Delft University of Technology
Master's Thesis in Electrical Engineering

Phase Cancellation and Range Extension in Backscatter T2T Networks

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Title

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Abstract

Tag-to-tag (T2T) communications, in which two embedded backscatter tags directly communicate without the need of a reader, has recently seen progress in research. There are, however, challenges to overcome before this technology can take off. For example, state-of-the-art solutions to the phase cancellation problem that occurs in such networks are still trivial and sub-optimal, especially in terms of resource utilization. This thesis aims to address this issue by designing a T2T multi-hop network. This is done by (i) characterizing and analyzing such networks to assess the potential of multi-hop, and (ii) experimentally demonstrating the concept in the largest decode-and-relay multi-hop network so far. Findings show that multi-hop not only matches current phase cancellation solutions in terms of robustness, but also extends the range of communication by a factor of two with only four hops and enables connecting networks served by separate exciters.

Dedicated to Joana, Antonio, Adrián and Marta

“To the optimist, the glass is half full. To the pessimist, the glass is half empty. To the engineer, the glass is twice as big as it needs to be.” – Unknown

Preface

This thesis has been submitted as a paper for possible publication [2] and has been carried out at the Embedded Software Group of the EEMCS faculty as the graduation project of my Master's degree in Electrical Engineering at Delft University of Technology. The project was first started about two years ago by the former student Michel Jansen, who designed the original hardware support of the tags [5]. I am grateful for the opportunity of following up the project and contributing with my work to create, study and optimize backscatter tag-to-tag networks by analytically and experimentally analyzing them.

Apart from summarizing my work in the project, this report also serves as a milestone marking the end of a stage in my education and a vital experience in my life. For all I have learned and experienced, I want to thank everyone who was involved in some way in the project. A special mention goes to Kasım Sinan for his help in validating and reviewing the analysis section and to Ioannis Protonotarios for his collaboration and mentoring in laboratory matters. I want to thank Amjad Majid for the inspiration in moments of uncertainty, a work of great quality that powered the communication protocol and for a smooth and friendly collaboration overall. In addition, I have to thank Przemek Pawełczak for his superb implication throughout the full process, guidance, enthusiasm, and for pushing ahead and never settling.

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Chapter 1

Introduction

With the goal of creating battery-less devices, energy harvesting has seen dramatic progress in the last years [14]. However, many application still require more power than collected from ambient sources. Therefore, some interest has pivoted to reducing the energy footprint. Backscatter technology, found today in a number of applications [7–9, 13, 19] like the ubiquitous RFID, are able to completely eliminate the most energy-hungry components such as oscillators or analog-to-digital converters (ADC) of wireless devices to create truly battery-less systems.

Unlike traditional backscatter, tag-to-tag (T2T) backscatter communications go one step further and do not require an external master reader to query information: tags can send and receive information at the same hierarchical level. This opens really interesting applications in the extremely popular IoT [10] and other fields.

1.1 Problem Statement

Backscatter T2T is a promising technology, but it also poses a few challenges that need to be addressed before it can become commonplace. Firstly, backscatter signals are very weak and therefore hard to detect [3], which makes receiver resign challenging and limits range of communication. If we also consider the required relative simplicity of receivers, this is not an easy feat. Furthermore, T2T nodes do require an external exciter to generate a carrier signal for them to modulate information on. This alone is not a problem, but because of the dislocation of energy and information sources, the phenomenon of phase cancellation arises. This effect is analyzed in detail in [17].

1.2 Research Goal

This thesis aims to introduce multi-hop to backscatter communications to address some of the current drawbacks and limitations of T2T networks. It also investigates desirable features by means of analysis and experimentation to lay some foundations with the goal of pushing a wider adoption of this technology. In particular, this thesis looks at backscatter T2T networking and proposes a novel multi-hop approach with the goal of countering the phase cancellation problem and extending communication range by relaying messages over other T2T nodes, creating a robust multi-hop network.

1.3 Organization overview

This work first covers the state-of-the-art and scientific publications in Chapter 2 that are relevant for the topic. Chapter 3 introduces the hardware design of a T2T node and explains how backscatter communications work. Then, T2T networks are analyzed in Chapter 4 to gain deeper insight on such systems and to assess the potential benefit of the proposal. Next, Chapter 5 presents and discusses core analytical results trying to predict the behavior of the real system, which is covered in Chapter 6 with a set of experimental results. Finally, the report closed by conclusions and future work in Chapter 7.

Chapter 2

Related Work

To locate this work within the research space of backscatter communications, a brief literature survey is presented next to assess the state-of-the-art in the field.

The first publication that showed an implementation of tag-to-tag communications [11] dates from 2012. It used an external signal generator as an exciter and it operated in the near field region, reporting an accordingly small range of 25 mm. Next year, a paper then showed that it is also possible to use preexisting sources [9] (such as TV or mobile signals) as a carrier to eliminate the need of a dedicated exciter. Results were not great, but were tremendously improved in a follow-up paper a short year later [12].

Many publications have presented interesting progress and/or applications using this technology [4, 19, 21, 23]. However, virtually all of them, like the aforementioned, are based on one-to-one communications involving only two devices (either a master reader and a tag or directly between tags). Attempts were made to push towards networking with the design a multi-tag protocol already in [9], but were not successful. Working backscatter-based networks are shown in [20,22] but these works still only present single-hop communication.

The phase cancellation problem of T2T communications is presented and examined in [17]. The authors propose to send two copies of every message with a phase shift of 90° between them to overcome the problem. This approach is used as a baseline and the presented method is compared against it.

Two very recent papers [15,16], published only when this project was in the final stages, are the closest to this work. They do successfully demonstrate a backscatter T2T network, albeit they are somewhat limited. They only exhibit one network topology with a single MAC protocol based on frame repetition and lack the implementation of a full network stack.

Chapter 3

Backscattering and Tag Design

This chapter introduces backscatter communications and networking, as well as the design of a T2T node to illustrate the inner workings of the lowest levels of the communication stack. Although tag design is original from Michel Jansen [5] and is outside the scope of this work, a short summary has been included for the sake of consistency and to make the report self-contained.

