Backscatter Communication for Wireless Robotic Materials

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Abstract

Robotic Materials can change their physical properties programmatically by integrating sensing, actuation, computation and communication. The latter can be carried out by wireless devices that are distributed in a dense network within the material and that operate with energy harvested from the environment. Recent progress on backscatter communications enables devices that, assisted by an external unmodulated carrier, receive and transmit data at short range with sub-milliwatt power consumption. We term this communication paradigm carrier-assisted communications. In this work we propose carrier-assisted communications for robotic materials and employ simplified analytical models to study the necessary unmodulated carrier strength. We find that relaying a message over multiple hops requires less intense carriers than doing a single transmission. Additionally we find that multiple distributed carrier generations can further reduce the necessary output power of the individual carrier generators.

1 Introduction

Wireless robotic materials have been identified as one of the future directions of wireless communications research [2]. Robotic materials are composite materials that can programmatically alter their physical properties such as shape or color in response to external stimuli or commands. Robotic materials can enable applications such as air-crafts that can adapt their aerodynamic profile to varying flight modes, intelligent robots with smart muscles that can be excited to specific configurations and commands, autonomous cars with tires that can recognize the ground and textiles that can sense pose and environment [2]. To this end, robotic materials must integrate sensing, actuation, computation and wireless communication. The latter is necessary when sensors need to trigger actuators. Because communication devices need to be embedded within the material, there is little room for batteries or power lines. Instead, the ideal communication devices for robotic materials operate without batteries on harvested energy from their environment.

A new class of carrier-assisted battery-free communication devices with dramatically reduced power consumption are particularly suited for robotic materials. These are devices that combine, on a single device, new backscatter communication techniques to transmit standard wireless protocols such as 802.15.4 [4, 5, 6, 12] with recent advances in receiver architectures to receive the same protocols [3, 13] by replacing the power-hungry local oscillator by an external carrier. We refer to this combination as carrier-assisted transceivers.

We believe that this new communications paradigm of carrier-assisted communication is ideal for robotic materials due to its ability to operate on small amounts of energy that can be harvested from the environment. The need for an external unmodulated carrier and the relatively short communication range, however, introduce unprecedented challenges. In this work we employ simple analytical models to study the feasibility of employing carrier-assisted communications to relay messages within a robotic material. Our goal is to reduce the necessary output power of the carrier generator which might be important, for example, in medical applications where one wants to reduce the electromagnetic radiation on the material or on the human body on which the material is placed. Another reason to reduce the output power might be the overall energy expenditure of a carrier generator to extend its lifetime or enable carrier generators that operate on harvested energy.

We investigate the impact of node density and number of carrier generators in multi-hop communication to reduce the output power of the carrier generator compared to single-hop communication over longer distances.

Approach. We study different configurations and densities of networks within the robotic material using simple analytical models. We employ the well known Radar Range equation [1] to model transmissions from backscatter devices and model the sensitivity of carrier-assisted receivers with a phenomenological model derived empirically.

Contribution and results. We show that in many scenarios, the carrier output power required to transfer packets within robotic materials can be reduced by relaying messages within the material using multiple hops. Having multi-

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ple carrier generators further improves the availability of sufficiently strong carriers without having exceedingly strong Radio Frequency (RF) emissions.

We make the following contributions:

- We introduce carrier-assisted communications to robotics materials and show their suitability to this technology.
- We show that relaying data over multiple hops allows to reduce the output power of the carrier generator in many scenarios.
- We demonstrate a further reduction of the required individual carrier's output power when using multiple carrier generators.

Outline. After a brief motivation we continue our paper with some necessary background in Section 3. Section 4 contains an evaluation to determine the suitability of applying backscatter to wireless robotics materials. While Section 5 presents related work, we conclude our work in Section 6.

2 Motivation

Wireless robotic materials are an evolution of robotic materials (see McEvoy and Correll [8] for an extensive list of examples) to enable new types of applications since wires make robotic material difficult to manufacture and susceptible to failure [2].

In this section, we provide some examples of wireless robotic materials. By introducing backscatter communication in wireless robotic materials, we enable useful applications that have to operate with low radiated power. We consider in particular two types of applications: (i) applications that are on or close to the human body and (ii) applications primarily used by children.

