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System-Level Analysis and Optimization in Large-Scale Wireless Networks

Coverage Analysis for Backscatter Communication Empowered Cellular Internet-of-Things

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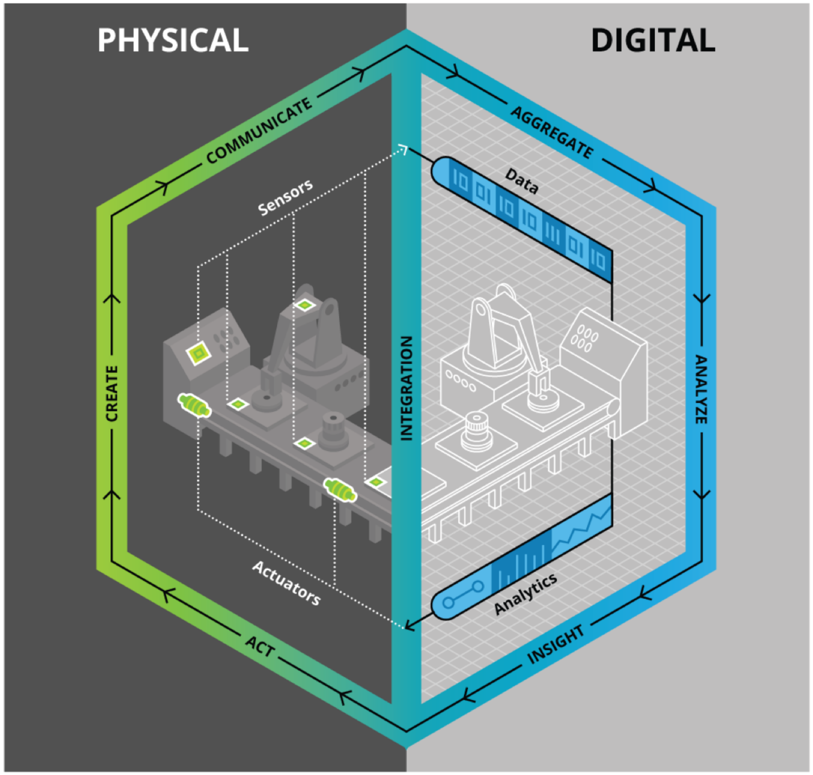
Agenda

- Motivation
- Background
