Anti-collision Tags for Backscatter Sensor Networks

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***Abstract*— This work analytically quantifies and attempts to alleviate the collision induced by a number of tags that operate via backscatter communication, i.e. modulate the reflection of a *common* carrier transmitted by a central hub. For omni hub antenna, it is shown that acceptable anti-collision performance can be engineered *only* when appropriate modulation at each tag is employed. When a beamforming hub antenna with moderate main lobe width and side lobe level (SLL) is instead used, the aggregate communication bandwidth is significantly reduced, or equivalently, the aggregate number of tags is amplified. Analytical results apply to general forms of backscatter communication, potentially useful in classic RFID systems.**

I. INTRODUCTION

Communication based on the modulated reflection of a transmitted carrier has had a long history and one of the first papers appeared in the middle of the previous century [1]. Recently, it was experimentally shown that such communication can be used for low-cost, low-bit rate sensor networks, with the use of simple, software-defined radio [2].

In such networks, each sensor does not actively transmit a signal, but instead modulates information on its antenna reflection coefficient, by switching a simple transistor, connected to the antenna, between two states. In that way, information from the sensor to the central hub is conveyed on the backscattered signal, and each *sensor radio* becomes low-power and low-cost: energy spent for communication is restricted to the energy used for switching on/off a transistor for modulation purposes, without any sensor requirements for signal conditioning (e.g. amplification, filtering or up/down-conversion) or even a receiver structure. Range restrictions, inherent in backscatter communication, are bypassed with the utilization of each sensor's battery, already present and necessary for the sensing electronics. Work in [2] assumes for a fixed hub carrier frequency that each tag has a modulating (subcarrier) frequency (i.e. the frequency of switching between two antenna states), *sufficiently* different from the rest of the tags. In that way, tag-collision among various sensors is not an issue.

In this work, the tag-collision probability is analytically derived and the minimum spacing between the sensor subcarriers for acceptable anti-collision performance is calculated. It is further shown that only specific modulations are appropriate for such backscatter sensor networks, especially when large number of tags are desired. Finally, it is shown that the use of a moderately directive, beamforming hub antenna can significantly decrease the aggregate required communication bandwidth, or equivalently amplify the number of allowable tags for acceptable anti-collision performance. Analytical derivations are not specific to battery-assisted or battery-less tags and could apply to various forms of backscatter communication, as in classic RFID systems where tag-collision (e.g. [3]) is a major headache.

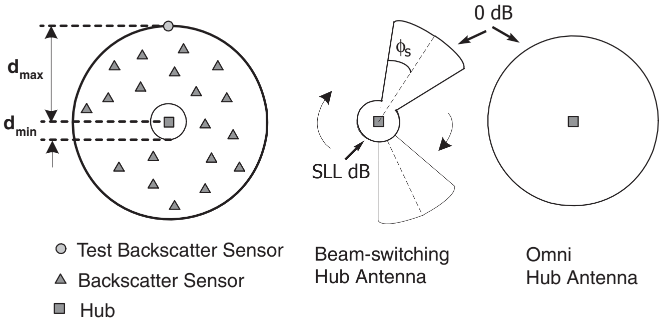

Fig. 1. $N+1$ sensors are randomly located in the periphery of the hub. A beamforming or an omni hub antenna are considered.

Section II provides the basic assumptions, section III summarizes the analytical results, section IV discusses the numerical results, and finally, section V provides the conclusion of this work.

II. SYSTEM MODEL

$N+1$ sensors (or tags) are placed randomly and independently around the hub, with the objective to monitor a geographical area of radius in $[d_{\min}, d_{\max}]$ (Fig. 1). All ranges in that interval are equally important in terms of the sensing objective, and therefore, the range d_i of sensor $i \in \{0, 1, \ldots, N\}$ is assumed uniform in the above interval. Similarly, the bearing angle ϕ_i of each sensor is assumed uniform in $[0, 2\pi]$.

