Coverage Analysis of Drone-Assisted Backscatter Communication for IoT Sensor Network

Ali HAYAJNEH[1,2], S. A. R. Zaidi[1], Maryam Hafeez[3], Des. C. McLernon[1], Moe Z. Win[4]

1- The University of Leeds, 2- The Hashemite University of Jordan
3- University of Huddersfield
4- Massachusetts Institute of Technology (MIT)

Layout

- Review and contribution
- How backscatter works
- System model
- Performance analysis
- Numerical results
- Conclusions and future vision.

Review and contribution

- 8.3 billion Internet-of-Things (IoT) devices currently around, 10% annual growth.
- Backscatter radio communication does not require expensive active components such as RF oscillators, mixers, crystals, decoupling capacitors.
- Achieving communication with different loads to control the antenna reflection coefficient.
- Smart agriculture, soil moisture, temperature sensors, etc.
- Large-scale model for the Air-to-Ground link.
- Statistical framework to characterize the performance of drone assisted backscatter.
- Approximation for the dyadic fading channel.

How Backscatter Works: the concept

Takes advantage of ambient RF waves

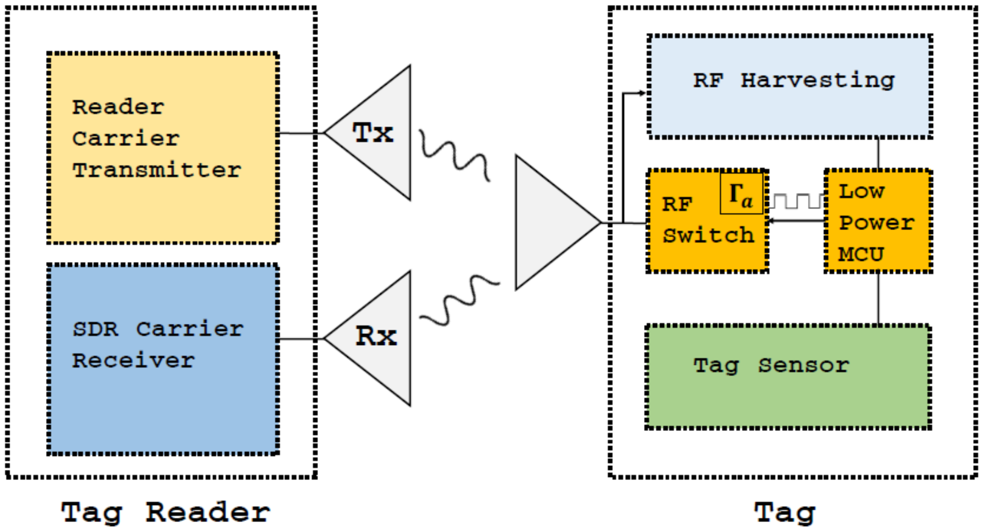
Small environmental footprint

- **No additional energy is consumed since it uses what's already in the air**

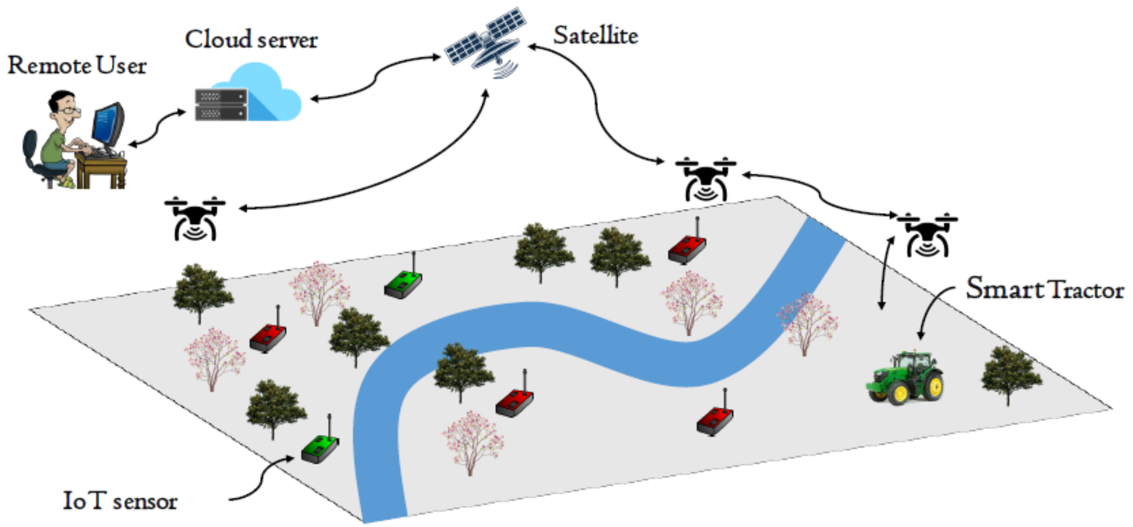
Changes the impedance of the antenna

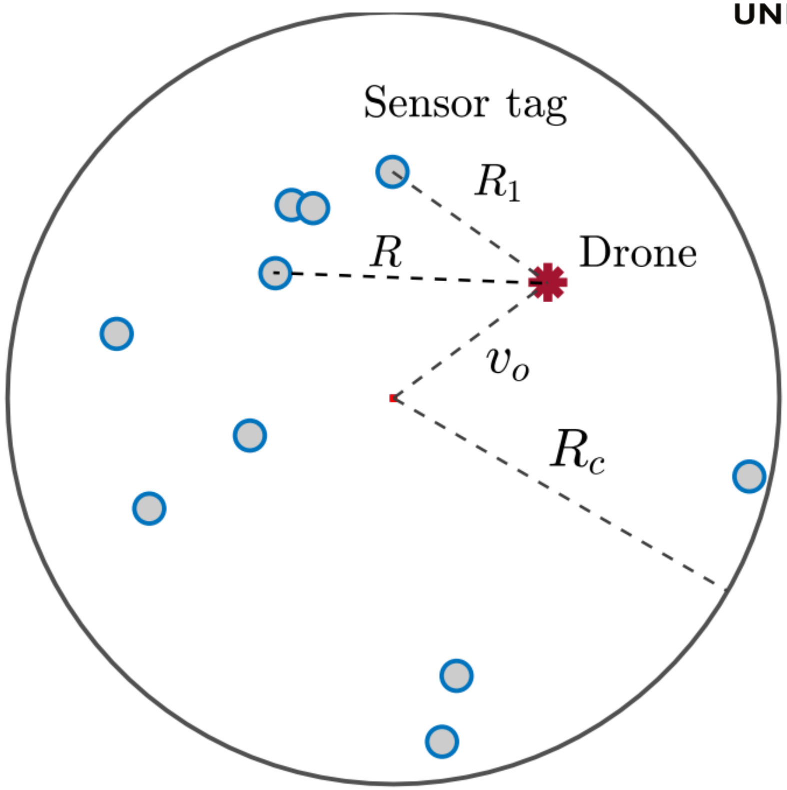
- **When a wave encounters an antenna with two different impedances, it reflects the wave**

Controlling the strength of the reflection energy allows for information to be transmitted (ASK as example)



$$x_{Tag}(t) = \begin{cases} \Gamma_a b_n(t - nT), & \text{Logic } 0, \\ 0, & \text{Logic } 1, \end{cases} \tag{7.2}$$





Network Geometry: System Model

Air-to-Ground Path loss model

- We assume that the large-scale fading model follows:

$$L_{\mathrm{LoS}}(h_{\mathrm{d}}, r) = K_{\mathrm{LoS}}\left(r^2 + h_{\mathrm{d}}^2\right),$$
$$L_{\mathrm{NLoS}}(h_{\mathrm{d}}, r) = K_{\mathrm{NLoS}}\left(r^2 + h_{\mathrm{d}}^2\right),$$

  - h_d: is the vertical difference in height between the BS and the SN.