- Performance Analysis
  - Distribution of Dyadic Channel Gain
  - Co-channel Interference Modelling
  - Coverage Probability Characterization
- Conclusion and Future Outlook

Motivation

AgriTwin



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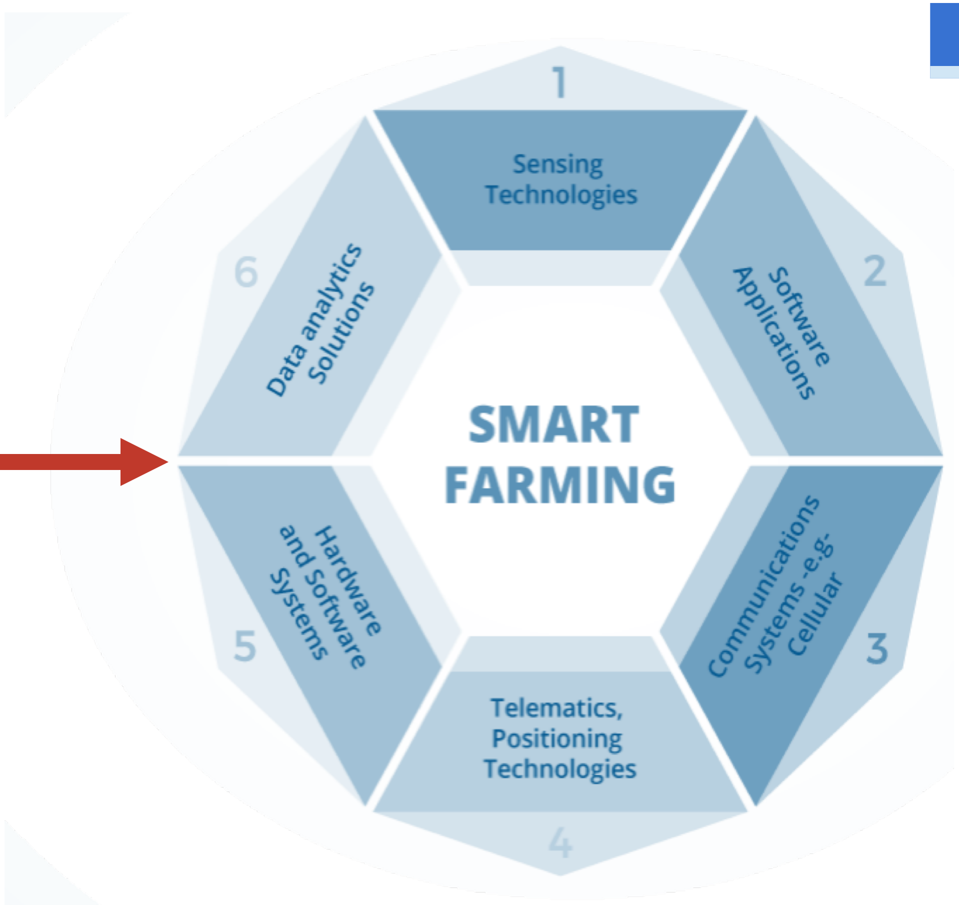
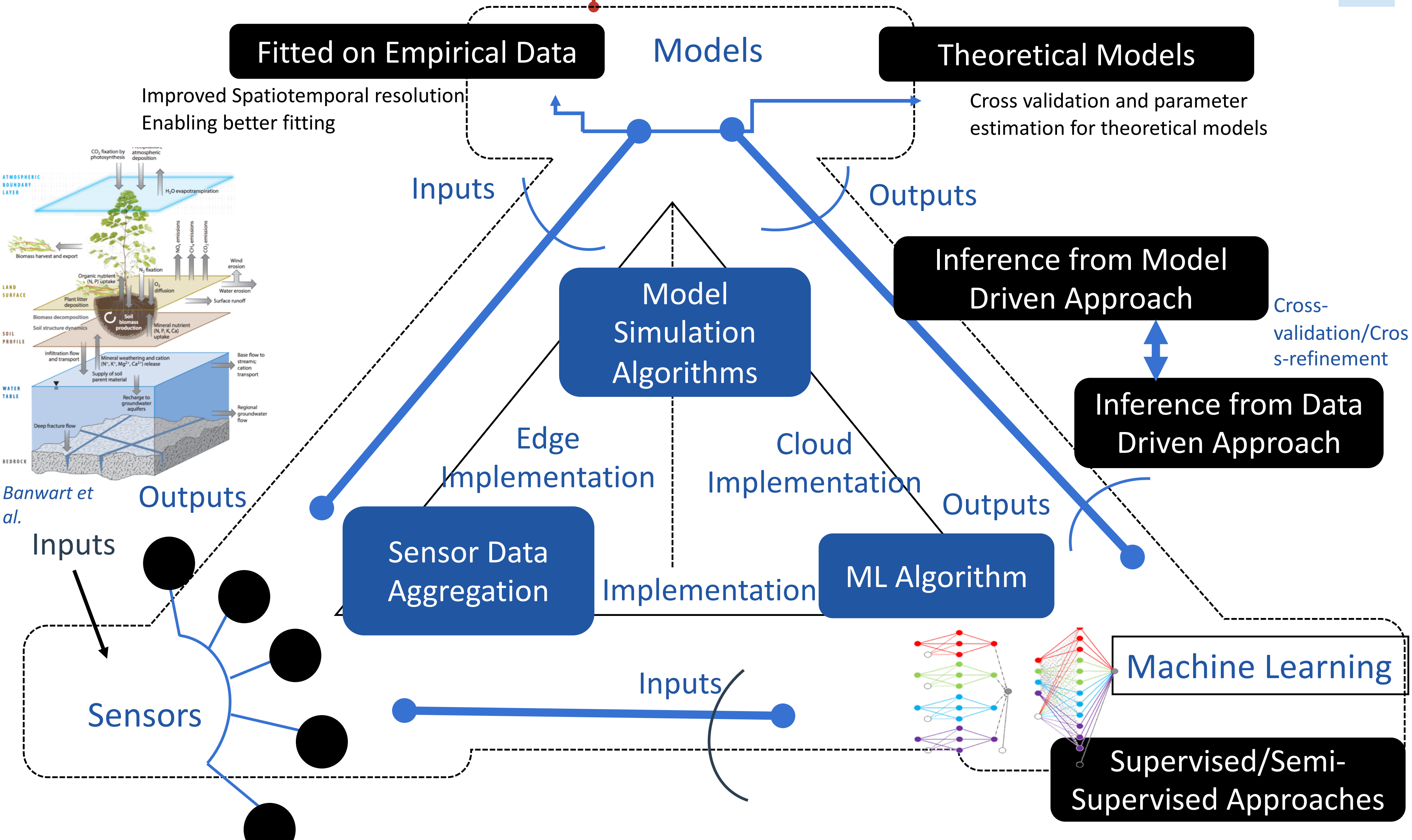


