Capacity Bounds for Backscatter Aided Wireless Transmission on High Speed Rails

Zhongzhao Dou (douzhongzhao@139.com)

South China University of Technology, China

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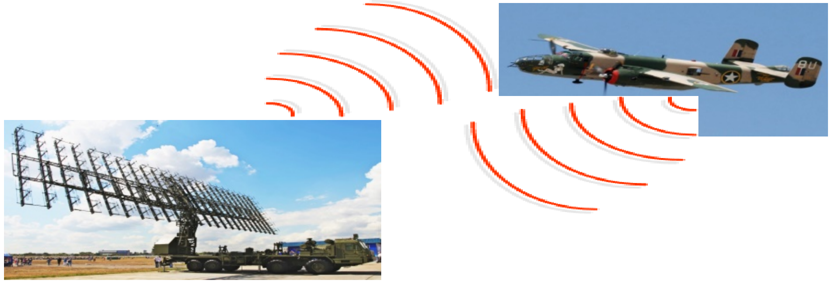
II. The content and findings of the paper
III. Conclusion and Open problems

History of Traditional Backscatter

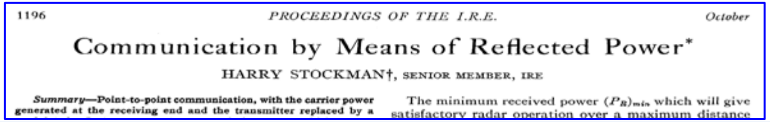


World War II 1939—1945 : Identify own or enemy plane by backscatter based on tag in the plane and radar

The first paper of backscatter technology

U.S. Air Force Research Laboratory.
The work was not sanctioned by the laboratory, and Stockman lost his job because of improper use of Air Force property soon after publishing his paper.

H. Stockman, “Communication by means of reflected power,” *Proc. IRE*, pp. 1196-1204, Oct. 1948.



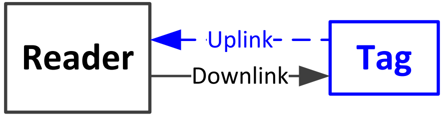
1196 *PROCEEDINGS OF THE I.R.E.* *October*

Communication by Means of Reflected Power*

HARRY STOCKMAN†, SENIOR MEMBER, IRE

Summary—Point-to-point communication, with the carrier power generated at the receiving end and the transmitter replaced by a

The minimum received power $(P_R)_{min}$ which will give satisfactory radar operation over a maximum distance



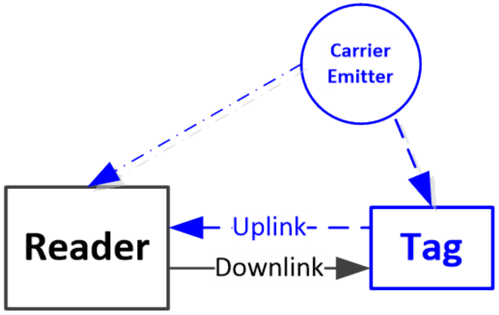
(a) Traditional backscatter

RFID Application

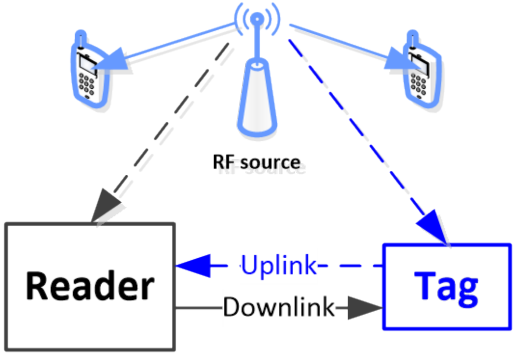
Limitation of traditional backscatter and improved solution

- The path loss is large, which limits the effective communication distance between tag and reader
- The backscatter receiver and the RF source are located in the same device (ie, reader), which may cause interference between the receiving antenna and the transmitting antenna, thereby reducing communication performance.

