frac{P_t}{P_r^{reader}}}$. As an example, using the above parameters $r_r^{uplink} = r_r^{downlink} \cong 7.5$ m. Consequently, the reader has a direct control over each of the tags. Thus, because the reader has a global view of the *NeTa*'s tags, the reader is in a much better position to determine the best routes and the tags' transmission scheduling times.[1]

As a demonstration of the proposed cross-layer routing protocol, we present in the next Section III how the protocol could implement routes on the uplink (i.e., from a tag back to the reader), using a multihop routing scheme.[2] The protocol has two stages: in the first stage, the protocol discovers all the tags that are in its control area (i.e., r_r). In the second stage, the protocol establishes tag adjacency information, which will assist later in determining the inter-tag routes. To reduce the complexity of the operation of the protocol, we divide the control area into, what we refer to as, *reachability regions*. More specifically, the control area around the reader is divided into annulus layers, where each layer represents one hop of the uplink path routing. For example, in the 1-hop layer (i.e., the

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[1] Since the reader acts as a central controller, one could question the need for *NeTa*, as in principle the controller could also serve as a "router" for information among the tags. However, a simple calculation shows that in a network of hundreds/thousands of tags, such a reader acting as a router would become a major "bottleneck" to the communications among tags.

[2] We note that this example is for demonstration only, and may not be practical in many scenarios.

direct communication area), tags can directly communicate with the reader, on both uplink (tag-to-reader) and downlink (reader-to-tag). In an i-hop layer ($i \geq 2$), tags can be directly reached from the reader on the downlink, but use at least i hops to communicate back to the reader.

III. THE TAGS' DISCOVERY PROTOCOL

In this section, we present, as an example, the proposed routing protocol as it is used to establish a route from tags to the reader. This includes: (a) discover all the tags, and (b) determine a routing path for each discovered tag. (Note that we assume that the locations of both the reader and the tags are static during a discovery cycle. Mobility could be accommodated through repeated discovery.) This process targets tags in one hop layer at a time by adjusting the transmit power of a reader to reach only tags within a certain distance from the reader. We start by introducing the transmit power control of the reader and then describe the discovery process. Complexity analysis and simulation results follow.

A. *Discovery Process*

The discovery process is performed sequentially for each hop layer in the reachability region model described in Section II. In each cycle, we attempt to discover tags in a particular i-hop region, progressively increasing i from 1 to the highest hop layer (in a practical setting, tags can reach back the reader in no more than 4~5 hops (proof omitted)). To achieve that, the reader transmits its commands at a power slightly higher than the theoretical transmit power needed to reach the outer edge of a hop layer. Each command is followed by CW for the tag(s) to respond by backscattering (Note that this power control of the reader is performed only when the reader transmits commands. When the reader does not transmit commands and acts as a source of CW, it operates at its full power to energize the tags.) This is because the theoretical results obtained based on the Friis formula are under the assumption of idealized conditions. In reality, however, due to environmental factors (e.g., obstacles, different planes, etc.), it is not feasible to exactly gauge the needed transmit power to cover tags in a certain hop layer. So a simple solution is to transmit at a slightly higher power to cover all tags in this hop layer. Note that with the adjusted transmit power, although tags in higher hop layers may also receive commands from the reader and respond, their responses will be discarded due to time-to-live (expressed in number of hops) expiry. As the power is only slightly larger than necessary for the particular layer, the transmission will not reach too far and will not cause too much extraneous traffic.