3.1 Backscatter Communication

Backscatter communication is very present nowadays, but is not new technology by any means. Only a few years after the introduction of radar in WWII, a paper [18] from 1948 presented the breakthrough idea of transmitting information on reflected power. The principle is simple and still applies: by changing the impedance of its antenna, a device can encode information on the reflection of a signal generated by an external source. Fig. 3.1 illustrates this concept.

The transponder or tag receives a power P_1' from the reader, which diodes D_1 and

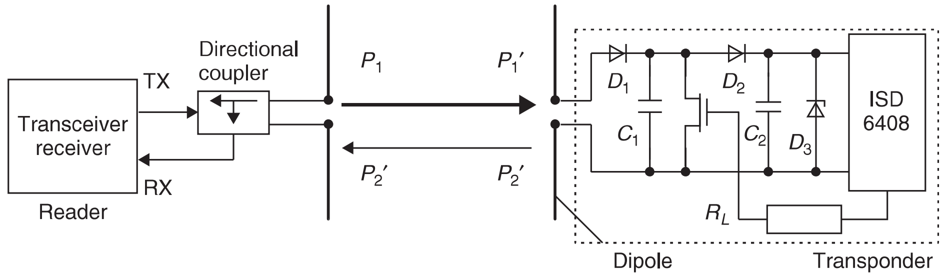


Figure 3.1: Working principle of a backscatter transponder [3].

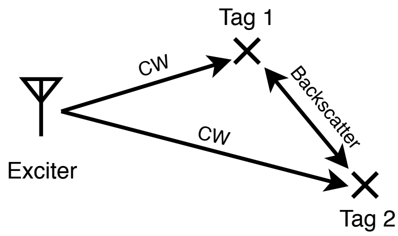


Figure 3.2: Backscatter T2T scenario. *CW*: continuous wave.

D_2 can rectify to feed the system. A fraction of the received power P_1' is reflected by the antenna back to the reader. This portion of reflected power, P_2, can be altered by changing the load R_L connected in parallel to the antenna, which is done by switching the transistor on and off according to the data to be sent, modulating the incoming carrier. Finally, the backscattered signal reaches the reader with power P_2' and can be interpreted.

3.2 Backscatter T2T Networking

Backscatter tag-to-tag (T2T) communications completely dislocate the transmitter and receiver from the power source, allowing nodes that have the same hardware architecture to communicate directly. The idea is that tags can send information, but also receive backscatter signals, and not only reply to a query from a master device. This breaks the master-slave design and sets the tags in the network at the same hierarchical level. From this idea, it naturally follows to think about backscatter networking, in which a number of tags are able to communicate between them, be it directly or hopping over intermediate nodes. A simple example of a T2T backscatter network of only two tags and one exciter is shown in Fig. 3.2.

Backscatter networking enables interesting super low-power scenarios such as distributed processing and/or data collection to track stock in a warehouse or other IoT applications. Furthermore, adding nodes to a network potentially boosts its performance and communication capabilities and enables to go beyond direct tag-to-tag range by means of backscatter T2T multi-hop.

3.3 T2T Node Hardware Design

The backscatter paradigm allows the transceiver design to be relatively simple in hardware terms, as it does no longer require high power components needed in active radio transmitters such as oscillators and amplifiers. The block diagram of the T2T node, shown in Fig. 3.3, is centered around the Texas Instruments MSP430FR5969 MCU that runs the MAC, processes incoming messages and manages transmission. The micro controller is connected to the backscatter transceiver developed in [5] and an energy source.

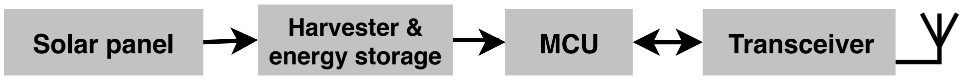


Figure 3.3: Backscatter T2T node block diagram.

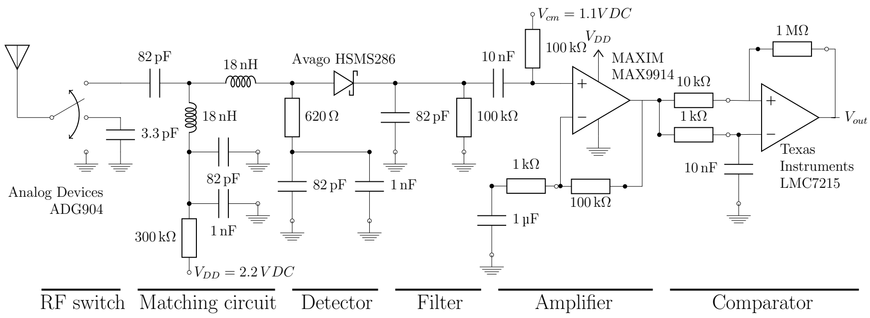


Figure 3.4: Backscatter T2T transceiver design with labeled logical blocks [5].

The general design is similar to the one presented in [6] and Fig. 3.4 shows the detailed schematic of the backscatter transceiver. To modulate the incoming carrier, the transmitter is composed of a radio-frequency (RF) switch that implements amplitude shift keying by changing the impedance of the antenna. Because the device has to be very low-power, the receiver is based on an envelope detector to demodulate backscatter signals. After down-conversion, the signal is digitized with a comparator as a one-bit ADC after filtering and amplification in baseband.

Chapter 4

Network Analysis

This chapter looks at backscatter T2T communications from a network perspective and gives insight on such systems to assess the potential benefit of the proposal, which is also presented. For this, a set of theoretical results are shown to prove the benefit of multi-hop in T2T networks. This analysis will provide fundamental insights which will be observed in both a simulation environment and a real T2T network implementation, presented in Chapters 5 and 6, respectively.