Similarly to [2], each sensor alternates the antenna impedance between two states, utilizing a simple RF transistor switch. In that way, binary modulation of the reflected carrier is possible, even though the sensor does not actively transmits any radio signal. The backscattered signal is picked by the hub and processed to extract the modulated information. Note that for each tag i two frequencies are involved: the frequency of the carrier f_c transmitted from the hub (common for all tags and on the order of MHz or GHz), and the subcarrier frequency of that tag f_{si}, which is the frequency of alternation between two switch states (on the order of Hz or KHz depending on the required low bit-rate).

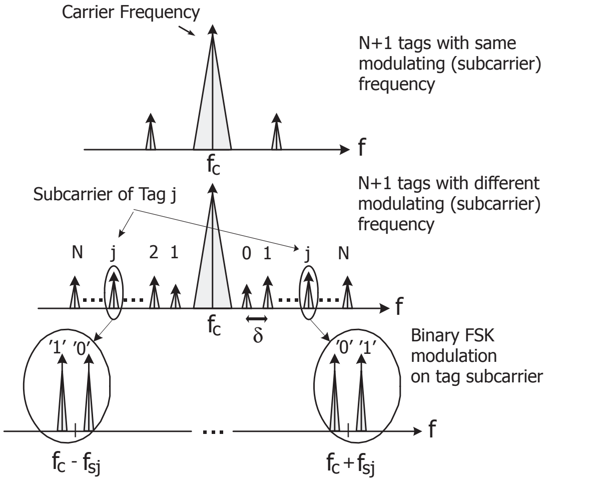

Fig. 2. $N+1$ sensors (tags) binary-modulate information on a subcarrier frequency, i.e. the frequency of switching a transistor between two states. The specific case of BFSK modulation at each sensor is depicted.

The modulation of that subcarrier frequency carries the transmitted message from a specific tag, and subcarrier frequency separation δ is assumed, amounting to aggregate communication bandwidth proportional to $(N+1)\ \delta$. Each tag has a unique subcarrier frequency, allocated randomly (i.e. not carefully), based on the uniform distribution among $N+1$ available subcarrier frequencies. In practice, such allocation requires that each sensor (tag) has a known and unique ID (which is not unreasonable to assume even for large N). Fig. 1 depicts this scenario for BFSK modulation implemented at each sensor.

The *average* received (at the hub) power p_i of the signal backscattered by tag i is described by:

$$p_i(d_i, \phi_i) = \eta\ L_i^2\ P_{\mathrm{H}}, \tag{1}$$

where P_{H} is the hub transmitted power, L_i is the one-way propagation loss and η is the *backscattering* efficiency of the tag antenna, assuming that all tags antennas are the same. Efficiency η depends on the tag antenna radar cross section (RCS). Note that propagation loss is squared, due to the round-trip nature of backscatter communication. One-way propagation loss L_i can be given by the familiar (free space) Friis equation:

$$L_i = \ G_{\mathrm{S}}\ G_{\mathrm{H}}(\phi_i)\ \left(\frac{\lambda}{4\pi d_i}\right)^2, \tag{2}$$

where G_{S} is the gain of the sensor antenna (assuming appropriate alignment for all tags), $G_{\mathrm{H}}(\phi_i)$ is the gain of the hub antenna at the direction ϕ_i of tag i, and λ is the wavelength of the carrier. For scenarios different than the free-space above, power drops faster with distance and various approximations can be used, dependent on the wireless environment. For example, when $d_i \geq \frac{4\pi h_{\mathrm{H}} h_{\mathrm{S}}}{\lambda}$, with $h_{\mathrm{H}}, h_{\mathrm{S}}$ the hub and tag antenna heights respectively, one way loss can be approximated by [4]:

$$L_i = \ G_{\mathrm{S}}\ G_{\mathrm{H}}(\phi_i)\ \left(\frac{h_{\mathrm{H}} h_{\mathrm{S}}}{{d_i}^2}\right)^2,\ \text{if } d_i \geq \frac{4\pi h_{\mathrm{H}} h_{\mathrm{S}}}{\lambda} \equiv d_{\mathrm{th}}, \tag{3}$$

while the Friis formula can be used for $d_i < \frac{4\pi h_{\mathrm{H}} h_{\mathrm{S}}}{\lambda}$.