1. **Operational efficiency** through real-time process analytics or even end-to-end process control.
2.Significantly enhance overall **productivity** by realizing zero-downtime through proactive response

Model Mediated AI



Climate Smart Agriculture

CSA is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support the development and ensure food security in a changing climate. CSA aims to tackle three main objectives: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible.

FAO Framework: https://csa.guide/

CSA implementations aim to exploit technological solutions which can enable efficiently:

(i) water management;
(ii) precision agriculture; and
(iii) livestock management.

This project is geared towards the development of new low-cost sensing platform which can accelerate implementation and adaptation of these CSA approaches.

Challenge

- CSA → Collection of information → Inferences and Deployment of Appropriate Response Mechanisms.
- Data-driven smart farming → Internet-of-Things (IoT)

Energy Efficiency

Background

RF Backscatter based IoT Nodes

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)

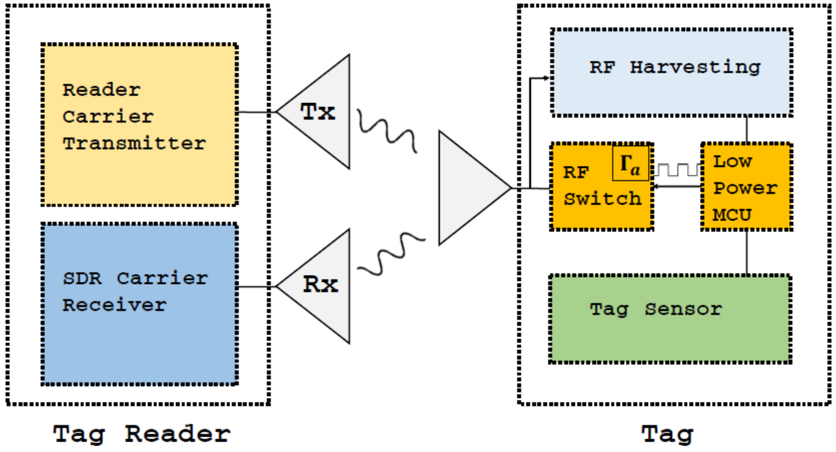
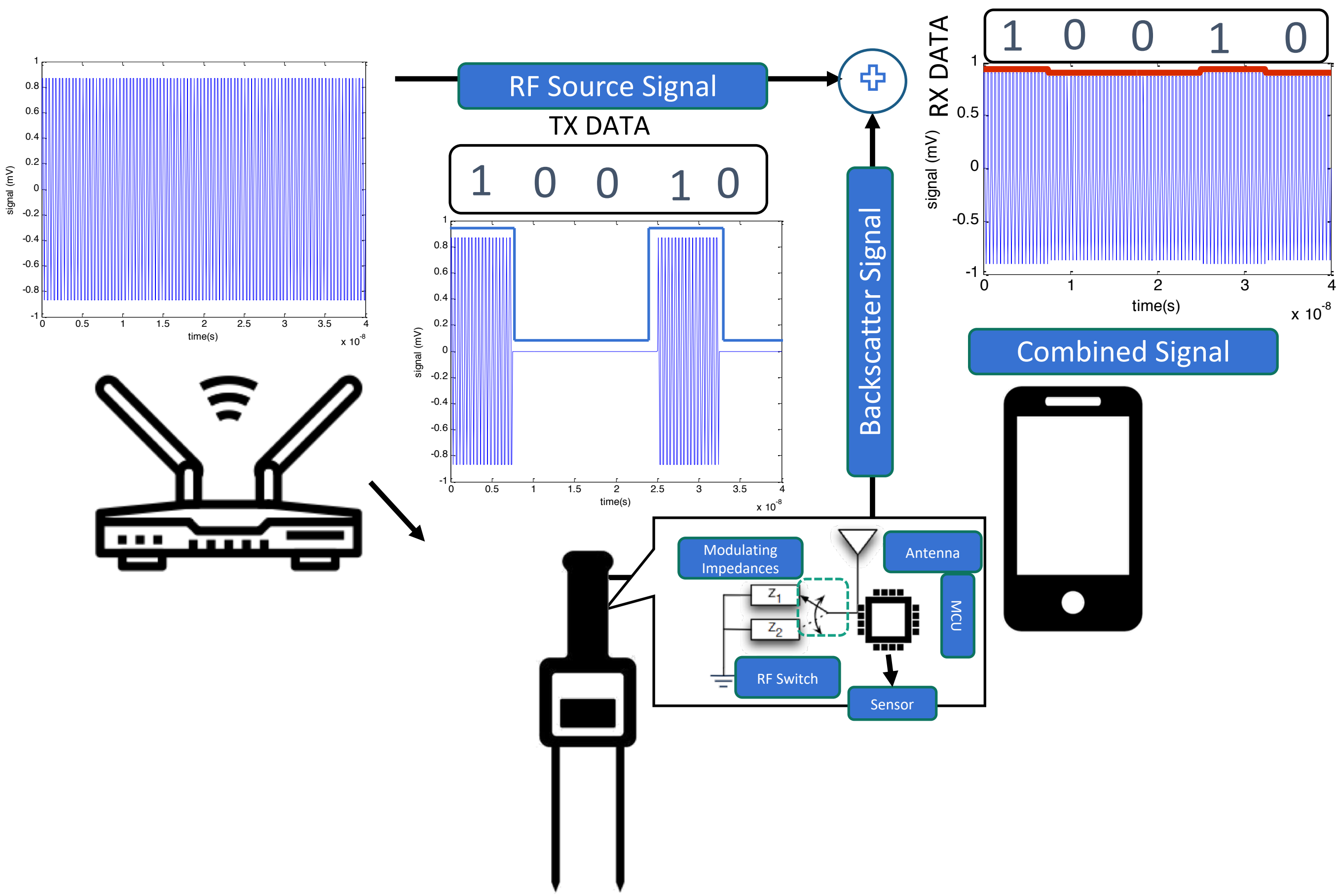


FIGURE 7.2: Architecture of backscatter DFR and SN.

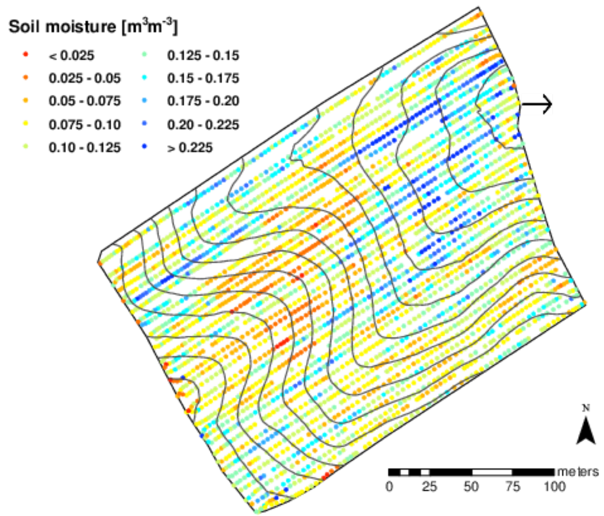
$$x_{Tag}(t) = \begin{cases} \Gamma_a b_n(t - nT), & \text{Logic } 0, \\ 0, & \text{Logic } 1, \end{cases}$$

RF Backscatter



Design Questions

- What is the maximum attainable range for Backscatter SN?
- How many SNs can be covered by a single reader?
- Can we exploit controlled mobility to reduce infrastructure costs?
- Can we compare theoretical results with actual hardware based prototypes?
- How can we enable multiple access for these SNs?

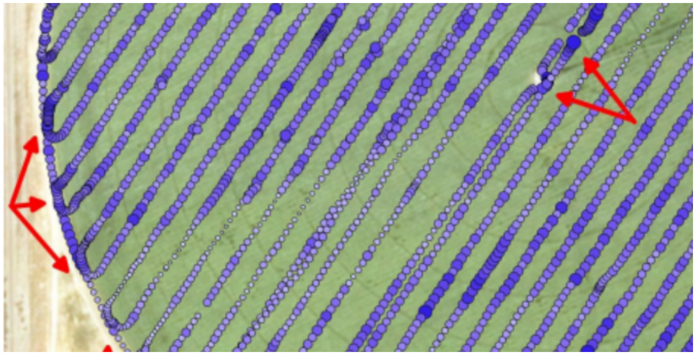


Optimal Spatio-temporal Estimation

Hardware Implementation

	OPEnS RFID	Meter Group 5TM[4]	DFRobot Gravity[5]	SMAP (Soil Moisture Active Passive Satellite)
Moisture Accuracy	Medium	High	Low	Low
Area Resolution	Point	Point	Point	100 Acre
Max Soil Depth	10 cm	2 m	2 m	5 cm[2]
Wireless Read Range	15 cm	N/A	N/A	685 km[3]
Cost per Sensor (cost per data point)	$0.25	$200	$5	Free*
Data Logger Cost	$600	$500	$300	N/A
Environmental Impact	Low	Medium	Medium	None
Requires Battery	No	Yes	Yes	No

*Through NASA's SMAP program.