4.1 Backscatter T2T Model Definition

Let us define a flat, square area of length S_a with one exciter E at position (x_E, y_E) and N static tags located at uniform random positions within the area. The exciter transmits a continuous wave (CW) signal of wavelength λ_c and power P_E, which tags can backscatter to communicate with other tags with reflection coefficients k_0, k_1 for symbols 0, 1, respectively. The receiver sensitivity threshold for all tags is P_s and the available power at tag n to backscatter is [17, eq. (2)]

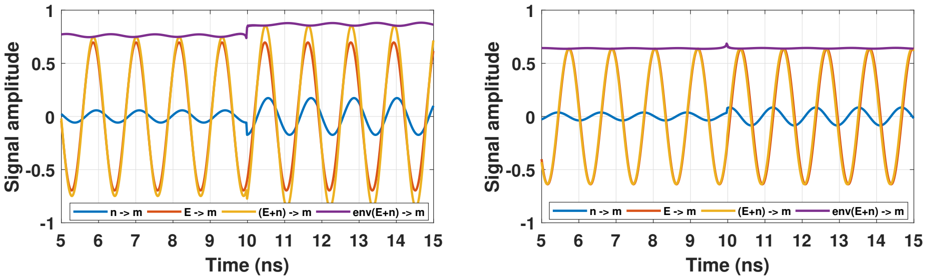
$$P_n = P_E G_E(\theta_{E,n}) G \lambda_c^2 (4\pi d_{E,n})^{-2} \tag{4.1}$$

where $d_{k,l}$ is the distance from device k to l (tag or exciter), $G_E(\theta_{E,n})$ is the antenna gain of the exciter in the angular direction of tag n, $\theta_{E,n}$, and G the antenna gain of the tags. Then, the power received at tag m from tag n is [17, eq. (6)]

$$P_{n,m} = P_n (k_0 G \lambda_c)^2 (4\pi d_{n,m})^{-2}. \tag{4.2}$$

For simplicity, only line of sight, free-space propagation with no fading or noise is considered, as the goal is to provide the simplest bounds on network performance. As $k_0 < k_1$, (4.2) serves as a lower bound to the received power.

The T2T network is modeled as a weighted graph with a set of nodes $\{1, 2, \ldots, N\}$ and a set of directional links $\{L_{n,m}\}$. The weight of a link $L_{n,m}$ from tag n to tag m



(a) No cancellation occurs

(b) Phase cancellation is present

Figure 4.1: Normalized signals involved in T2T communication. From 5 to 10 ns, the source tag is backscattering a 0, and from 10 to 15 ns, a 1. The envelope of received signal varies according to backscattered symbol in Fig. 4.1a, but remains constant irrespectively in Fig. 4.1b. *E*: exciter, *n*: source tag, *m*: destination tag, *env*: envelope. Simulations according to parameters of Table 5.1.

is defined as $L_{n,m} = P_{n,m}$ iff $P_{n,m} \geq P_s$ and $L_{n,m} = \varnothing$, otherwise. A single-hop T2T network is deemed connected if $L_{n,m} \neq \varnothing, \forall n,m$. Meanwhile, a multi-hop T2T network is connected if there exists a path $\forall n,m$ node pairs.

4.2 Phase Cancellation in a T2T Network

Stemming from the fact that the energy source is dislocated from the T2T transmitter, it is possible that the backscatter and the un-modulated exciter signals interfere destructively upon arrival at the destination tag [1]. This phenomenon is called *phase cancellation* [17] and depends on the phase difference of arrival $\theta_{d,m}$: the difference of the phases of the signals arriving at T2T tag m coming from the exciter and the transmitter. Phase cancellation effectively creates signal blind spots in the network and happens when [17, Eq. (18)]

$$\theta_{d,m} = \theta_c = \cos^{-1}\left(-\frac{(k_0+k_1)d_{E,m}\lambda_c G_n}{8\pi d_{E,n} d_{n,m}}\right). \tag{4.3}$$

A practical example of phase cancellation is shown in Fig. 4.1 by simulation, where all signals can be seen separately. As the receiver design of the tags uses a simple envelope detector, it is only able to discern between a zero and a one if there is enough signal level difference in the envelope of the received voltage. What causes the difference between Fig. 4.1a and Fig. 4.1b is only a displacement of 0.16 m of the destination tag away from the exciter, which is also the cause of a lower signal level overall.

[1]Note that by design this is a TDMA system, meaning that only one tag can talk at the same time. Therefore it is enough to study the case of one transmitter and one receiver.

4.3 Non-symmetric T2T Links

From now on, the term 'forward link' will refer to a link going away from the exciter, and conversely for 'backward link'. As seen in (4.1), a tag's available power to backscatter is dependent on its distance to the exciter. This implies the following straightforward observation.

Observation 1. *The ratio of received power between tags n and m in the forward link (from n to m), over the power received in the backward link (from m to n) is quadratically proportional to* $d_{E,m}/d_{E,n}$.

Proof. Directly from (4.2) we can write

$$\frac{P_{n,m}}{P_{m,n}} = \frac{G_E(\theta_{E,n})}{G_E(\theta_{E,m})}\left(\frac{d_{E,m}}{d_{E,n}}\right)^2. \tag{4.4}$$

□

This means that in the useful case where tags are spread away from each other, each T2T link is non-symmetric, with $P_{n,m}/P_{m,n} \gg 1$, meaning that there is a much higher reception probability at the forward link (i.e. a link from the tag closest to the exciter to a tag further away).

4.4 Multi-hop Optimization

Let us start by analyzing the range capabilities of T2T multi-hop networks in two ways: comparing received power with single-hop, and computing the maximum distance such networks can cover. With this purpose we will consider the linear topology depicted in Fig. 4.2.