- The probability of the mobile user to be in LoS/NLoS with the associated BS can be written as:

$$\mathcal{P}_L(h,r) = \frac{1}{1 + a\,\mathrm{e}^{-bc\,\tan^{-1}\left(\frac{h}{r}\right) + b\,a}}, \; \mathcal{P}_{NL}(h,r) = 1 - \mathcal{P}_L(r)$$

Distance analysis

- Probability density function of the distance from the Drone reader to any SN

$$f_{\mathrm{R}}(r|v_{\mathrm{o}}, R_{\mathrm{c}}) = \begin{cases} f_{\mathrm{R}}^{(1)}(r|v_{\mathrm{o}}, R_{\mathrm{c}}) = \frac{2r}{R_{\mathrm{c}}^2}, & 0 \leq r \leq R_{\mathrm{c}} - v_{\mathrm{o}} \\ f_{\mathrm{R}}^{(2)}(r|v_{\mathrm{o}}, R_{\mathrm{c}}) = \frac{2r}{\pi R_{\mathrm{c}}^2} \arccos\left(\frac{r^2+v_{\mathrm{o}}^2-R_{\mathrm{c}}^2}{2v_{\mathrm{o}}r}\right), & R_{\mathrm{c}} - v_{\mathrm{o}} < r \leq R_{\mathrm{c}} + v_{\mathrm{o}}, \end{cases}$$

- Probability density function of the distance from the Drone reader to the nearest SN

$$F_{\mathrm{R}_1}(r_1|v_{\mathrm{o}}, R_{\mathrm{c}}) = \begin{cases} (1 - F_{\mathrm{R}}^{(1)}(r_1|v_{\mathrm{o}}, R_{\mathrm{c}}))^{N_{\mathrm{s}}}, & 0 \leq r \leq R_{\mathrm{c}} - v_{\mathrm{o}} \\ (1 - F_{\mathrm{R}}^{(2)}(r_1|v_{\mathrm{o}}, R_{\mathrm{c}}))^{N_{\mathrm{s}}}, & R_{\mathrm{c}} - v_{\mathrm{o}} < r \leq R_{\mathrm{c}} + v_{\mathrm{o}}. \end{cases} \quad (19)$$

Drone assisted Backscatter setup

- Sensor nodes distribution is captured by a binomial point process (BPP):

$$\Phi = \{\mathbf{x}_0, \mathbf{x}_1, ..., \mathbf{x}_{\mathbf{N_s}}, \forall\ \mathbf{x}_i \in \mathbb{R}^2\},$$

- The received channel power gain is given by:

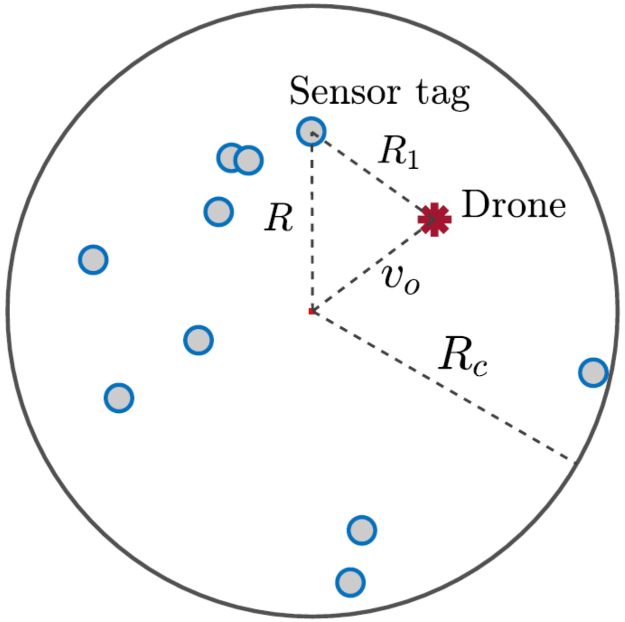
$$f_{\mathcal{H}_f,\mathcal{H}_b}(h_f, h_f; \rho) = \frac{2}{\tilde{\rho}\sigma_f^2\sigma_b^2} \exp\left(-\frac{1}{\tilde{\rho}}\left[\frac{h_f}{\sigma_f^2} + \frac{h_b}{\sigma_b^2}\right]\right) \times \mathcal{I}_o\left(\frac{\rho\sqrt{h_f h_b}}{(1-\rho^2)\sigma_f^2\sigma_b^2}\right),$$