The discovery process starts by the reader sending a message *Query* to the tags in the 1-hop region only, with the 1-hop tags responding and identifying themselves to the reader. After each *Query*, the reader sends an *Acknowledge* message to the discovered tags, so that the discovered tags cease from responding to future *Query* messages. Due to the possibility of transmission collisions, the *Query* messages are repeated, as described later. After all tags in the 1-hop region have been discovered, the reader proceeds to send another *Query* with enough power to reach the 2-hop region. The discovered tags in the 1-hop region now remain silent, but tags in the 2-hop region reply. Any tag in the 1-hop region that hears such a reply (from a tag in the 2-hop region) forwards the reply directly to the reader, thus identifying itself as able to rely communication from a 2-hop region tag. The reader then: (1) sends an *Acknowledge* message to the newly discovered 2-hop tags, (2) for each 2-hop tag determines which 1-hop tag will be responsible for relaying the 2-hop tag's transmissions, and (3) informs each such selected 1-hop tags which 2-hop tag it is responsible relaying for. Similarly, the process continues to discover and determine routing for tags in the next i-hop region. We note that most of the protocol complexity is in the reader, while the tags' operations remain relatively simple.

In the above operation, even with the division of the coverage area into reachability regions, when the reader sends a *Query* to any particular i-hop region, multiple (presumably all) tags will respond, leading to possibly large number of collisions. To avoid this, we propose a collision avoidance MAC protocol by adapting the EPC Gen-2 protocol. The basic idea of collision avoidance is that each frame is divided into slots and, to respond, each tag randomly selects one of the slots in the frame to send the reply message. The size of the frame, which is sent in each *Query* message, is chosen large enough so that the probability of two tags selecting the same slot is very small (but not necessarily negligible). The optimal frame length for time efficiency has been investigated in [11]. When a *Query* is sent for the first time (to an i-hop region), it will discover some tags, while some other tags may collide in the selected slots. The discovered tags are acknowledged and remain silent for future *Query* messages. The *Query* is then repeated (to the same i-hop region) with an adjusted frame length. With a large enough frame, it is very unusual that all the nodes collide at a same time slot. So when a reader does not receive any reply in a certain number of read cycles, it can conclude that all the tags in this area have been discovered with a high probability. Note that although there exists a possibility of missed tags, the missed tags can still be "found" in following *Query* cycles, since they have not received an *Acknowledge* message. After discovery in i-hop layer is complete, the reader increases the transmit power to proceed to the $(i+1)$-hop region. To avoid collisions in an i-hop ($i \geq 2$) discovery process, the $(i-1)$-hop routing tags take turns to forward the response messages from the i-hop tags following previously assigned paths, as instructed by the reader. Note that even without collision, the transmission can be unsuccessful when there are accidental errors in the transmitted data ([12]). To address this issue, we use a cyclic redundancy check (CRC) ([13]) to detect this type of unsuccessful transmissions, and instruct the corresponding tag to retransmit when a failed transmission has been detected.

B. *Complexity Analysis*

In this section, we approximate the complexity of this protocol in terms of the average total number of messages that need to be sent in an entire discovery cycle. We make the following assumptions: (1) the reader proceeds to query the next group of tags when there is no *Response* received in a *Query* cycle. Although in the proposed mechanism the reader can repeat *Query* cycles for a certain number of times to decrease the probability of missed tags, it will not affect our results of complexity. (2) The frame length for collision avoidance (denoted as Q) is a constant in an entire discovery cycle. But from cycle to cycle, the frame length can be adjusted as the number of unread tags decreases in a following *Query* cycle. For simplicity, we consider the same Q value for the discovery cycle to calculate the worst-case complexity. (3) We assume that the areas of the reachability regions are approximately equal and that the tags' density is constant across the whole coverage area. So in the complexity analysis, we assume that the number of tags in every hop layer is approximately the same and denote it as N. (4) According to the values of optimal Q in Table I from ([11]), we approximate $2^Q - 1 \approx N$. Then, by calculating and summing the number of times each message needs to be sent in an entire discovery cycle, the average complexity is derived as $O(HN(N+H))$ (proof omitted due to space limitation), where H denotes the maximum number of hops (i.e., 5, as previously stated). When $N \gg H$, the complexity can be approximated as $O(M^2)$, where M denotes the total number of tags in the coverage area (i.e., $M = NH$). Thus the protocol complexity depends mainly on the number of tags in the coverage area.