4.4.1 Power Optimization

Observation 2. *Considering tags 1 and N, the received power from the transmitting tag using multi-hop is always greater than that using single-hop in the backward link, but not necessarily in the forward link.*

Proof. With a little abuse of notation, let $d_{E,1} = d_1$ and $d_{k-1,k} = d_k, \forall k \in [2,N]$. As shown in Fig. 4.2, the received power in the forward link is $P_{1,N}$ for single-hop and $P_{i,N}$ for multi-hop, which depends on the tag i over which the last hop is performed. For presentation compactness, let us define $\ell_a^b \triangleq \sum_{k=a}^b d_k$ that denotes the length of the path between tag a and tag b on the line topology. Using (4.2) again we can compute the power ratio

$$\frac{P_{i,N}}{P_{1,N}} = \frac{P_i(d_{1,N})^2}{P_1(d_{i,N})^2} = \left(\frac{d_{E,1}d_{1,N}}{d_{E,i}d_{i,N}}\right)^2 = \left(\frac{d_1\ell_2^N}{\ell_1^i\ell_{i+1}^N}\right)^2. \tag{4.5}$$

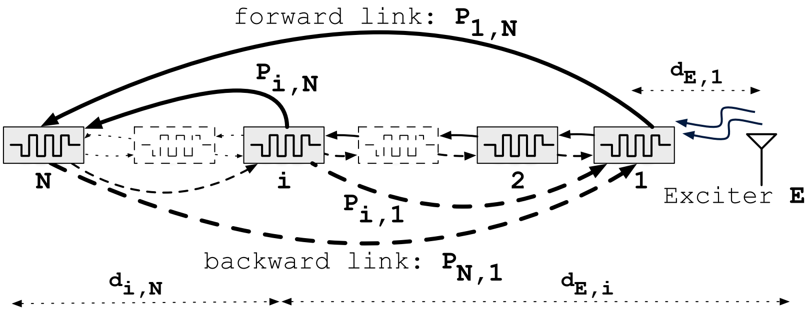


Figure 4.2: Diagram of multi-hop T2T received power analysis scenario.

In the same way, for the backward link the ratio is

$$\frac{P_{i,1}}{P_{N,1}} = \left(\frac{d_{E,N}d_{1,N}}{d_{E,i}d_{1,i}}\right)^2 = \left(\frac{\ell_1^N \ell_2^N}{\ell_1^i \ell_2^i}\right)^2. \tag{4.6}$$

Note that (4.5)>0 and that (4.6)>1, as $1>i>N$. □

Corollary 1. *Assuming that tags are equally spaced on the line topology, i.e.* $\forall k \in [2,N] : d_k = d_1 = d$*, the node i over which the last hop is performed that maximizes received power is* $i = N-1$ *in the forward link and* $i = 2$ *in the backward link.*

Proof. For the forward link (1 to N)

$$\arg\max_i \frac{P_{i,N}}{P_{1,N}}\bigg|_{d_k=d} = \arg\max_i \frac{(N-1)^2}{(i\,(N-i))^2} = N-1. \tag{4.7}$$

The same reasoning applies to the backward link, which results in $i=2$. □

Furthermore, it makes intuitive sense to hop as far as possible as we will be minimizing both the delay introduced by multi-hop and the use of resources in the network in terms of air time. Although this is a 1D network, the derived expressions can be adapted for a 2D one by changing the definitions of distances d_k.

4.4.2 Range Optimization

Still using the topology of Fig. 4.2, let us now derive the distribution of tags that maximizes range in a backscatter T2T network.

Observation 3. *Consider the multi-hop network of N tags placed on a line. The optimal value of the distance between any two tags i and* $i-1$ *that maximizes range and ensures communication in both ways is given by*

$$d_i^* = \frac{1}{2}\left(\sqrt{\left(\ell_1^{i-1}\right)^2 + 4\varepsilon} - \ell_1^{i-1}\right) \tag{4.8}$$

with $\varepsilon \triangleq \lambda^2/(4\pi)^2 G k_0 \sqrt{P_E G_E(\theta_{E,i}) G/P_s}$.

Proof. As shown in Observation 1, the forward link (from $i-1$ to i) is less costly in power. Then, it suffices to guarantee communication in the backward link (from i to $i-1$) by ensuring $P_{i,i-1} = P_s$ so that the received power is greater than the receiver sensitivity threshold. Therefore, it follows

$$d_{E,i}d_{i-1,i} - \varepsilon = d_i^2 + \ell_1^{i-1} d_i - \varepsilon = 0,$$

from which $d_i^* = d_i$ can be solved. □

As more tags are added, they are placed closer together and eventually d_i^* becomes so small that tags are in the near field of their antennae. To avoid this, a minimum inter-tag distance is set to the value of the Fraunhofer distance: $d_{\min} = d_F = 2D^2/\lambda \leq d_i^*$ with D being the largest linear dimension of tag's antennae.

4.5 Multi-hop Robustness

For any network configuration there is a probability that adverse effects drop the received power of one of the links below P_s, rendering a single-hop network disconnected. Since there are multiple, possibly redundant paths between tag pairs in the multi-hop case, the probability of non-connectivity is reduced as more links would need to be eliminated to disconnect the network.

This reasoning also applies to phase cancellation, for which the use of multi-hop helps counter its effects. In fact, the multi-hop gain[2] of a network with phase cancellation effects is higher than that of a network without these effects due to the inherent robustness of multi-hop and relative fragility of single-hop.

4.5.1 Node Count

The number of links L in a complete graph K_N with N nodes is $L = N(N-1)/2$, meaning that the number of potential links in a backscatter network increases with the square of its node count. This implies the following:

Observation 4. *A higher node count enhances connectivity in multi-hop networks, but is actually be counterproductive in a single-hop network, as the probability of non-connectivity scales with the number of links.*

Nonetheless, adding more nodes to a T2T multi-hop network does not necessarily improve connectivity.

Conjecture 1. *The connectivity curve of a multi-hop network as a function of node count is, in general, non-monotonous.*

There are two opposite tendencies working at the same time when adding more tags to a multi-hop network. Firstly, it is more likely that one of the tags is far

[2] Multi-hop gain refers to the ratio of multi-hop connectivity over single-hop connectivity.

enough to not reach P_s in the backward link. Furthermore, more nodes in the same area bring the average maximum inter-tag distance up, making the event of received power go under P_s more likely. This tendency reduces the connectivity of the network. Secondly, more nodes make the network denser and more paths are created. On top of that, the effect of increased average maximum inter-tag distance is less notable for higher node counts, increasing connectivity probability.

There is a certain number of nodes from which the second tendency outweighs the first one. This value depends on the square area size S_a and transmit power P_E and will be studied in the next chapter.

4.6 Combating Phase Cancellation

State-of-the-art solutions to fight phase cancellation in T2T networks consider repeating every packet twice with a 90°-shifted phase, as proposed in [15, 17], to ensure correct reception. This technique is called *phase shifting*. This thesis proposes a different approach in which messages are relayed over other T2T nodes.