Dirt Cheap to Manufacture

Enclosure 5¢

RFID Sensor 22¢

Manufacturing Labor 18¢

+ Install Labor 45¢

System Level Performance

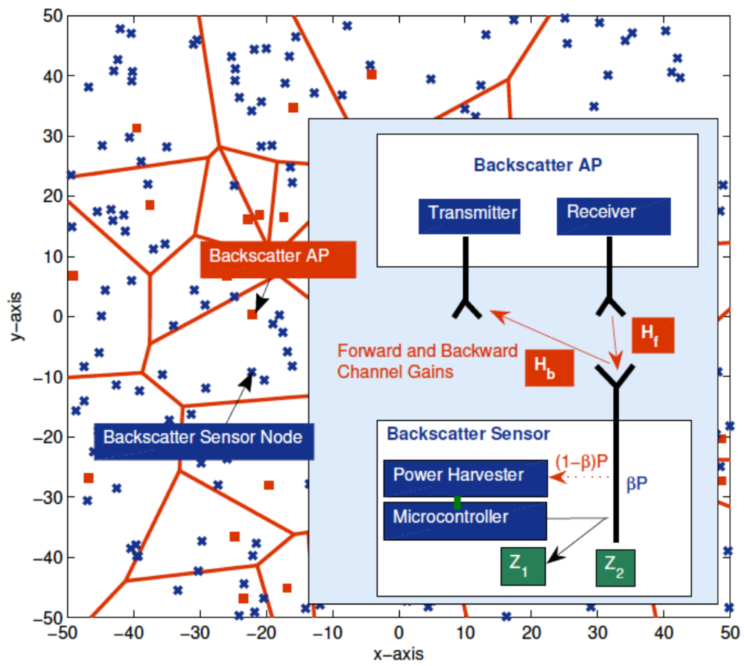


Fig. 1. Network Model and Architecture of Backscatter AP and SN.

- The spatial distribution of both APs and SNs is captured by a two independent homogeneous Poisson point processes (HPPPs);
- Dyadic Fading Channel Model;
- Monostatic-Architecture;
- Interference Limited operation;

S. Zaidi et al. *Coverage Analysis for Backscatter Communication Empowered Cellular Internet-of-Things* in proceedings of IEEE European Signal Processing Conference, A Coruna, Spain, 2019.

Dyadic Fading Channel

- Joint PDF of Channel Gains:

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

- Approximation

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

Proposition 1 [Montonicity of Product]: Let $\mathcal{I}_v$ and $\mathcal{K}_v$ be the modified Bessel functions of first and second kind of order v, then their product $x \mapsto P_v(x) = \mathcal{I}_v(x)\mathcal{K}_v(x)$ is monotonically decreasing on the interval $(0,\infty)$. Also following bounds hold from asymptotic Hankel expansion

$$\mathcal{I}_v(x) \sim \frac{\exp(x)}{\sqrt{2\pi x}}\left(1+\mathrm{O}(x^{-1})\right), \tag{9}$$

$$\mathcal{K}_v(x) \sim \frac{\sqrt{\pi}\exp(-x)}{\sqrt{2x}}\left(1+\mathrm{O}(x^{-1})\right). \tag{10}$$

Dyadic Fading Channel

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

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

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

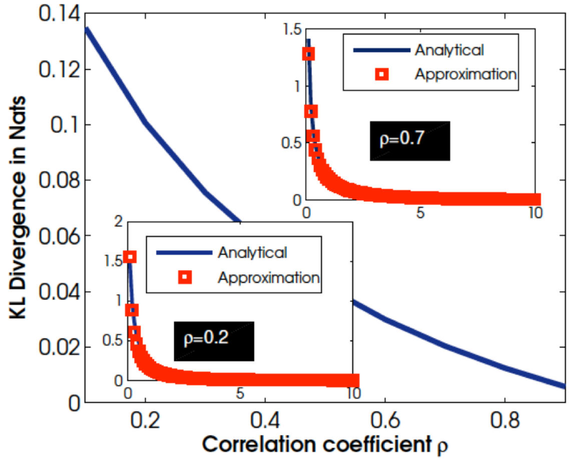


Fig. 2. Accuracy of the approximation in Eq. (13) vs. the exact PDF in Eq. (8) for varying correlation coefficient ρ using KL divergence.

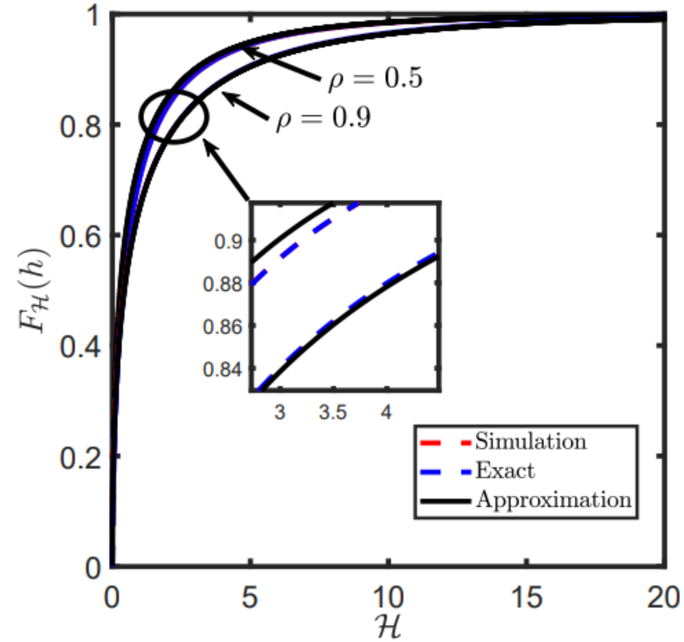


Fig. 4: Cumulative distribution function for the backscatter dyadic fading channel coefficient $\mathcal{H}$.