- The PDF of the equivalent dyadic fading channel coefficient:

$$f_{\mathcal{H}}(h, \rho) = \frac{1}{2\tilde{\rho}\sigma_f^2\sigma_b^2}\mathcal{I}_o\left(\frac{\rho\sqrt{h}}{\tilde{\rho}\sigma_f\sigma_b}\right)\mathcal{K}_o\left(\frac{\rho\sqrt{h}}{\tilde{\rho}\sigma_f\sigma_b}\right)$$

$$\mathcal{K}_o(z) \approx \frac{\sqrt{\pi}}{2}\exp(-z),$$

$$\mathcal{I}_o(z) \approx \frac{1}{z\sqrt{2\pi}}\exp(z).$$



Drone assisted Backscatter setup (continued)

- We can write the approximate PDF and CDF for the dyadic channel as:

$$\text{PDF:} \quad f_{\mathcal{H}}(h,\rho) \approx \frac{h^{-\frac{1}{2}}}{2\sqrt{\rho}} \exp\left(-\frac{2(1-\rho)\sqrt{h}}{1-\rho^2}\right) \tag{7.10}$$

$$\text{CDF:} \quad F_{\mathcal{H}}(h,\rho) \approx 1 - \exp\left(-\frac{2(1-\rho)\sqrt{h}}{1-\rho^2}\right). \tag{7.11}$$

- Coverage Probability

$$\text{SNR} = \underbrace{\frac{P_t \mathcal{H}_f \mathcal{H}_b \Gamma_a [L_{LoS}(r_1)]^{-2}}{\sigma_N^2} \mathcal{P}_{LoS}(r_1)}_{\text{SNR}_L} + \underbrace{\frac{P_t \mathcal{H}_f \mathcal{H}_b \Gamma_a [L_{NLoS}(r_1)]^{-2}}{\sigma_N^2} \mathcal{P}_{NLoS}(r_1)}_{\text{SNR}_{NL}}$$

$$\begin{aligned} P_c(\beta|v_o) &= \mathrm{P_r}[\text{SNR} \geq \beta], \\ &= \mathbb{E}_{r_1}\left[1 - F_{\mathcal{H}}(\beta\sigma_N^2 [L_L(r_1)]^2 / P_t\Gamma_a, \rho)\right] \mathcal{P}_L(r_1) \\ &+ \mathbb{E}_{r_1}\left[1 - F_{\mathcal{H}}(\beta\sigma_N^2 [L_{NL}(r_1)]^2 / P_t\Gamma_a, \rho)\right] \mathcal{P}_{NL}(r_1). \end{aligned}$$