C. *Simulation Results*

In this section, we evaluate the missing tag probability with varying the number of queried tags and the strategy of when the reader proceeds to discover the next hop layer. In Fig. 2, with 10,000 Monte Carlo tests, we obtain the average fraction of missed tags, which is defined as the ratio of the total number of missed tags to the total number of queried tags.

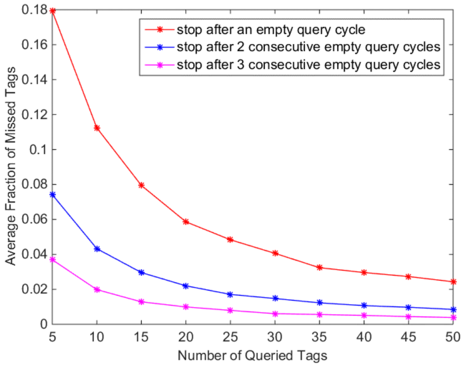

Fig. 2: Average Fraction of Missed Tags vs. Number of Queried Tags

As shown in Fig. 2, the expected fraction of missed tags can be significantly reduced by increasing the number of empty *Query* cycles before the discovery process is terminated. This is especially evident for small number of tags (i.e., sparser networks). Furthermore, we find that the missed tag fraction decreases as the number of queried tags increases, which shows that the denser the network is, the better the performance of this protocol is with respect to missing tag probability. It implies that from the perspective of suppressing missing tag probability, tags in each hop layer should not be divided and discovered separately. To keep the fraction of missed tags approximately constant, for large densities, the number of empty *Query* cycles for discovery termination should be small, and vice-versa. The last observation, which appears to be counter-intuitive, is due to the way the frame is sized. In the proposed protocol, we aim to coordinate transmissions of tags to reduce the effect of interference and to enhance the number of concurrent transmissions.

IV. THE TAG-TO-TAG ROUTING PROTOCOL

In this section, we describe the operation of the centralized routing protocol. The main challenge of tag-to-tag routing design is the interference of one transmission on another. In other words, although existence of a link between two nodes can be easily determined in the absence of other transmissions, the existence of the link when other transmissions are present is more difficult to establish. In particular, although tag i may not be able to decode the transmission of tag j, when tag j transmits, it may still create interference at tag i. Furthermore, interference adds, so if there is sufficient amount of interference coming from such other nodes, tag i may not be able to receive. In the proposed protocol, we aim to coordinate transmissions of tags, as to reduce the effect of interference and to enhance the number of concurrent transmissions. To this extent, we propose a novel neighbor sensing procedure to tackle this problem, as presented in Section IV-A. Then we describe the steps of the proposed tag-to-tag routing scheme in Section IV-B. Complexity of the protocol is discussed and simulation results are provided in Section IV-C and Section IV-D, respectively.

A. *Neighbor Discovery*

We assume that all the tags in the coverage area of the reader have been identified, as per the procedure described in section III.A. The routing protocol starts with neighbor discovery to establish a “neighbor table” for each tag; the table contains the IDs of the tag’s one-hop neighbors (i.e., tags located close enough that this tag can receive and decode transmission from them) and the tag’s interfering tags (i.e., tags that may create interference to this tag when they transmit). To achieve this, the reader transmits at two different power levels in the neighbor discovery process: P_H and P_L, where $P_L < P_H$. To be more specific, the reader transmits at a relatively low power level P_L to detect possible communication links among the tags, but the reader transmits with the higher power level P_H to discover potential interfering links, so that the corresponding neighbor tags can be inhibited from transmitting to protect the selected transmission. The rationale behind this approach is as follows. The tags have no ability to measure the amount of power that a tag receives from another tag’s transmission; tags can only determine whether a link exists at a particular level of the reader’s power. By transmitting at the higher power level P_H during the discovery of interfering tags, the protocol will discover the tags whose transmission power is insufficient to establish a link (when the reader transmits at the lower power level P_L), but can still cause interference at the receiving tag (presumably with other interfering tags). We refer to the links discovered by P_L and P_H as *transmission links* and *interfering links*, respectively. The reader sends discover commands to instruct each tag to broadcast its ID in turn. When a tag receives ID information from another tag, it will record this information in its neighbor table (including transmission links and interfering links). Note that due to the asymmetry of links between tags, a tag that can transmit directly to tag i, may not necessarily be able to hear tag i.