4.6.1 Multi-hop Flooding for Phase Cancellation

A very simple decode-and-relay protocol is presented in Algorithm 1. Tags receive incoming frames and relay them when the destination ID does not match their own. They also use the redundancy check (CRC) of recently forwarded messages as a frame identifier to not relay the same information more than once, which eliminates the need of a time to live (TTL) field. Furthermore, since the intended destination tag potentially receives every frame multiple times, some redundancy is introduced in the network. In addition, the observed channel in the experimental results chapter makes the system very sensitive and either frames have very few errors, or they are not able to be decoded. These two characteristics suggest that forward error correction (FEC) is a non-requirement. Note that due to the simplicity of this method, neighbor discovery is also not required.

Algorithm 1 Multi-hop flooding

```
procedure onFrameArrival
    if frame.CRC correct then
        if frame.destinationID == self.ID then
            process frame
        else if frame.CRC not in recentCRCs then
            forward frame
            recentCRCs ← frame.CRC
```

To evaluate the goodness of this solution to the phase cancellation problem, the next section will look at its average network use (in terms of resources) and compare it with the phase shifting method.

Table 4.1: Backscatter T2T Network Efficiency Analysis; 'MH': multi-hop range, 'SH': single-hop range

		Case A: *phase shifting*	Case B: *multi-hop flooding*
Known topology	MH	$E[m] = 2$ $E[t] = 2t_f$ $\Pr(s) = 0$	$E[m] = H$ $E[t] = H(t_f + t_p) - t_p$ $\Pr(s) = 1$
	SH	$E[m] = 2$ $E[t] = 2t_f$ $\Pr(s) = 1$	$E[m] = 1$ $E[t] = t_f$ $\Pr(s) = 1$
Unknown topology	MH	$E[m] = 2$ $E[t] = 2t_f$ $\Pr(s) = 0$	$E[m] = M + 1$ $E[t] = M\left(t_f + t_p\right) + t_f$ $\Pr(s) = 1 - p_c^M$
	SH	$E[m] = 2$ $E[t] = 2t_f$ $\Pr(s) = 1$	$E[m] = M + 1$ $E[t] = M\left(t_f + t_p\right) + t_f$ $\Pr(s) = 1 - p_c^{M+1}$

4.6.2 Network Efficiency Comparison

Let us look at the average number of messages $E[m]$ and average transmission time $E[t]$ it takes to deliver a frame for any source-destination pair, as well as the probability of successfully doing so, $\Pr(s)$. Then, let us consider two cases: (i) known topology: nodes have complete information of all links, and (ii) unknown topology. These two cases are in turn split into cases where source and destination tags are within single-hop range or otherwise (denoted as 'SH' and 'MH', respectively).

Table 4.1 collects all combinations for cases A and B. Case A is the single-hop phase shifting solution and case B is the multi-hop flooding protocol discussed above. When network topology is known the optimum path can be computed, which also enables avoiding links which are down due to phase cancellation (which happen with probability p_c) by preemptively switching the phase of the transmitted frame. Furthermore, the minimum hop count, H, is reached and $E[t]$ is minimized, which is composed of the time-of-flight of a frame, t_f, and the processing time taken by a node to forward a frame, t_p. In the case of unknown topology, an average number of relay nodes M is assumed to be able to forward the message and reach destination.

Comparing cases A and B of Table 4.1, we see that the proposed solution, i.e. Case B, improves network utilization or communication success probability in most cases. However, if source and destination happen to be in direct range when the topology is unknown, it is possible that T2T network use is increased and/or success rate is reduced depending on M and p_c.

Chapter 5

Analytical Results

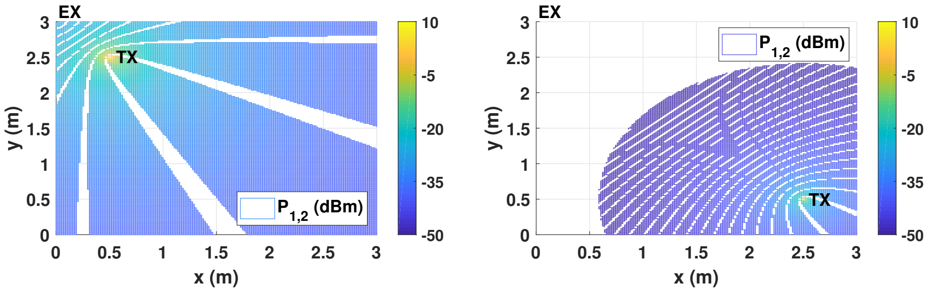
With the goal of illustrating core analytical results and serve as support for the previous chapter, a numerical example is presented next. An instance of a backscatter T2T network is simulated according to the model described in Section 4.1 with the set of parameters given in Table 5.1. Each instance of a T2T network is generated by randomly placing nodes on the area and checking connectivity at every iteration. Each simulation point is an average of 10^4 runs, code can be found in [1].

5.1 Multi-hop Connectivity

To provide a visual representation of phase cancellation in T2T networks, Fig. 5.1 depicts a pairwise tag connectivity map for both forward a backward links. In the first case (see Fig. 5.1a), the transmitter has enough available carrier power to cover the full area. However, white bands of non-coverage appear because of phase cancellation, which describe hyperbolas in the network area. Fig. 5.1b shows the

Table 5.1: Network model parameters used in numerical examples

Symbol	Value	Units	Description
f_c	868	MHz	Center frequency
$(k_0; k_1)$	(0.4; 0.9)	—	Reflection coefficients for symbols 0 and 1
$(P_E; P_s)$	(33; -50)	dBm	Output power of exciter; sensitivity of tags
$(G; G_E)$	(0; 4)	dBi	Antenna gain: tags; exciter
$(\theta_E; \theta_c)$	(-45; 40)	$^\circ$	Exciter antenna: beam direction; beam width
(x_E, y_E)	(0, 3)	m	Cartesian coordinates of exciter
S_a	3	m	Side of the square area of the T2T network
P_T	-6	dBm	Output power of tags (only in Fig. 5.2b)
d_1	3	m	Distance from exciter to first tag (only in Fig. 5.3a)
N	10	—	Number of tags (only in Fig. 5.3b)



(a) Forward link

(b) Backward link

Figure 5.1: Pairwise tag connectivity with simulation parameters of Table 5.1. *EX* and *TX* mark the positions of the exciter and transmitter, respectively; receiver position variable. Phase cancellation bands are clearly visible. Fig. 5.1a transmitter can cover the network area. Fig. 5.1b transmitter offers limited coverage.

case for backward link and the same phase cancellation bands show up as white stripes, although this time the transmitter is not able to cover the full area because available power at its position is not sufficient. Notice in this case the regular radiation pattern due to the omni-directional antenna of the T2T node.