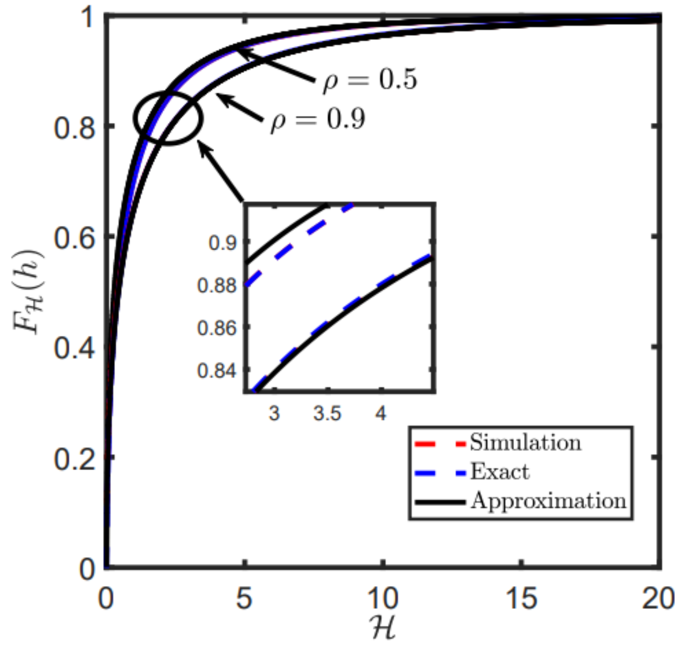
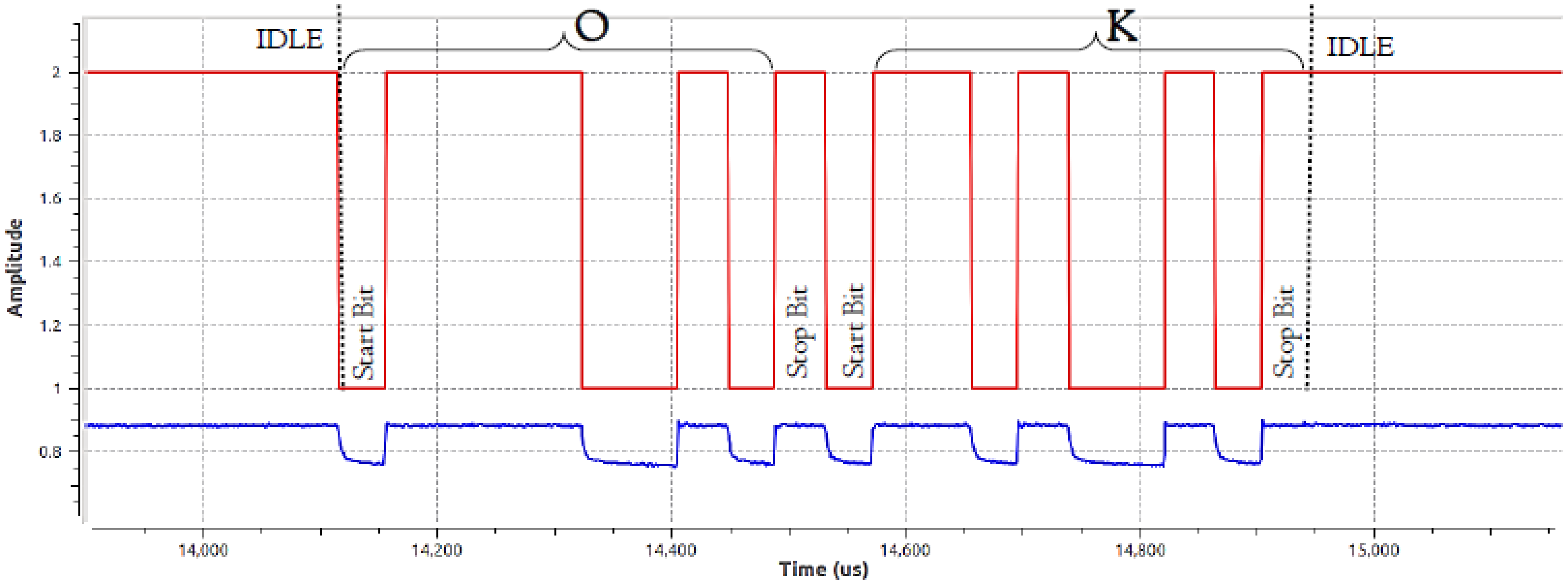


Fig. 4: Cumulative distribution function for the backscatter dyadic fading channel coefficient $\mathcal{H}$.

Practical results



Backscatter transmission of the serial data for the word "OK" which is equivalent to the hexadecimal representation of "0x4F,0x4B" from a sensor node tag. The lower curve is the ASK modulated carrier at the reader antenna. Serial data bit rate is 2.4 kbps.