The reader then instructs each tag to send to the reader its neighbor table under the two different transmit power levels. Upon receiving all the needed information, the reader can combine the information and construct a complete connection map (i.e., a map showing all tags and possible connections between them) and a collision map (i.e., a map showing all tags and possible interference between them). The connection map is used to find routing paths for source/destination pairs, while the collision map is used to disable transmissions that otherwise would interfere with another ongoing transmission. We note that for some source/destination pairs, there can be multiple routing paths. The routes are evaluated at the reader, so that the process does not burden the processing-limited tags.

B. *The Proposed Tag-to-Tag Routing Protocol*

The routing protocol operates on two cycles: *Message Discovery (MD)* and *Message Routing (MR)*. During *MD*, the reader queries the individual tags for newly generated messages. When a message is generated at a tag, the identity of the message is transmitted to the reader.

Although a tag may store multiple messages, in each *MR* a tag can transmit at most one message. At the beginning of each *MR*, the reader chooses the subset of tags to transmit in this *MR*, and sends an appropriate command to those nodes to transmit. After the selected nodes transmit, the reader adjusts the list of pending messages of each tag.

The choice of the tags to transmit in each *MR* is based on the following algorithm, which assigns weights to each pending message. In general, a message with larger weight is more likely to be chosen for transmission. A tag may have more than one message with different weights based on their priorities, path lengths, and delays. The weight of the j^{th} message at tag i, w_{ij}, is defined as:

$$w_{ij} = p_{ij}\ (1 + d_{ij}\ \alpha)(1 + h_{ij}\ \beta), \tag{4}$$

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

The algorithm assigns binary variables x_i and c_{ij} to signify the state of a tag i and the j^{th} message at tag i, respectively. When $x_i = 1$ the tag is chosen to transmit and when $x_i = 0$ the tag holds its messages. Similarly, when $c_{ij} = 1$ the j^{th} message is transmitted at tag i and when $c_{ij} = 0$ the j^{th} message is withheld at tag i.

The goal of the algorithm is to select a subset of messages for transmission in the current *MR*, such that the nodes that transmit those messages do not interfere, and as to maximize the sum of the weights of the selected messages. The problem is formulated as a binary optimization problem as follows:

$$\text{Maximize:}\quad F(\mathbf{x}, \mathbf{c}) = \sum x_i c_{ij} w_{ij}, \tag{5}$$

Subject to:

$$\text{C1: } \forall_i\, x_i \in \{0,1\}, \forall_{i,j}\, c_{ij} \in \{0,1\}$$

$$\text{C2: } \forall_i\, x_i \sum_j \left(c_{ij} \prod_{k \neq j} c'_{ik}\right) + x'_i \prod_j c'_{ij} = 1,\ \ j, k \in \Phi_i$$

$$\text{C3: } \forall_{i,j}\ \ g\left(c_{ij}, \sum interfering\ nodes\right) = 1$$

where $\mathbf{x} = [x_1, x_2, \dots, x_n]$, $\mathbf{c} = \{c_{ij}\}$ and $g(x, y) = xy' + x'$, which indicates that if x occurs then y cannot occur. Φ_i denotes the indices of messages at tag i. The constraint C1 indicates that x_i and c_{ij} are binary. The constraint C2 represents that each tag can transmit at most one message in each *MR* (first term), and that a tag can transmit if and only if at least one of its messages is selected for transmission. Note that by constraint C2, the objective function can be simplified as $F(\mathbf{x}, \mathbf{c}) = \sum x_i c_{ij} w_{ij} = \sum c_{ij} w_{ij}$. The constraint C3 represents the collision constraints for all the messages. For each message being transmitted, the next-hop receiver of its routing path should be protected from potentially interfering tags. Via the collision map, the reader can obtain all nodes (referred to as "*interfering nodes*") that can interfere with the next-hop receiving tag when the message c_{ij} is transmitted.