Smart textile material that can adapt color and thickness to environmental conditions such as temperature and humidity is one such application. The system needs to communicate messages with sensor values across the material at low power. This is an ideal situation to use battery-free carrier-assisted device that meet these requirements. A similar application, also mentioned by Correll et al. [2], are active bandages that monitor and adapt to the status of a healing wound and seal over it.

Applications primarily used by children should also use low-power communication as the negative effect of strong RF waves on the human body cannot be ruled out and children might be more susceptible. We imagine Lego-like mini toys that can communicate a signal for actuation of a unit within itself with minimum power. Another application of this communications paradigm is disseminating messages among a set of miniature toys to make them change colours or other functions.

3 Background

In this section we introduce carrier-assisted communications and explain link characterization, pointing out important differences to conventional radios.

3.1 Carrier-assisted Communications

Carrier-assisted transceivers leverage an external unmodulated carrier for transmissions and for reception with drastically reduced power consumption when compared to conventional radio transceivers. To transmit, the devices employ backscatter communications, while for reception they employ a receiver with an external carrier instead of a local oscillator. We now present the operating principles of each of these techniques.

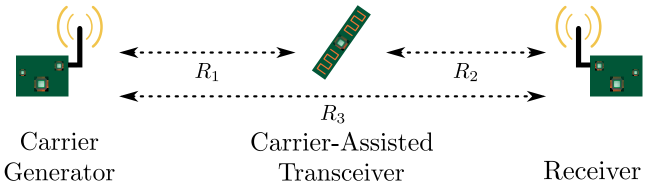

Figure 1. Devices involved in carrier-assisted communications. The received signal strength depends on both distances R_1 and R_2. The receiver sensitivity depends on the distance R_3.

Backscatter transmissions. Backscatter transmitters work by reflecting an external RF signal to convey useful information [6, 7]. This technique is attractive because it allows to transmit data with up to three orders of magnitude lower power consumption than traditional radios, as transmitters do no need to generate their own RF waves. Instead, the transmitter modulates its antenna's radar cross-section by simply toggling a switch across the antenna terminals, which consumes very little power. The radar cross-section changes cause variations in the way the external RF signal is reflected. A receiver can then observe those changes to decode the transmitted data.

Carrier-assisted receiver. In a way analogous to backscatter transmitters, an external carrier can help a receiver operate with a power consumption well under 1 mW [3, 13] while remaining compatible with unmodified commodity devices. Such a carrier-assisted receiver sidesteps power-hungry blocks commonly found in traditional radio receivers such as local oscillators and Analog-to-Digital Converters (ADCs) by employing passive circuits whenever possible. Specifically, it offloads the Local Oscillator (LO) to an external device that broadcasts an unmodulated carrier. The receiver then employs a passive diode mixer to downconvert the RF signal to a low Intermediate Frequency (IF), where it can be further treated easily and efficiently.

A receiver of this kind, when paired with a backscatter transmitter enables battery-free devices that can receive and transmit data with sub-milliwatt power consumption while assisted by an external carrier. These devices are particularly adequate for smart robotic materials owing to their ultra-low power consumption.

3.2 Carrier-assisted Link Characterization

Carrier-assisted radio links have particular characteristics that differ significantly from traditional ones. In both types of links, the information carrying signal is emitted from one device and received by another after suffering a certain path loss. In carrier-assisted links, however, the carrier must additionally be supplied through a radio link from an external device. The need for an external carrier is the main difference between carrier-assisted communication devices and their traditional counterparts.

Signal strength for backscatter transmissions. The Radar Range equation [1, 6] describes the power (P_r) of a backscattered signal observed at a receiver and coming from a backscatter device separated from the carrier generator by a distance R_1 and from the receiver by a distance R_2 (Figure 1).

$$P_r = \left(\frac{\lambda^2 P_t G_t}{16\pi^2 R_1^2}\right)\left(G_b^2 \alpha \frac{|\Delta\Gamma|^2}{4}\right)\left(\frac{\lambda^2 G_r}{16\pi^2 R_2^2}\right) \quad (1)$$

Here P_t is the output power of the unmodulated carrier, G_t, G_b and G_r are the antenna gains of the carrier generator, battery-free device and receiver respectively, λ is the wavelength of the signal, α is a constant that describes losses incurred in modulating the signal using backscatter and $|\Delta\Gamma|^2$ is the backscatter coefficient [6], which is a measure of the efficiency of the backscatter process.