Coverage Analysis

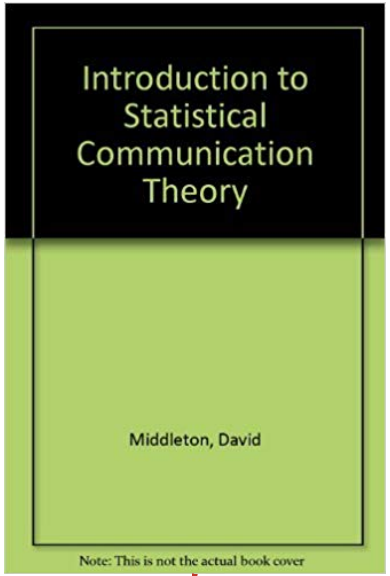
Proposition 2 [Coverage Probability]: The coverage probability of a SN located at a distance r from the transmitter can be upper-bounded as:

$$p_c\left(\gamma_{th}|\, r\right) \lessapprox \exp\left(-\lambda_{SN}\pi\mu_1^{\delta}\gamma_{th}^{\delta/2}\Gamma(1-\delta)\mathbb{E}(\mathcal{H}^{\delta})r^2\right), \quad (16)$$

where $\delta = {}^{2}/_{\alpha}$ and $\mathbb{E}(\mathcal{H}^{\delta}) = \mathbb{E}(\mathcal{H}_f^{\delta}\mathcal{H}_b^{\delta})$ and $\Gamma(x)$ is the Gamma function. The unconditional coverage probability can be quantified by deconditioning $p_c\left(\gamma_{th}|\, r\right)$ by employing PDF of R as:

$$p_c\left(\gamma_{th}\right) \approx \frac{1}{1+\tilde{\lambda}\mu_1^{\delta}\gamma_{th}^{\delta/2}\Gamma(1-\delta)\mathbb{E}(\mathcal{H}^{\delta})}, \quad (17)$$

where $\tilde{\lambda} = {}^{\lambda_{SN}}/_{\lambda_{AP}}$ is the average number of SNs per AP.

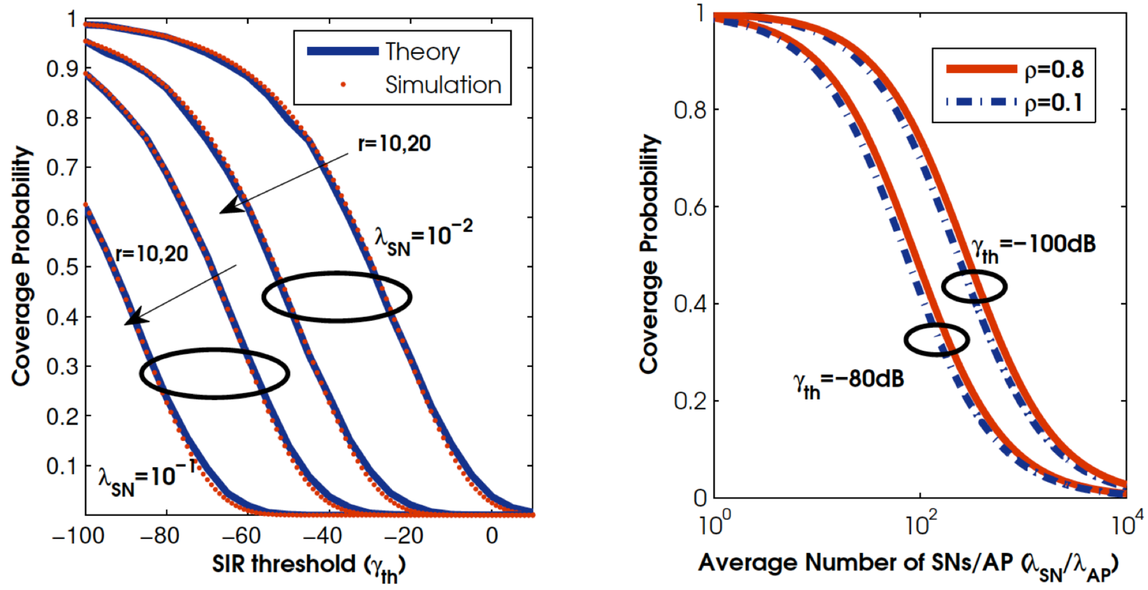


Proposition 4 [Joint Moments]: The joint moments of correlated bivariate Exponential random variable with correlation factor ρ can be computed as:

$$\begin{aligned}\kappa_{\mathcal{H}}\left(n,m\right) &= \mathbb{E}\left[\mathcal{H}_f^{n}\mathcal{H}_b^{m}\right], \\ &= \frac{\tilde{\rho}\Gamma(n+1)\Gamma(m+1)\,{}_2\mathcal{F}_1(n+1,m+1,1;\rho^2)}{\Omega_f^{n}\Omega_b^{m}}, \\ &= 2^{n+m}\left(1-\rho^2\right)^{n+m+1}\sigma_f^{2n}\sigma_b^{2m}\Gamma(n+1) \\ &\times \Gamma(m+1)\,{}_2\mathcal{F}_1\left(n+1,m+1,1;\rho^2\right). \quad (18)\end{aligned}$$

where $\Gamma(x)$ is the Gamma function and ${}_2\mathcal{F}_1\left(a,b,c;z\right)$ is the Gauss hypergeometric function.