The main challenge of this binary optimization problem is to deal with the nonlinear equality constraints consisting of summation of products of binary variables (i.e., c_{ij} variables and x_i variables, and their binary negations). A nonlinear expression can be linearized by introducing an auxiliary variable y. For example, let B_i denote a binary variable. The multiplication of k binary variables B_1, B_2,…, B_k can be replaced by y_{1k} ($y_{1k} \in \{0,1\}$) such that:

$$y_{1k} \leq B_i,\ \ i = 1,2, \dots, k,$$

$$y_{1k} \geq B_1 + B_2 + \dots + B_k - (k - 1), \tag{6}$$

The constraints from eq. (4) force $y_{ik} = B_1 B_2 \dots B_k$. By introducing auxiliary variables all constraints can be converted to linear forms. Then, our optimization problem becomes a linear binary optimization problem and can be easily solved by existing efficient tools, such as CPLEX and MATLAB.

We note that the above algorithm could be further improved by allowing nodes that overhear a transmitted message to retain the copy of the message and to try to route such a copy on a non-preferred path. By accommodating this modification, the algorithm continues to select messages for transmission on their preferred routes, but after the optimization is completed, the reader sequentially checks each of the other copies of the messages to see if they could still be transmitted. This could be done by encoding the constraints of transmitting the message, substituting the values of variables that were already chosen to transmit or not, and seeing whether transmitting a copy violates the constraints. The messages are checked in the following order: (i) copies of all the non-transmitted messages, starting from the shortest path to the longest paths, until all the copies are checked, (ii) the copies of messages that are being transmitted, starting from the shortest path to the longest paths until all the copies are checked. Once a message or its copy reaches its destination, the receiving tag backscatters an *acknowledge* to the reader. All the copies of the message are then erased from the nodes according to the instruction of the reader.

C. *Complexity analysis*

Although the complexity of a routing protocol is critical for real time applications, the complexity of the proposed algorithm is hard to analyze analytically. This is because the order of the number of constraints highly depends on the tag density, which technically does not have any limit. Even with a limit, the impact of density on the order of interfering tags is difficult to be modeled mathematically. Thus, to give us some indication on the algorithm complexity, we evaluated the computation time of a MATLAB implementation of the algorithm on a computer with an Intel (R) Core (TM) i5-4590 CPU @ 3.30 GHz processor and a 4.00 GB RAM. With 50 binary variables, 100 inequality constraints and 100 equality constraints, the optimization problem can be solved within 100 ms. Since in practice only an approximation of this problem will need to be solved, this provides us confidence that the algorithm could be used in practical systems.

D. *Simulation Results*

We performed Monte Carlo simulations for tags uniformly distributed in a 10 m × 10 m square area. The simulation parameters are to values as those in Section II. We assume that each tag which has at least one transmission link (i.e., who has sufficient backscattering power to reach another tag) has at least one message copy to transmit.

1) Predicted vs. Actual Data Throughput

In Fig. 3, we compare the predicted data throughput and the actual data throughput with different tag densities of μ=0.1 m^{-2} and 0.2 m^{-2}. The high transmit power level of the reader is set to be $P_H = 1$Watt. Here the predicted data throughput is referred to as the maximum number of concurrent transmissions calculated by the proposed routing algorithm, which only considers interferences from individual neighbor tags, rather than the total interference from all the neighbor tags. It is shown in Fig. 3 that the actual data throughput is generally less than the predicted data throughput. The denser the tags are, the larger is the difference between the actual data throughput and the predicted data throughput. In addition, when tags are dense (e.g., when $= 0.2\ m^{-2}$), the actual data throughput may decrease as the transmit power of the reader P_L increases. This figure demonstrates that judicious selection of the P_L is critical for achieving maximal capacity of the routing algorithm, especially for large tag densities.