Accordingly, a general two-slope model for one way propagation loss is adopted in this work:

$$L_i = \begin{cases} G_{\mathrm{S}}\ G_{\mathrm{H}}(\phi_i)\ \chi_1\ (1/d_i^{A_1}), & \text{if } d_i < d_{\mathrm{th}} \\ G_{\mathrm{S}}\ G_{\mathrm{H}}(\phi_i)\ \chi_2\ (1/d_i^{A_2}), & \text{if } d_i \geq d_{\mathrm{th}} \end{cases} \tag{4}$$

with $A_2 > A_1 \geq 2$ and all involved quantities above being positive.

For the case of an omni hub antenna, $G_{\mathrm{H}}(\phi_i)$ is simplified to $G_{\mathrm{H}}(\phi_i) = 1$. For the case of beamforming at the hub antenna, the pattern is simplified to:

$$G_{\mathrm{H}}(\phi_i) = \begin{cases} G_0, & \phi_0 - \phi_S \leq \phi_i \leq \phi_0 + \phi_S \\ G_0\ 10^{\mathsf{SLL}/10} = G_0\ a_0, & \text{elsewhere} \end{cases} \tag{5}$$

where ϕ_0 is the direction of antenna observation, $2\phi_S$ describes the opening of the beam and SLL denotes the antenna side lobe level in dB (Fig. 1). It is further assumed that the beamforming antenna scans the whole area (i.e. $\phi_0 \in [0, 2\pi]$), with such speed that allows number of reads per sensor per second, equal to that in the omni case.

Consecutively, the signal-to-interference-noise ratio SINR for each tag i can be given by:

$$\mathsf{SINR}_i \quad = \quad \frac{\frac{1}{R}\ g_i\ p_i}{\frac{1}{R}\ \sum_{j \neq i} s_{ij}\ g_j\ p_j + \mathcal{N}_0}, \tag{6}$$

where $\mathcal{N}_0$ is the average noise power spectral density (Watt/Hz) at the hub, R is the bit-rate of each tag and g_i is an exponential random variable with $\mathbb{E}\{g_i\} = 1$, corresponding to Rayleigh fading for the round-trip path between hub and tag i. It is further assumed that fading is independent across the various tags. The parameter s_{ij} is inversely proportional to the subcarrier frequency separation between tag i and tag j. It depends on the spectral efficiency of the specific binary modulation implemented at each tag and the filtering functions at the hub:

$$s_{ij} = \kappa^{-\nu} |f_{si} - f_{sj}|^{-\nu}. \tag{7}$$

For BPSK modulation, $\nu = 2$, while for MSK modulation, $\nu = 4$ [5]. The latter is a special case of BFSK, with continuous phase transition between consecutive symbols (bits) and as such, power spectrum drops faster than non-continuous phase counterparts (e.g. BPSK, general BFSK). Implementing MSK modulation at each sensor can be done with the use of low-cost, phase-locked loops (PLL).

III. Anti-Collision Analysis Summary

Outage probability for a test sensor at the edge of coverage is the performance criterion. The test sensor 0 is located at $d_0 = d_{\max}$ and $\phi_0 = 0$. The latter coincides with hub antenna direction of observation. The outage event $\mathsf{SINR}_0 < \Theta$ occurs when the SINR for the test sensor drops below a predetermined threshold Θ, necessary for detection at the hub receiver. Exact expressions are summarized below (proofs are omitted due to space constraints):

$$\mathbb{P}_{\text{out}} \triangleq \mathbb{P}\left\{\mathsf{SINR}_0 < \Theta\right\} \to 1 - e^{\left(-\frac{R\ \Theta\ \mathcal{N}_0}{p_0}\right)} \mathsf{Y}^N, \quad (8)$$

where $\mathsf{Y} = \mathbb{E}\left\{\frac{1}{1+\Theta\ s_{0j}\ \frac{p_j}{p_0}}\right\}$ and N large $(\frac{N-1}{N} \to 1)$.