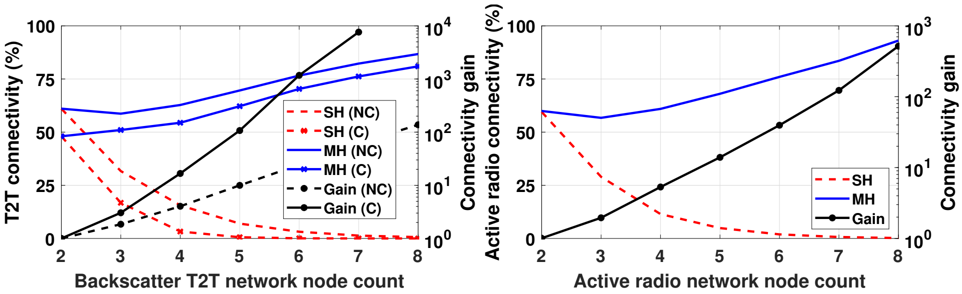
As predicted in Observation 4, backscatter T2T single-hop connectivity does rapidly decrease with N, see Fig. 5.2a, and more so when accounting for phase cancellation, improving the multi-hop gain. Also, phase cancellation effects become less relevant with a denser T2T network as both multi-hop curves converge as N grows.

Conjecture 1 gains weight considering the slight convexity of multi-hop connectivity for the case of no cancellation. What is more, this behavior is not unique to backscatter networks since it depends on network topology as explained in Section 4.5.1. This is confirmed by the connectivity curve of a comparable active radio network –shown in Fig. 5.2b– in which radio links are symmetric and there is no phase cancellation.

5.2 Multi-hop Range

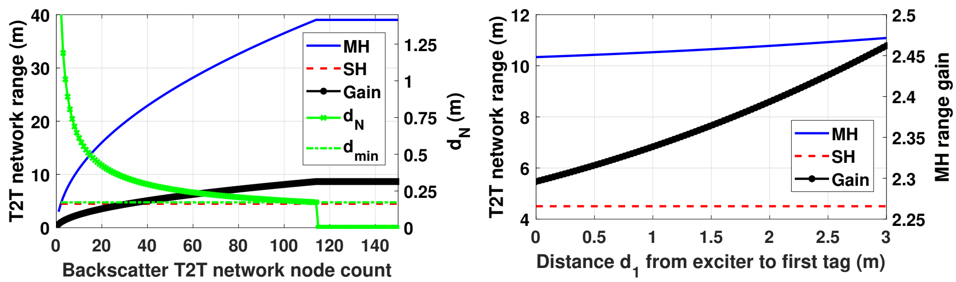
Fig. 5.3 presents the maximum communication range achieved by a one-dimensional backscatter T2T network while ensuring two-way communication. The maximum range was computed according to analysis presented in Observation 3. When $d_N \leq d_{\min}$, network range can no longer be increased, see Fig.5.3a, but until then, multi-hop range increases logarithmically with the number of nodes, opposite to inter-tag distance d_N.

To portray multi-hop range extension with a lower number of nodes as well, Fig. 5.3b illustrates the range of a network of only ten nodes as a function of d_1. It also allows to more clearly see that range can be more than doubled with only this



(a) Backscatter T2T network **(b)** Active radio network

Figure 5.2: Numerical example of network connectivity with simulation parameters listed in Table 5.1. Fig. 5.2a: multi-hop versus single-hop full connectivity (*all* nodes connected with each other, either only directly, SH, or through other tags, MH) with and without phase cancellation; Fig. 5.2b: output power of tags (-6 dBm) chosen to match connectivity of backscatter network; *SH*: single-hop, *MH*: multi-hop, *NC*: no phase cancellation, *C*: phase cancellation.



(a) Maximum range over node count **(b)** Maximum range over d_1

Figure 5.3: Maximum range of a one-dimensional T2T multi-hop network. Simulation parameters listed in Table 5.1. Node count is critical for range extension, while d_1 hardly makes a difference. *SH*: single-hop, *MH*: multi-hop, d_N: inter-tag distance, d_{min}: minimum value of d_N.

amount of tags. In addition, it shows that, as for node count, multi-hop range also increases with d_1, albeit it does so moderately, while the former is critical. Note: A maximum d_1 value of 3 m was chosen, as a larger distance is impractical in a realistic scenario.

Limitation of T2T backscatter networks

As backscatter signals are very weak, the main bottleneck of T2T networks is the signal detection threshold of the tags, P_s, which causes reduced coverage and range. Precisely because of this, traditional tag-to-reader networks would outperform a T2T counterpart in in this regard.

Chapter 6

Experimental Results

The theoretical results are now demonstrated in practice by means of a few experiments that show the performance of the proposed approach in the largest multi-hop backscatter T2T network demonstrated to date, to the best of the author's knowledge. The setup and measurement methodology is introduced first.