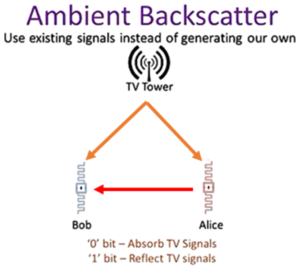
Two new backscatter technology are proposed to:



(b) Bistatic backscatter



(c) Ambient backscatter



This work presented the bistatic scatter radio system, which can be utilized to build large scale low-cost and low-power backscatter sensor networks with extended field coverage.

J. Kimionis, A. Bletsas, and J. N. Sahalos, "Increased range bistatic scatter radio," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 1091-1104,Mar. 2014.

V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: wireless communication out of thin air," in Proc.ACM SIGCOMM, Hong Kong, China, 2013, pp. 1-13.

More Researches on improving range of communication, coding and modulation, etc.

Ambient backscatter technology harvests energy from the surrounding wireless signal, so that the wireless sensor can get rid of battery constraints, reduce maintenance operations, and has good application prospects. At present, ambient backscatter is becoming a hot research direction.

Turbocharging Ambient Backscatter Communication

Aaron N. Parks†, Angli Liu†, Shyamnath Gollakota, Joshua R. Smith
University of Washington
{anparks, anglil, gshyam, jrsjrs}@uw.edu
†Co-primary Student Authors

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unication primitives such as coding and multiple antenna
g have provided significant benefits for traditional wire-
ms. Existing designs, however, consume significant power
putational resources, and hence cannot be run on low com-
power constrained backscatter devices. This paper makes
contributions: (1) we introduce the first multi-antenna
ion design that operates on backscatter devices while re-
small form factor and power footprint, (2) we introduce a
ling mechanism that enables long range communication as

Figure 1—Our Prototype integrates both μmo and μcode in a single design. It can operate using both RFID and TV transmissions.

The designs provide benefits for both RFID and ambient backscatter systems: they enable RFID tags to communicate directly with each other at distances of tens of meters and through multiple walls.

They also increase the communication rate and range achieved by ambient backscatter systems by 100X and 40X respectively.

We believe that this paper represents a substantial leap in the capabilities of backscatter communication.

B. Kellogg, A. Parks, S. Gollakota, J. R. Smith, and D. Wetherall, "Wi-Fi Backscatter: Internet connectivity for RF-powered devices," in *Proc. ACM SIGCOMM*, Chicago, USA, 2014, pp. 1-12.

IEEE TRANSACTIONS ON COMMUNICATIONS, ACCEPTED FOR PUBLICATION 1

Backscatter Communication and RFID: Coding, Energy, and MIMO Analysis

Colby Boyer, *Student Member IEEE*, and Sumit Roy, *Fellow IEEE*

Abstract—Radio Frequency IDentification (RFID) is intended to supplant legacy (optical) bar code scanning technology found in many logistic and retail applications. RFID is distinguished by *inexpensive, low power and compact form factor* tags, whose longevity and efficacy are predicated on using passive communication techniques and on-tag power harvesting. Such tags employ *backscatter modulation*, which does not require any active RF components. As a result, backscatter has become an attractive design choice for *short-range* communications in power constrained wireless sensor networking scenarios.

The purpose of this work is two-fold. First, it aims to

Fig. 1. The wireless identification and sensing platform (WISP) [8] is a programmable sensor platform based on RFID. It is wirelessly powered and uses backscatter modulation to relay sensor information to a RFID reader.

The primary objective of this paper highlights the coupling of coding and modulation with power harvesting for passive backscatter, that presents unique results and design insights vis-a-vis traditional active communication.

C. Boyer and S. Roy, "Backscatter communication and RFID: coding, energy and MIMO analysis," IEEE Trans. Commun., vol. 62, no.3, pp. 770-785, Mar. 2014.

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Key findings of the paper

- In this paper we introduce backscatter technology into wireless communication systems on high speed rails (HSRs).
- We propose a backscatter aided wireless transmission (BAWT) scheme and demonstrate its outperformance over the existing direct wireless transmission (DWT) scheme.
- We derive the upper and lower bounds of channel capacity for BAWT and prove that the channel capacity for BAWT is larger than that of DWT on certain conditions.
- Simulation results are provided to corroborate the proposed studies.