Notice that interference to the test tag (a.k.a. *collision*) is restricted to the term $0 < \mathsf{Y} \leq 1$. The collision parameter Y is further simplified for the two cases of hub antenna below, assuming $d_{\text{min}} < d_{\text{th}} < d_{\text{max}}$.

A. Omni Hub Antenna:

$$\mathsf{Y} = \mathbb{E}\left\{\frac{1}{1+\Theta\ s_{0j}\ \frac{p_j}{p_0}}\right\} = \frac{1}{d_{\text{max}} - d_{\text{min}}} \sum_{\mu=1}^{N} \frac{2(N+1-\mu)}{N(N+1)} \times$$

$$\times \Big[g_1(d_{\text{th}}, \Theta_1(\mu), 2A_1) - g_1(d_{\text{min}}, \Theta_1(\mu), 2A_1) +$$

$$+ g_1(d_{\text{max}}, \Theta_2(\mu), 2A_2) - g_1(d_{\text{th}}, \Theta_2(\mu), 2A_2)\Big], \quad (9)$$

where

$$\begin{cases} \Theta_1(\mu) & = \Theta\ \kappa^{-\nu}\mu^{-\nu}\delta^{-\nu}\ \left(\frac{\chi_1}{\chi_2}\right)^2\ d_{\text{max}}^{2A_2}, \\ \Theta_2(\mu) & = \Theta\ \kappa^{-\nu}\mu^{-\nu}\delta^{-\nu}\ d_{\text{max}}^{2A_2}, \end{cases} \quad (10)$$

and

$$g_1(y; \Theta, 2A) = \int \frac{1}{1+\Theta\ y^{-2A}}\ dy \quad (11)$$

$$= \begin{cases} y - y\ {}_2F_1\left(\frac{1}{2A}, 1; 1+\frac{1}{2A}; -\frac{y^{2A}}{\Theta}\right), & |\Theta\ y^{-2A}| > 1, \\ y\ {}_2F_1\left(-\frac{1}{2A}, 1; 1-\frac{1}{2A}; -\frac{\Theta}{y^{2A}}\right), & |\Theta\ y^{-2A}| < 1, \\ \frac{1}{2}\ y, & \Theta\ y^{-2A} = 1, \end{cases}$$

where ${}_2F_1\,(a, b; c; z)$ is the Gauss hypergeometric function [6] which can be evaluated numerically. For the special case of $A = 2$ or $A = 4$, (11) is further simplified to expressions with elementary trigonometric functions, omitted due to space constraints. Our case, is a special case of eq. (11) with Θ, y, A positive.

Furthermore, a sufficient condition for collision-free performance $\mathsf{Y} \simeq 1$ has been derived (when $d_{\text{th}}^{-2A_2} < \frac{\chi_1^2}{\chi_2^2}\ d_{\text{min}}^{-2A_1}$):

$$\delta_0 = \left[\Theta\ \frac{\chi_1^2}{\chi_2^2}\ \frac{1}{\kappa^\nu}\ \left(\frac{d_{\text{max}}^{A_2}}{d_{\text{min}}^{A_1}}\right)^2\right]^{1/\nu} << \delta. \quad (12)$$

B. Beamforming Hub Antenna:

$$\mathsf{Y} = \frac{\phi_S}{\pi}\,\mathbb{E}\left\{\frac{1}{1+\Theta\ s_{0j}\ \frac{p_j}{p_0}}\Big|\ G_{\text{H}}(\phi_j) \to 0\ \text{dB}\right\}$$

$$+ \frac{\pi - \phi_S}{\pi}\ \mathbb{E}\left\{\frac{1}{1+\Theta\ s_{0j}\ \frac{p_j}{p_0}}\Big|\ G_{\text{H}}(\phi_j) \to \mathsf{SLL}\ \text{dB}\right\}. \quad (13)$$

The first expected value in the above bound has been already calculated in subsection III-A. The second expected value in the above bound can be readily calculated from the same expressions by using $a_0^2\Theta$ instead of Θ. Notice that the maximum hub antenna gain G_0 does not affect the interference term Y, but only received power p_0 in the exponential term of eq. (9), under the basic assumptions of this work.