Results

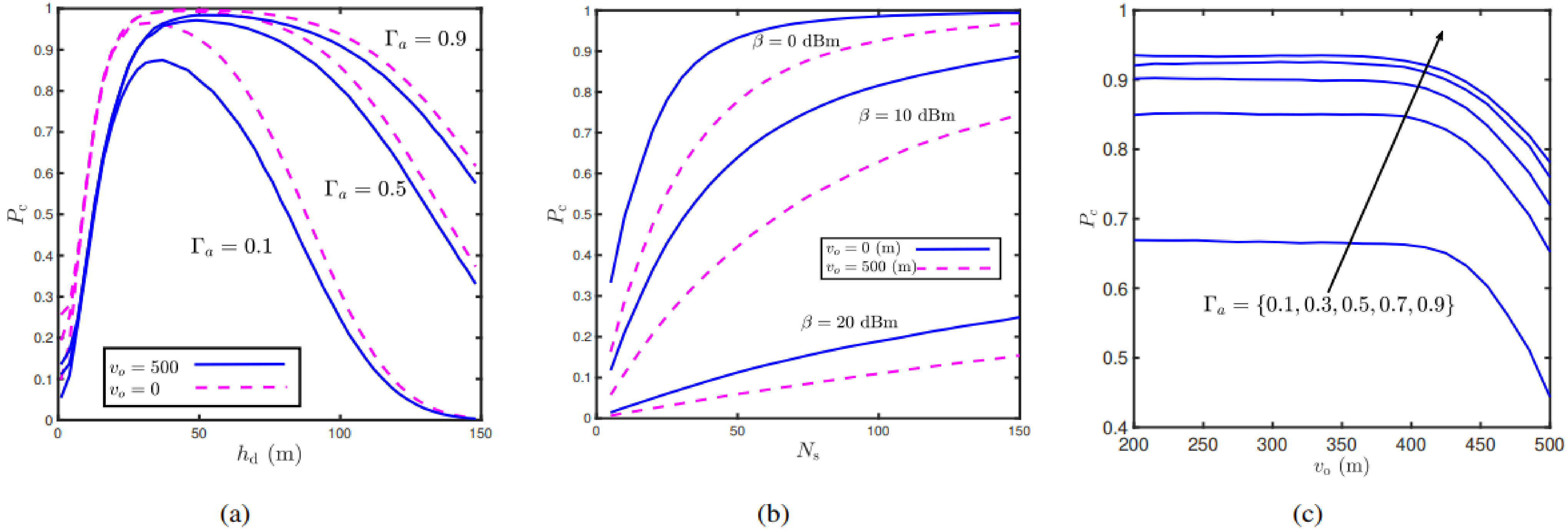


Fig. 5: (a) Coverage probability with $N_s = 200$, $R_c = 500$, $\rho = 0.5$, $\sigma_N^2 = -110$ dBm, $\beta = 10$ dBm. (b) Coverage probability with $R_c = 500$, $\rho = 0.5$, $\sigma_N^2 = -110$ dBm, $\Gamma_a = 0.9$ and (c) Coverage probability with $h_d = 50$ (m), $N_s = 50$, $R_c = 500$, $\rho = 0.5$, $\sigma_N^2 = -110$ dBm, $\beta = 0$ dBm.

UNIVERSITY OF LEEDS

Conclusions

Conclusions

- First study which presents such a statistical framework to characterize the performance of drone assisted backscatter based IoT SNs.
- We presented alternative closed-form expressions for the dyadic fading channel.
- The performance of SNs is measured and quantified in terms of the well known coverage probability metric.
- The model incorporates realistic propagation dynamics of communication between DFR and SNs by.
- Practically implement a tag and software-defined radio (SDR) based reader and parametrize the developed framework to investigate the coverage performance of SNs.

Future extensions

- Do a practical fading model using the practical setup.
- Study the effect of inter-tag interference on the performance.
- Study different geometries with the use of MIMO and beamforming.

Any question?