Coverage Analysis

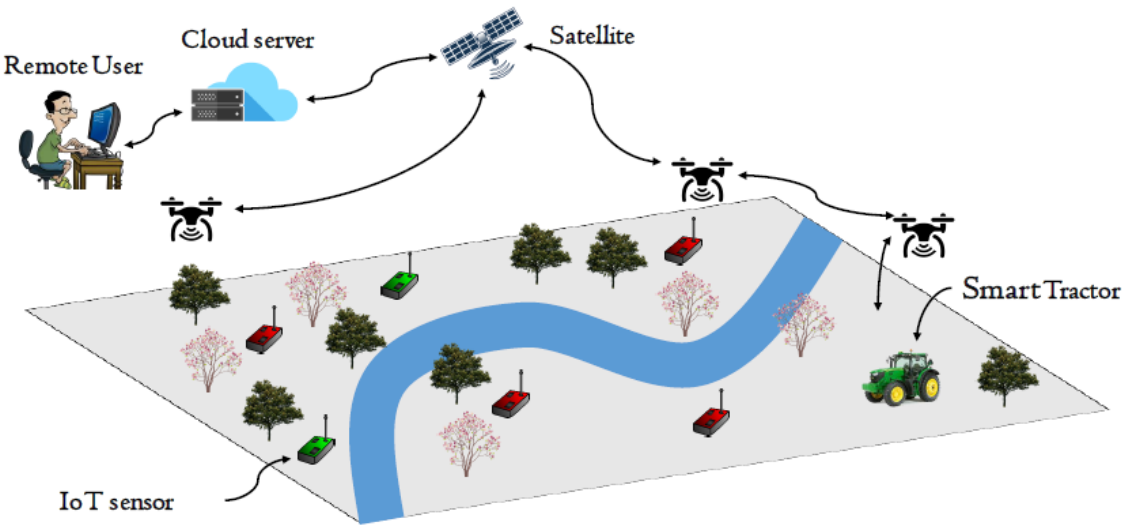


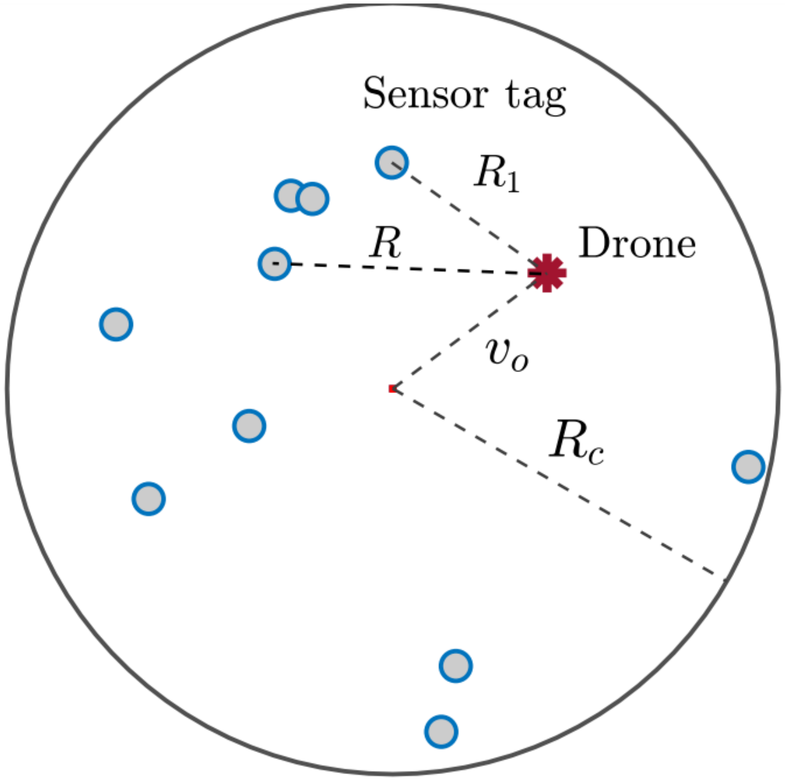
(a) Conditional coverage probability with varying desired SIR threshold (γ_{th}), link distance (r) and SN density (λ_{SN}) for the fixed $\rho = 0.5$ and $\alpha = 4$ (see Eq. (16)).

(b) Coverage probability for varying SN to AP ratio ($\tilde{\lambda}$) and channel correlation (ρ) for $\alpha = 4$ (see Eq. (17)).

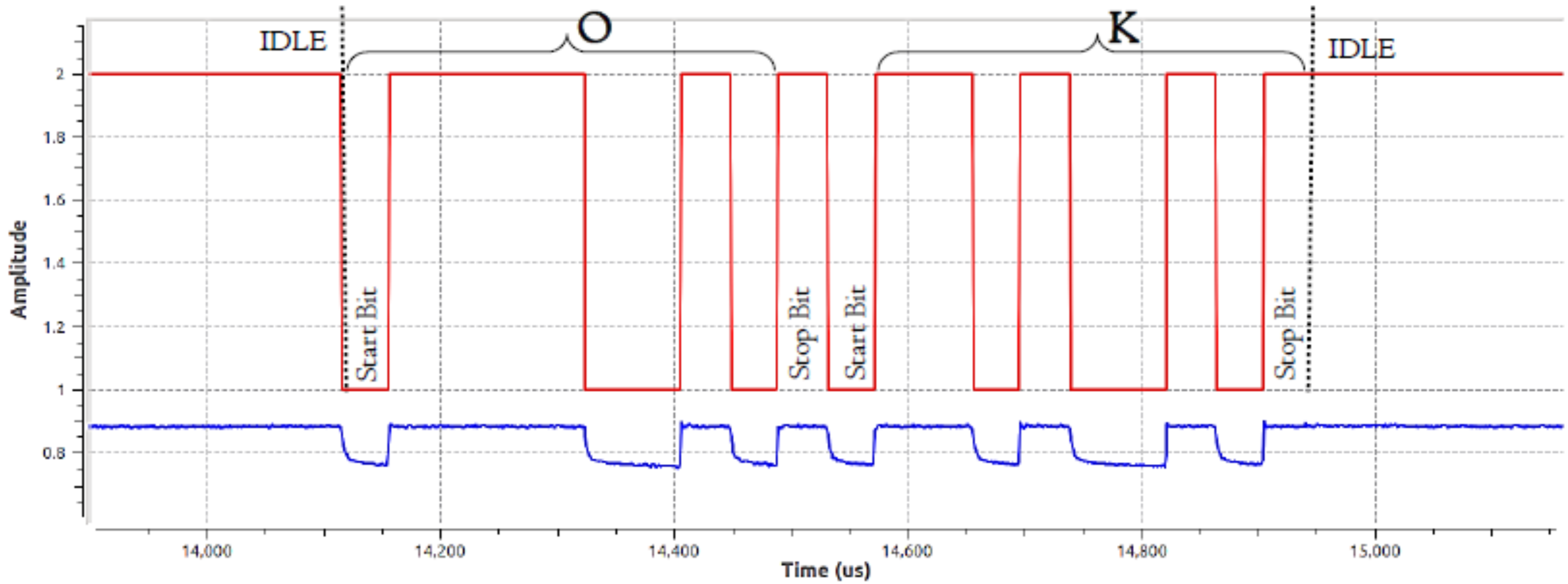
Fig. 3. Validation of Results and Impact of Parametric variations on Coverage Probability.