TABLE I
PARAMETERS FOR NUMERICAL RESULTS

P_{T} = 30 dBm	G_{S} = 3 dBi	η = -10 dB	κ = 0.5 sec
$\mathcal{N}_0$ = -174 dBm/Hz + NF	λ = 0.33 m	R = 10 bps	d_{min} = 3.5 m
NF = 10 dB, G_0 = 1	h_{H} = 3 m	h_{S} = 0.25 m	d_{max} = 65 m

IV. NUMERICAL RESULTS

The parameters of (4) are set according to (2),(3) and Table I. The sensor antenna is placed close to the ground resulting in a small $d_{\text{th}} = 28.5$ m. This could be the case in backscatter networks of vegetable plants at an agricultural field. At the absence of interfering tags ($N = 0$), the outage probability criterion should provide acceptable performance at maximum distance d_{max}. Therefore, d_{max} is set for $N = 0$, $\Theta = 10$ dB and $\mathbb{P}_{\text{out}} = 1\%$. The minimum distance d_{min} is set larger that 10λ, assuring the validity of the far-field power loss equations of section II.

Fig. 3 shows that analysis result match simulation for omni hub antenna, $N + 1 = 100$ tags and two specific values for tag modulating frequency separation δ. Moreover, it is shown that doubling δ significantly reduces collision probability, even though collision is not eliminated. The same plot includes the performance floor for a single tag ($N = 0$) and one can see how far away the network operates from the collision-free case. Notice that increasing δ by a factor of 2, translates to increasing the overall required communication bandwidth by the same factor.

Fig. 4 plots edge collision probability against various values of δ and omni hub antenna. The first observation is there are values of δ where outage probability approaches the performance of single-tag operation, and collision is eliminated. The same figure plots vertically 5 δ_0, where δ_0 is the bound calculated from eq. (12). It is shown that this value of frequency separation provides near collision-free performance. The same bound for $\nu = 2$ (BPSK) provides prohibitively large δ, implying that this modulation might not be appropriate for large number of tags. This finding suggests that acceptable anti-collision performance is possible only with appropriate modulation at each tag.

The second observation is that the plots are identical for two values of large N; that is equivalent to claiming that collision is affected by *neighboring* in subcarrier frequency tags, and not *all* tags (the second value of $N+1 = 15001$ tags corresponds to approximately 1 tag/m^2). That is true given the fact that aggregate communication bandwidth in this work is proportional to $(N + 1)\ \delta$ and thus, increasing number of tags keeps δ constant (while increasing the overall required communication bandwidth). For $\Theta = 10$ dB and $\mathbb{P}_{\text{out}} = 2\%$, it is found $\delta \simeq 210$ Hz, amounting to $(N + 1)\delta \simeq 3.1$ MHz, (for communication bandwidth of $R = 10$ bps/sensor and ~ 1 tag/m^2 or $N = 15001$).

Fig. 5 shows how such aggregate bandwidth can be reduced by a factor of ~ 5. Specifically, beamforming with a moderate antenna lobe width of $2\phi_S$, with $\phi_S = \pi/6$ and SLL=-13 dB, reduces δ by a factor of ~ 5.5. This major improvement

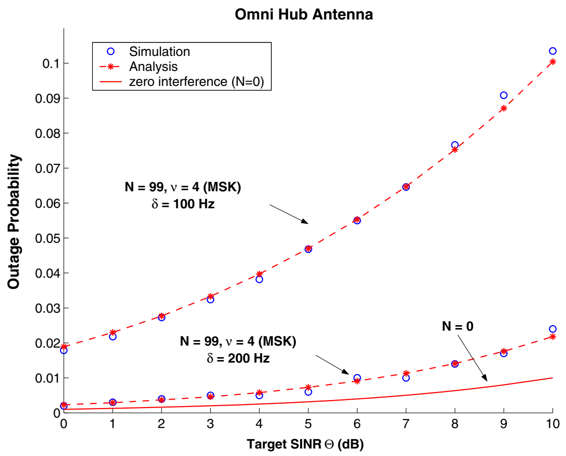

Fig. 3. Analysis match simulation results for two cases of modulating (subcarrier) tag frequency separation δ among 100 tags.