Carrier-assisted receiver sensitivity. The sensitivity of carrier-assisted receivers depends on the strength of the unmodulated carrier signal [13]. Carrier-assisted receivers rely on a passive diode mixer to downconvert the RF signal at sufficiently low power consumption. The efficiency of the diode mixer (conversion loss [10]), depends on the strength of the unmodulated carrier [13]. This is the main reason why, unlike in traditional receivers, there is no single sensitivity value in these devices. Instead, we must model the dependency of the sensitivity on the incident unmodulated carrier signal strength. To that end, we have evaluated the sensitivity threshold S_{th} of a real carrier-assisted prototype like the one presented in [13] and extracted the following empirical model:

$$S_{th} = \frac{C}{P_i} \quad (2)$$

Here P_i is the incident carrier power and $C = 10^{-12.5}$ is a constant obtained experimentally.

To model how S_{th} varies with the carrier output power we employ the Friis Equation [1] to compute P_i:

$$P_i = P_t G_t G_r \frac{\lambda^2}{16\pi^2 R_3^2} \quad (3)$$

Where R_3 is the distance between the receiver and the carrier generator.

4 Evaluation

In this section we evaluate if relaying a message over multiple hops of carrier-assisted devices requires less output power from the carrier generator than a single hop. We evaluate the role of the distance from the carrier generator to the carrier-assisted devices in communications within a robotic material. We also show how having multiple carrier generators further reduces the necessary unmodulated carrier output power.

We base our analysis on the assumption that the signal power at the receiver P_r must overcome the sensitivity threshold S_{th} of the receiver for successful decoding of the data. This leads to the condition: $P_r > S_{th}$. Substituting Equations 1, 2 and 3 into the condition, we obtain the following equation for the minimum required carrier generator output power P_t after rearranging terms:

$$P_t > \frac{\sqrt{C}}{G_t G_b G_r \sqrt{\alpha}\frac{|\Delta\Gamma|}{2}} \frac{4\pi R_1}{\lambda}\frac{4\pi R_2}{\lambda}\frac{4\pi R_3}{\lambda} \quad (4)$$

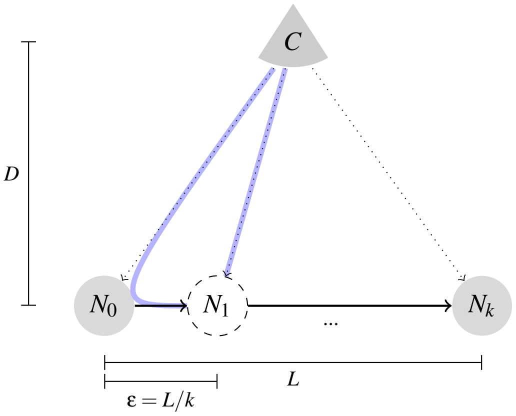

Figure 2. Single carrier generator setup. With this setup we evaluate single hop and multihop scenarios with a single carrier generator (C). Carrier-assisted devices ($N_0 \ldots N_k$) are arranged on a regular linear grid of $k+1$ nodes covering the distance L.

4.1 Single Carrier Generator

We first study the properties of multi-hop scenario with a single carrier generator assuming the robotic material is embedded with carrier-assisted devices forming a dense network. We evaluate how the distance between the carrier generator and the carrier-assisted nodes affects the power required from the carrier generator for successful reception of the data signal.

We further evaluate how the distance between two consecutive carrier-assisted devices affects the communication in the material.

Setup. We analyze a setup that consists of one carrier generator and k carrier-assisted devices arranged in a uniform unidimensional grid of spacing ε covering a distance L. We approximate the distance from the carrier generator to the devices as a constant D. Figure 2 represents this setup where C is the carrier generator, N_0 is the transmitter and N_1 is the receiver. We evaluate the minimum carrier generator power needed for the reception using Equation 4. Note that the communication distance covered is very small. The reason for this is that we are aiming at receiving a signal that has been backscattered (and therefore is weak) with a carrier-assisted receiver that has a relatively poor sensitivity [13].