Exploitation of Mobility





Practical Tests



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

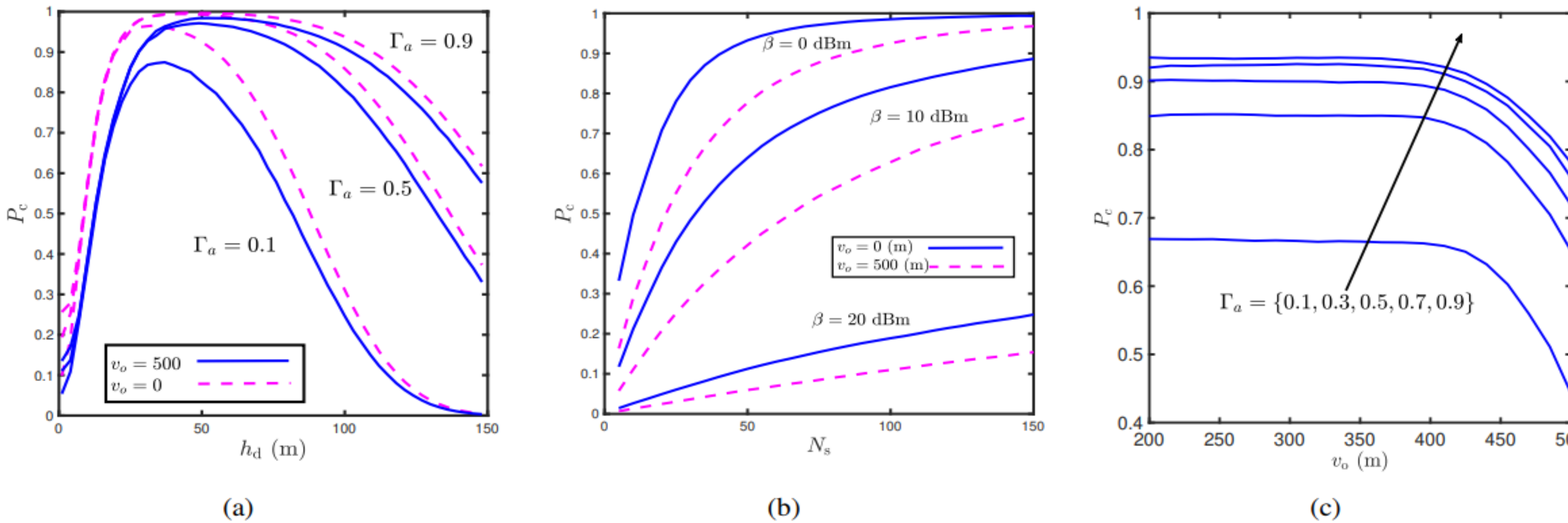
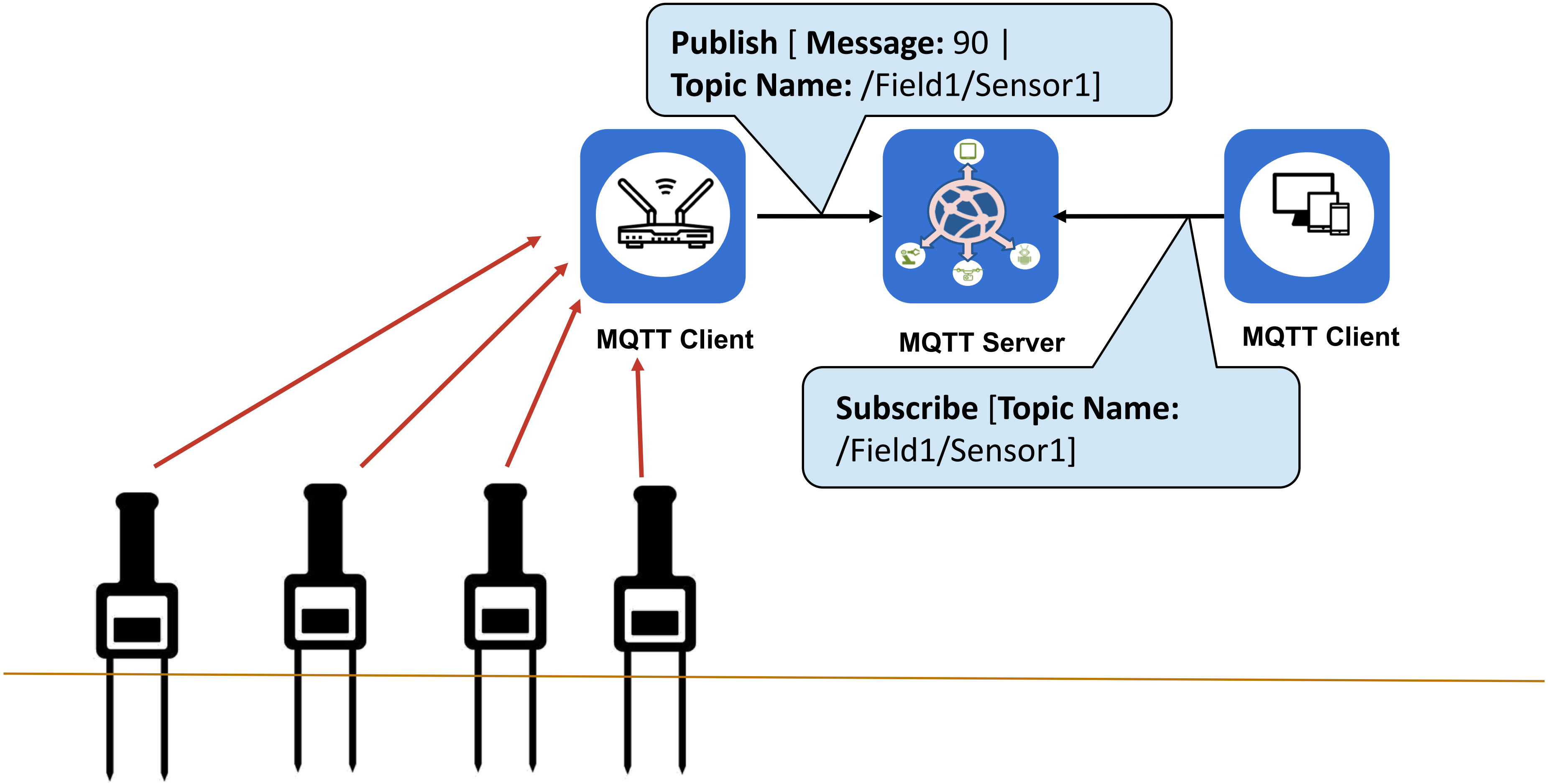