System Model

- The direct wireless channel between the antenna of BS and that of mobile user is $h_0(t)$. In case of DWT, BS transmits straight forward to the mobile user through the channel $h_0(t)$.
- Suppose the channel between the antenna of the BS and the outside antenna of the train is $f_0(\mathrm{t})$. The signal received at the train antenna is $u(t)$, BAWT scheme requires that the signal $u(t)$ will be delayed for one symbol duration *Ts* , and then amplified and backscattered by another antenna inside the train.

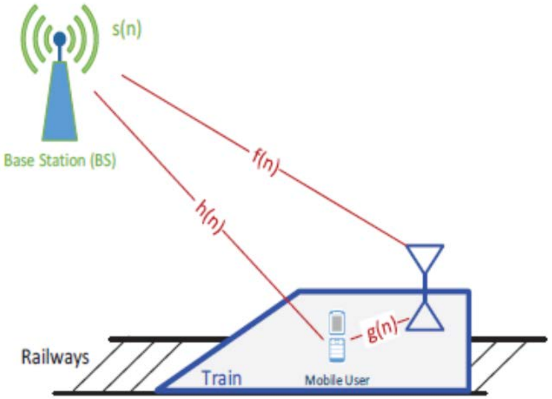

Figure 1. System model.

- Suppose that the BS transmits baseband signals *s*(*t*) with the carrier frequency *fcs* and the initial phase *θs* . Assume that the transmission of *s*(*t*) follows a general slotted structure in Fig. 2. Each slot contain *Np* training symbols and *Nd* data symbols, and *Np* + *Nd* = *N*. There is zero padding, i.e., one or several empty symbols, at the end of each slot to avoid interference between slots or different users. We consider two transmission schemes: DWT and BAWT.

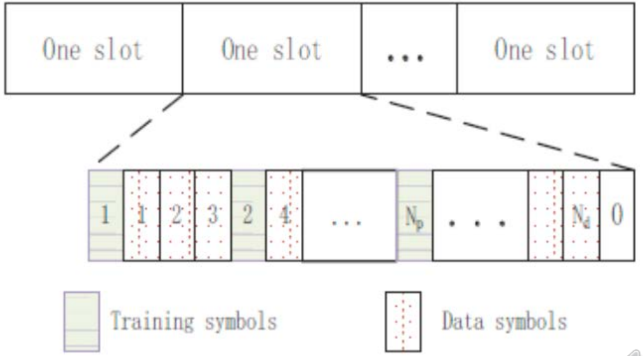

Figure 2. Transmission slot structure.

Capacity Analysis of DWT and BAWT

Theoretical derivation results

Capacity of DWT

$$C_{DWT} = \frac{1}{N}\mathbf{E}\left\{\text{logdet}\left(\mathbf{I}+\gamma\mathbf{D}(\Delta_f)\mathbf{H}\mathbf{H}^{\mathbf{H}}\mathbf{D}^{\mathbf{H}}(\Delta_f)\right)\right\}$$

$$= \frac{1}{N}\sum_{n=1}^{N}\mathbf{E}\{\log(\mathbf{I}+\gamma|h(n)|^2)\}$$

$$C_{DWT} = -\exp\left(-\frac{1}{\gamma\sigma_h^2}\right)\text{Ei}\left(-\frac{1}{\gamma\sigma_h^2}\right)$$

Lower and upper capacity bound of BAWT

$$C_{\text{BAWT}}^{\text{up}} = \frac{1}{N+1}\left[(N-1)\log\left(1+\gamma\sigma_h^2+\gamma\sigma_f^2\right) - \exp\left(\frac{1}{\gamma\sigma_h^2}\right)\times \text{Ei}\left(-\frac{1}{\gamma\sigma_h^2}\right) - \exp\left(\frac{1}{\gamma\sigma_f^2}\right)\times \text{Ei}\left(-\frac{1}{\gamma\sigma_f^2}\right)\right]$$

$$C_{\text{BAWT}}^{\text{low}} = \frac{1}{N+1}\left[\frac{1}{2}\log\left(\sigma_h^2\right)+\frac{N}{2}\log\left(\sigma_f^2\right)+\frac{N+1}{2}\left(\log(\gamma)-C\right)+\log(2)-\frac{N-1}{2}\exp\left(\frac{1}{\gamma\sigma_h^2}\right)\text{Ei}\left(-\frac{1}{\gamma\sigma_h^2}\right)\right]$$