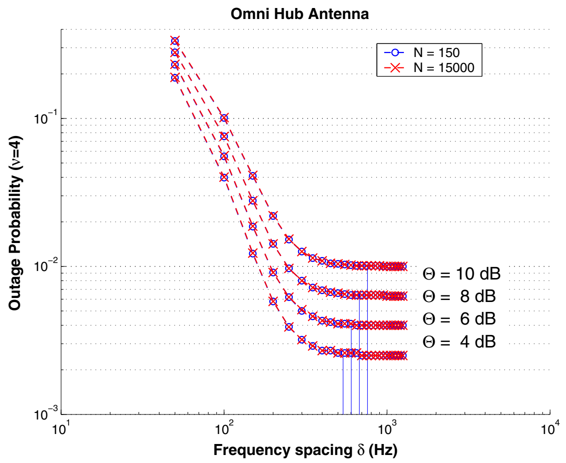

Fig. 4. There exists minimum modulating (subcarrier) tag frequency separation δ that provides acceptable, or collision-free performance (logarithmic horizontal axe).

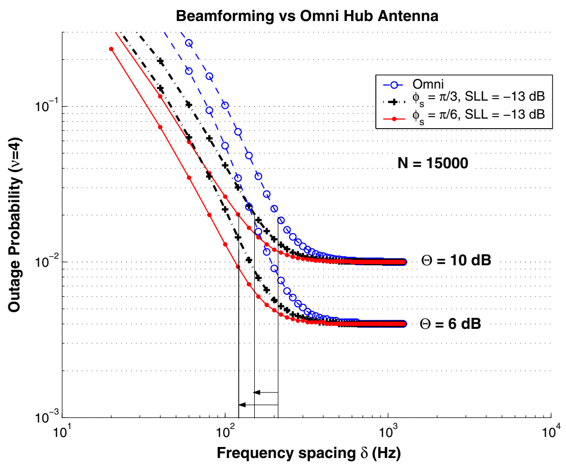

Fig. 5. A moderately directive hub antenna can significantly reduce the minimum modulating tag frequency separation δ (logarithmic horizontal axe).

TABLE II

CAPACITY (NUMBER OF SENSORS) FACTOR

	$\frac{\delta(G_{\mathrm{H}}=1)}{\delta(\phi_S=\pi/3)}$	$\frac{\delta(G_{\mathrm{H}}=1)}{\delta(\phi_S=\pi/6)}$
$(\mathbb{P}_{\mathrm{out}}=2\%,\ \Theta=10\ \mathrm{dB})$	2.4	5.5

might seem surprising, given the moderate value of ϕ_S. Nevertheless, the intuitive explanation is simple: subcarrier (modulating) frequency division in this work amounts to restricting sources of collision to neighboring in subcarrier frequency tags. Further utilizing a moderately directive hub antenna pattern, restricts sources of collision to tags which are neighboring in subcarrier frequency *and* bearing angle ϕ as well. In that way, benefits of frequency and space division are jointly exploited. Implementing in practice directive antennas with moderate main lobe width and moderate SLL, is feasible and relevant designs have been thoroughly studied in the literature (e.g. see [7]). In short, a moderate, easy-to-implement beamforming pattern for the hub antenna, significantly reduces the aggregate required communication bandwidth for all tags, or equivalently increases the number of allowable tags for given bandwidth (Table II), while offering acceptable anti-collision performance.

V. CONCLUSION

Acceptable anti-collision performance can be engineered in low bit-rate backscatter sensor networks with appropriate tag modulation and omni hub antenna. When a beamforming hub antenna with moderate main lobe width is utilized, significant system gains are observed. Such gains amount to either reduction of aggregate communication bandwidth, or amplification of aggregate number of tags. Relevant gains depend on the propagation environment, and analytical results were provided for a general model of backscatter communication. That could potentially help anti-collision studies in classic RFID systems.

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