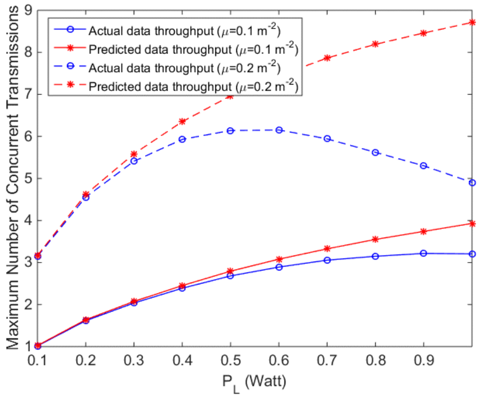

Fig. 3: Actual data throughput vs. Predicted data throughput

2) Actual Data Throughput vs. P_H vs. P_L

We now investigate the impact of both P_H and P_L on the actual data throughput. The simulation parameters are set as in the previous section. P_H varies from 0.1 Watt to 1 Watt and $P_L$varies from 0.1 Watt to the value of P_H. In Fig. 4 and Fig. 5 we can see that when the tag density is low, the impact of P_L on the maximum number of concurrent transmissions is much larger than that of P_H. This is because when tags are scarce, inter-tag distances are generally large, so that interference (and thus interference detection at P_H) does not play much of a role in affecting the data throughput. As the passive RFID tag-to-tag network becomes denser (e.g., when μ=0.5 m^{-2}, as shown in Fig. 5), the impact of P_H becomes larger. With a too high P_H, there are tags that cannot transmit even though they would not interfere when the reader transmits at P_L.

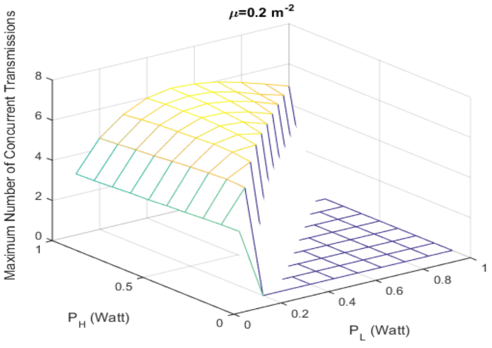

Fig. 4: Actual Data Throughput vs. P_H vs. P_L (μ=0.2 m^{-2})

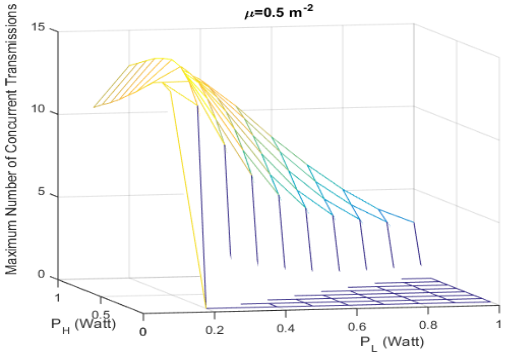

Fig. 5: Actual Data Throughput vs. P_H vs. P_L (μ=0.5 $/m^2$)

V. CONCLUSIONS AND FUTURE WORK

The multi-hop passive RFID T2T network with turbo backscattering operation proposed in this paper significantly increases the inter-tag distances, which enables construction of a Tag-to-Tag network with sufficiently large enough coverage area for applications of interest. We showed that judicious selection of the discovery powers, P_H and P_L, are required to optimize the performance of the routing protocol. Our future work will include routing protocol design of passive RFID T2T networks with multiple readers, which introduces additional technical challenges, such as new interference scenarios.

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