Note: by Fischer's inequality and Jensen's inequality

where γ stands for signal-to-noise ratio (SNR)

$C \approx 0.5772$ is Euler's constant

σ_f^2 and σ_h^2 are channel variance

$$\text{Ei}(x) = \int_{-\infty}^{x}\frac{e^t}{t}dt$$

Simulation Results of DWT and BAWT

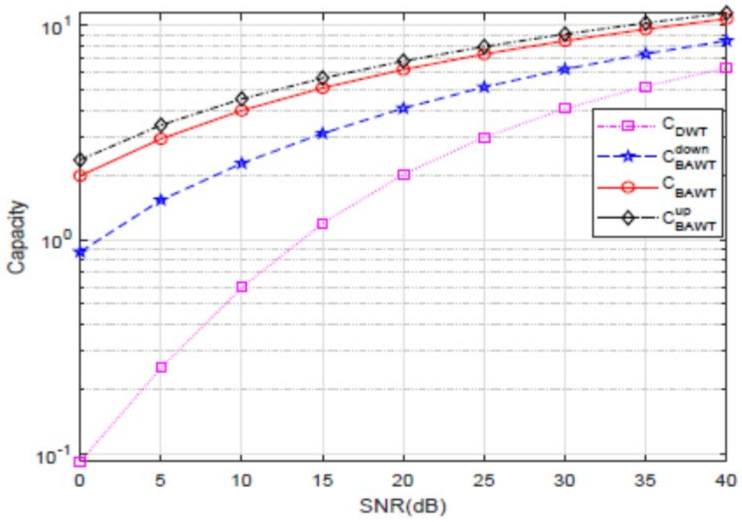

Figure 3. Capacity versus SNR.

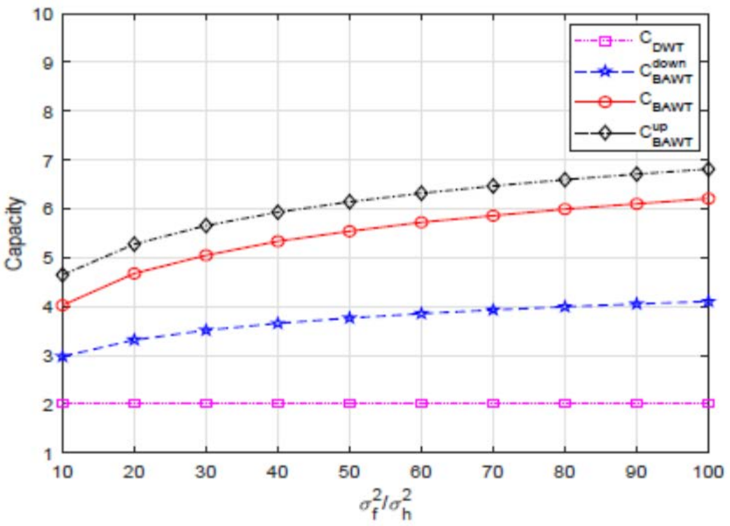

Figure 4. Capacity versus σ_f^2/σ_h^2 when $\gamma = 20dB$.

- It can be found that the upper bound and lower bound of channel capacity are close to the exact channel capacity.
- Besides, the BAWT scheme can achieve higher data transmission rate with increasing channel variance σ_f^2 compared with the DWT scheme.

Conclusion and open problems

- In this paper, we introduced backscatter technology into wireless communication systems on HSRs.   We compared the capacity performance between BAWT and DWT schemes. To our best knowledge, our work was the first study about backscatter aided wireless communications on HSR system. We prove that the channel capacity for BAWT is larger than that of DWT on certain conditions.

- Compared with other existing technologies, utilizing backscatter technology to overcome the signal fading has the advantages of low complexity of signal processing and low cost of circuit implementation.

- Many open problems about this topic await further investigation, such as training sequence design, channel encoding, estimation and detection.

Thank you!

douzhongzhao@139.com