In our analysis we change the density of the network by altering the number k of carrier-assisted nodes deployed over the distance L. With a single carrier-generator, we evaluate the dependency of the minimum necessary carrier generator power with the network density.

Result. The results show that the necessary carrier output power decreases with the distance between transmitter and

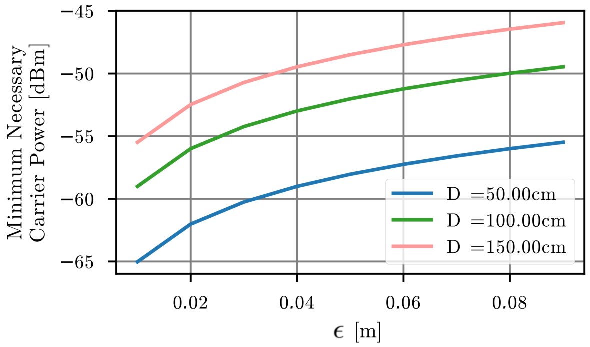

Figure 3. Power required from Carrier generator. The further the distance between carrier-assisted devices, the higher the power required.

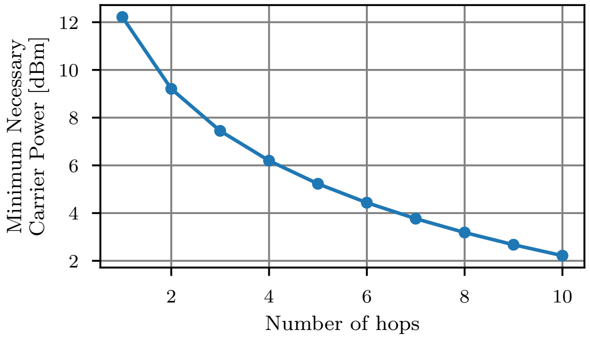

Figure 4. Power required from the carrier generator for different number of hops. As the number of hops increases, the required power from the carrier generator decreases.

receiver (ε) as expected. Likewise, according to Equation 4, when the distance to the carrier generator increases, the required power increases linearly. Figure 3 shows the results.

Figure 4 explains how the node density affects the minimum carrier-generator power needed for reception. As expected, when we increase the number of hops (k) by adding relay nodes, the required power from the carrier-generator decreases. This implies that we can relax the requirements on the carrier output power by increasing the number of hops in the network.

Figure 5 further exemplifies the dependency of the required carrier generator power with the number of hops and the distance to the carrier generator. As the carrier generator moves away from the nodes, the necessary output power increases. Increasing the number of hops decreases the distance between consecutive nodes, offsetting the necessary carrier output power.

Asymmetric Relay Density. In an actual wireless robotic material, wireless nodes may not be distributed uniformly with equal distance to all their neighbors as in our assumption. Even in such a scenario, it would be possible to define a maximum, worst case, distance between neighbor nodes and this would establish the minimum necessary carrier power.

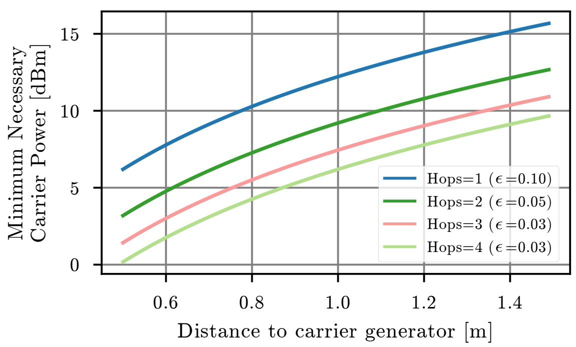

Figure 5. Minimum Carrier Power required for Multiple Hops. As the carrier generator moves away from the nodes, the necessary output power increases. Increasing the number of hops decreases the distance offsets the necessary carrier output power.