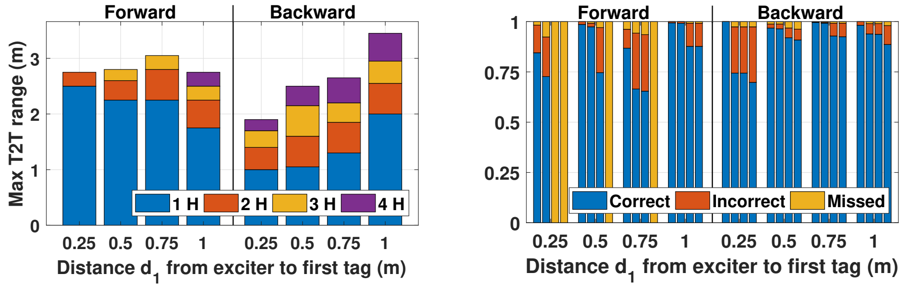
6.1 Setup and Methodology

All experiments were performed indoors, in a 6.75 m×10.80 m office space with many metallic shelves and concrete walls. A total of seven tags with 868 MHz, 3 dBi whip antennae were used in the experiments, mounted on tripods elevated 1 m above ground. Two signal generators (Agilent E4438C ESG and Hewlett-Packard HP8648C) were used as exciters. They were set to a power output of 21 dBm (with an amplifier for the HP) and connected to a 915 MHz, 8 dBic right-hand circularly polarized antenna also mounted on a 1 m tripod within line-of sight of the tags.

6.2 Range and Performance of Multi-hop

Measurement Methodology. Each measurement (data point in Fig. 6.1) is the average of five runs, each of them consisting of a hundred frames sent by the source tag. The maximum distance of a hop is assumed to be reached when 75% of the frames are correctly received at the destination and was found experimentally.

Fig. 6.1 presents the core results on the multi-hop T2T link properties. Measurements of the range improvement that multi-hop brings to backscatter T2T networks are given in Fig. 6.1a, both for forward and backward links. The figure shows the maximum distance that can be covered in a line multi-hop backscatter T2T network as a function of the number of hops and the distance d_1 from the exciter to the first



(a) T2T multi-hop range at hop H

(b) Received frame distribution

Figure 6.1: T2T link metrics for forward and backward link. Fig. 6.1a: the backward link has a higher multi-hop gain, *doubling the range* as receiving tag moves away from the exciter; Fig. 6.1b: frame distribution per hop (ordered from left to right in each bar group)—backward link is less prone to errors .

T2T node. The maximum number of hops is shown, meaning that, for instance for $d_1 = 0.25$ m only two hops were achievable in the forward link.

The core observation is that the ratio of first versus subsequent hops distance (i.e. multi-hop range gain) increases with d_1 mainly because the first hop becomes shorter as less power to backscatter is available at the first node. Furthermore, when tags are moved away from the exciter, equivalent changes in distance have less impact on available carrier power due to the logarithmic nature of path loss, enabling more hops and further increasing total T2T range. This is also the reason why the overall range remains approximately constant irrespective of d_1 in the forward link, but increases in a linear trend in the backward link. Additionally, as predicted by Observation 2, multi-hop gain is higher in a backward link, increasing range by about a factor of two already at four hops.

In Fig. 6.1b the cumulative received frame distribution per hop is shown as a function of d_1, for both forward and backward links. Bars are grouped in order of hops, such that the leftmost bar of a group refers to the first hop, and the rightmost to the last possible hop for that distance. A completely yellow bar means that the hop was not achievable. The main observation here is that the *backward link has a more stable* behavior.

6.3 Phase Shifting vs Multi-hop Flooding

Measurement Methodology. A 2 m×2 m area is divided into a grid of 0.5 m increments. The exciter is positioned at relative location (0,0) m and the source tag is located at (0.5,0.5) m and (1.5,1.5) m for forward and backward link testing, respectively. Each data point in Fig. 6.3 is the average of three runs of twenty five frames each.

The performance of multi-hop as a solution to phase cancellation is covered next.

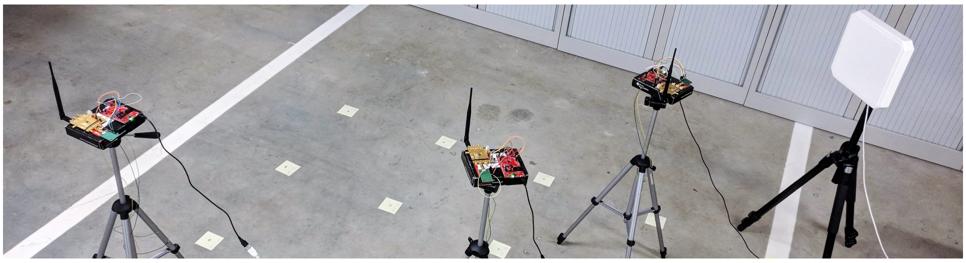


Figure 6.2: Photograph of the setup to evaluate phase cancellation countermeasures in T2T networks, discussed in Section 6.3: Three backscatter T2T tags on tripods, next to white panel antenna. Grid coordinates marked with yellow squares.

It is also compared against phase shifting for the same purpose (i.e. sending every frame twice with a phase offset of 90°). This experiment also shows the robustness increase in the T2T network by the use of multi-hop, as adding or subtracting relaying tags simulates the case of message forwarding during interference and network reshaping, e.g. from T2T tag mobility.

A destination tag is placed at each coordinate of the grid and the rate of correct frame reception is measured. Then, the result of this benchmark is compared the two approaches. Relaying tags are added at the closest grid coordinates to the middle point between source and destination tags, forming a two-dimensional network, see Fig. 6.2. For the sake of comparison fairness, the multi-hop approach uses only one relaying tag (e.g. two hops) so that both solutions are balanced in network utilization: twice the original number of frames in both methods.