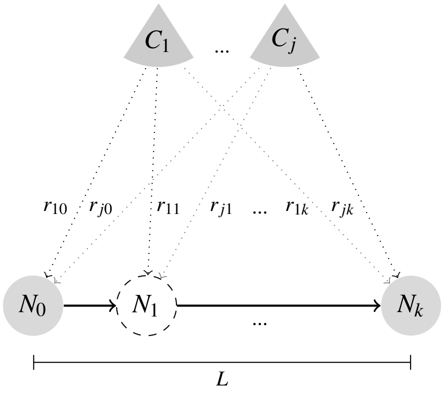

Figure 6. Multiple carrier generators providing carrier for multiple carrier-assisted devices. Messages are relayed by k nodes to traverse the distance L.

4.2 Multiple Carrier Generators

We evaluate how multiple carrier generators help reduce the necessary carrier output power of the individual carrier generators in wireless robotic materials.

Setup. We analytically evaluate the same scenario as in Section 4.1 but place multiple carrier generators distributed uniformly in parallel to the line of carrier-assisted nodes that cover the segment L. Figure 6 shows the setup. The distances from the carrier generators to the carrier-assisted devices ($r_{10} \dots r_{jk}$) is much larger than the separation among them ($r_{10} \dots r_{jk} \gg \varepsilon = L/k$). We make the approximation that the distance between carrier generator and transmitter is equal to the distance between carrier generator and the adjacent receiver, that is $R_1 = R_3$ in Equation 4. So in Figure 6, if we consider the carrier generator C_1 providing the carrier to transmit a message from N_0 to N_1, the distance r_{10} is considered equal to r_{11}. For every transmitter receiver pair, we compute a new value of R_1.

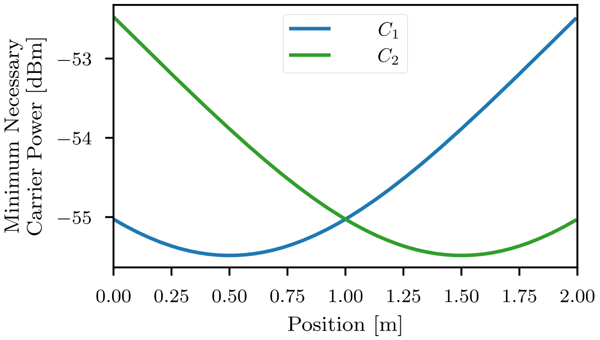

Figure 7. The carrier generator requires minimum power when it is aligned with the carrier-assisted node. The further the distance, higher the power required. After a threshold the carrier source can be transferred to another carrier generator to reduce the necessary power.

Result. Figure 7 depicts the result of the experiment. The further the distance between carrier generator and carrier-assisted node, the higher the power required from any individual carrier generator. After a threshold distance a neighboring carrier generation can take over in assisting to relay a message. This implies that delegating the task of carrier generation to multiple nodes helps reduce the minimum power required from any individual carrier generator.

Suitable Number of Carrier Generators. The result above is useful in situations where one needs to convey a message over a given distance in the robotic material subject to limited carrier power. In such a case, it is possible to compute the number of necessary carrier generators. For example, in Figure 6, the fixed length of the material is 2 m and the minimum carrier power required -55 dBm. In Figure 7, we see that C_1 exceeds this limit at 1.50 m. By using two carrier generators, we can cover the entire distance while supplying sufficient carrier power to all nodes.

5 Related Work

Communications in robotics material are necessary to support sensing and actuation. The service can be supported by wireless devices distributed inside the material [2]. Carrier-assisted devices have been developed to support transmissions as well as receptions of standard wireless protocols at sub-milliwatt power consumption [3, 13], which is ideal for robotic materials. We have recently designed and implemented a simulator that supports these ultra-low power communication mechanisms [11].

There have been recent attempts to introduce multi-hop backscatter networks [9, 14]. Our work is different from these as we first receive a backscattered transmission and then forward it rather than backscattering the same signal twice.

6 Conclusions

We have introduced carrier-assisted communications to robotic materials. We show that the carrier output power required for the carrier-assisted devices, to transfer packets within the robotic material can be reduced by relaying messages within the material using multiple hops. Our analytical evaluations show that having multiple carrier generators further reduces the carrier output power needed from each carrier generator for reliable communication.

7 Acknowledgments

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