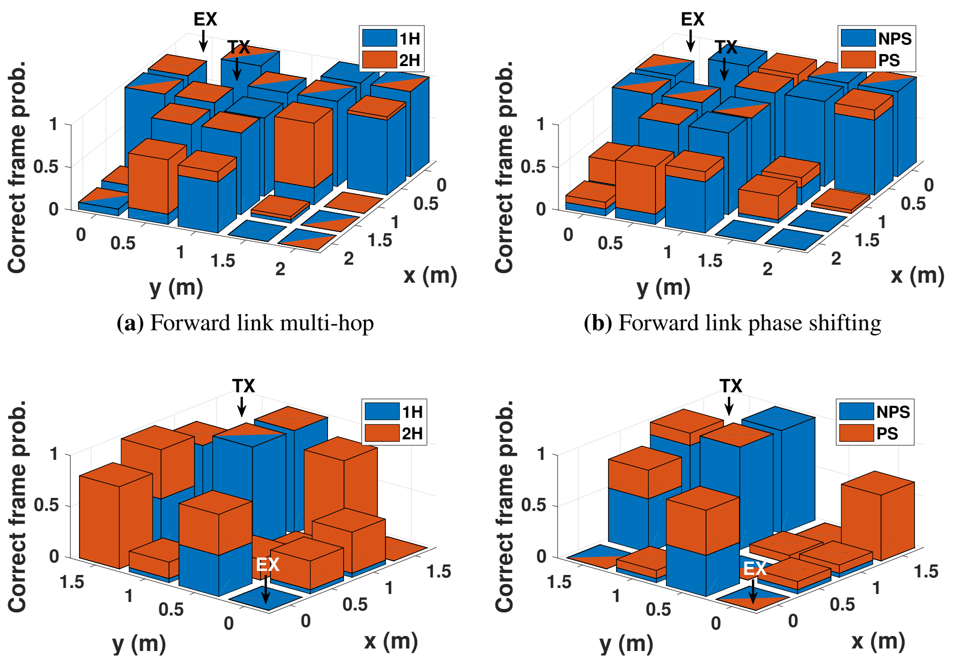
Fig. 6.3 presents the results of the experiment, while global (average) coverage values are shown in Table 6.1. Note that for the backward link the network area was reduced to 1.5 m×1.5 m due to the weaker nature of this link (transmitter available carrier power would be too low other). Points of weak reception in the area can be caused by phase cancellation or by multi-path fading due to the unfavorable testing environment. This explanation gains relevance when reception is greatly improved by adding a relay tag or by using phase shifting. However, other points could not be enhanced by either method, probably because of other uncontrolled factors that hinder the RF channel.

In the forward link, multi-hop and phase shifting as means to fight phase cancellation report close results, improving coverage moderately by about 1.13×. On the other hand, the backward link is better handled by the multi-hop solution, almost doubling T2T network coverage. Multi-hop is therefore preferred in either case, as it also adds range extension and robustness to the T2T network.

Table 6.1: T2T Network Coverage: Summary of Fig. 6.3 results

	Vanilla* (%)	Phase shifting† (%)	Multi-hop flooding†(%)
Forward link	58.1	67.3	65.0
Backward link	28.0	40.9	54.3

* No phase cancellation fighting mechanism, i.e. traditional single-hop T2T communication
† As analyzed in Section 4.6



(a) Forward link multi-hop
(b) Forward link phase shifting
(c) Backward link multi-hop
(d) Backward link phase shifting

Figure 6.3: Backscatter T2T network phase cancellation experiment. *EX* and *TX* mark the positions of the exciter and transmitter, respectively. *(N)PS*: (no) phase shifting. Fig. 6.3a and 6.3b: forward link. Both methods yield comparable results. Fig. 6.3c and 6.3d: backward link. Multi-hop is superior in network coverage. Note: *1H* and *NPS* is the same case.

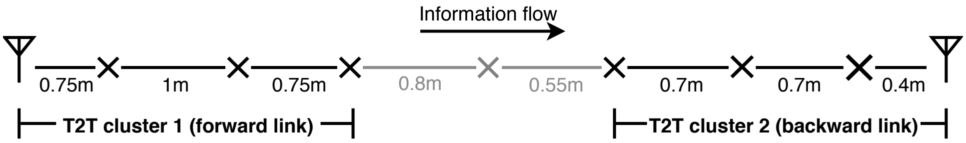


Figure 6.4: Two multi-hop T2T clusters are joined together by a bridging node.

6.4 Proof of Concept: Joining T2T Backscatter Clusters

As a final experiment, a small proof of concept showcasing the junction of two tag clusters is presented. This example demonstrates the possibility of joining distinct backscatter T2T networks with their own exciters by placing an extra node such that both groups are able to exchange information through it.

The first cluster was located at one side of the laboratory and consists of three tags, spanning a distance of 2.5 m from their exciter. At the other side of the laboratory there is a second cluster, also composed of three tags, reaching 1.8 m from the other direction. Fig. 6.4 illustrates this setup. By placing an seventh tag in a middle point between the two groups, both clusters are able to reach it and successfully establish a communication flow from one side to the other. There is a forward link in the first cluster (left side in Fig 6.4), followed by a backward one in the second cluster of tags, covering a total distance of 5.65 m.

The concept of joining separate T2T clusters fed with different exciters proves to be of interest, as it can open up a few applications in cases where a larger area has to be covered, such as warehouses or commercial spaces.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

In this thesis, backscatter tag-to-tag networks have been modeled, analyzed and simulated to gain a better understanding of the system and to assess how key parameters affect different metrics of such networks. After that, a set of experiments have been conducted to verify and quantify the predicted behavior in a demonstration of the largest multi-hop decode-and-relay T2T network using distributed embedded backscatter transceivers. The theoretical analysis and numerical results were able to correctly predict the trends and behaviors observed in the experimental results, as well as finding the optimum parameters for multi-hop range extension, amongst others interesting remarks.

A multi-hop mechanism was proposed to counter the phase cancellation problem of T2T backscatter networks. Results show that such approach is superior to phase-shifted frame repetition in mitigating effects of dead spots in the network and that it benefits the backward T2T link (tag far from the exciter sending to the tag close to the exciter) much more than the forward link. Furthermore, it also enhances network connectivity and extends the communication range, which can open up new applications for this technology.

7.2 Future Work

In spite of the fact that progress was made, the work on T2T communications and networking is of course not complete. Receiver sensitivity is the main parameter that holds back the range of T2T networks, so it should be one of the first points to address. However, doing so without increasing energy consumption proves to be a challenging task. Other improvements are also needed, including a transceiver design with antenna diversity to leverage redundancy for space-time coding or to implement a full-duplex protocol.

A good simulation tool was built for analysis and rapid prototyping, but a more accurate propagation and network models would yield more reliable numbers that could enable more sophisticated network planning and deployment.

Furthermore, the communication protocol can be improved on a few aspects. To speed up the design process, security and data authenticity was not considered. Cryptography or other message obfuscation techniques are an interesting addition, especially on information-sensitive applications. Although the flooding protocol proved to be useful, a different routing protocol paired with a dynamic rate adaptation mechanism are also points of improvement.

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