Fig. 5: (a) Coverage probability with $N_s = 200$, $R_c = 500$, $\rho = 0.5$, $\sigma_N^2 = -110$ dBm, $\beta = 10$ dBm. (b) Coverage probability with $R_c = 500$, $\rho = 0.5$, $\sigma_N^2 = -110$ dBm, $\Gamma_a = 0.9$ and (c) Coverage probability with $h_d = 50$ (m), $N_s = 50$, $R_c = 500$, $\rho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

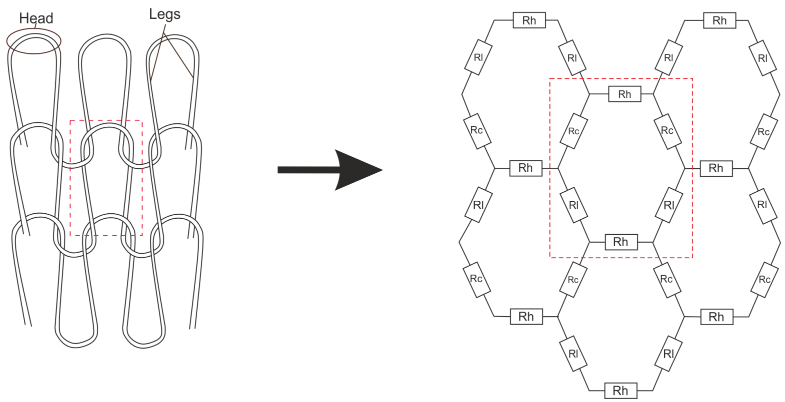
Hayajneh et al. *Coverage Analysis of Drone-Assisted Backscatter Communication for IoT Sensor Network*, in proceedings of IEEE DCOSS WiDRIoT, Santorini, Greece, 2019

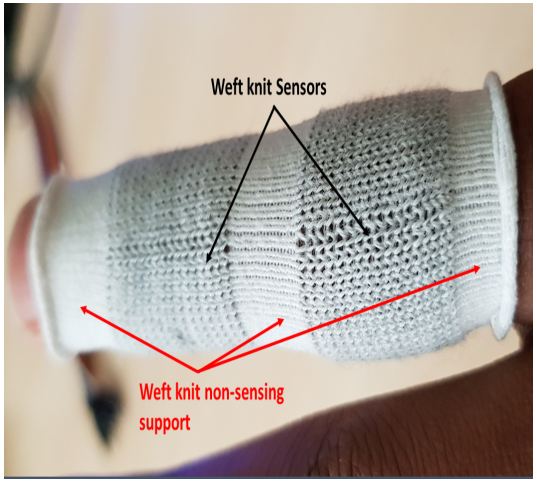
Connecting RF Backscatter to IoT Eco-System



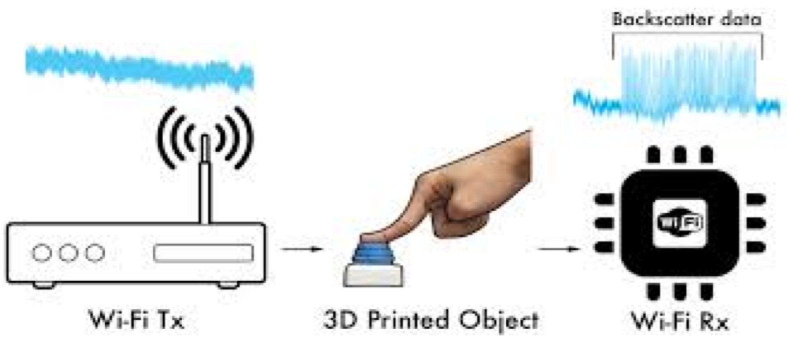
Future Outlook for Backscatter Sensors

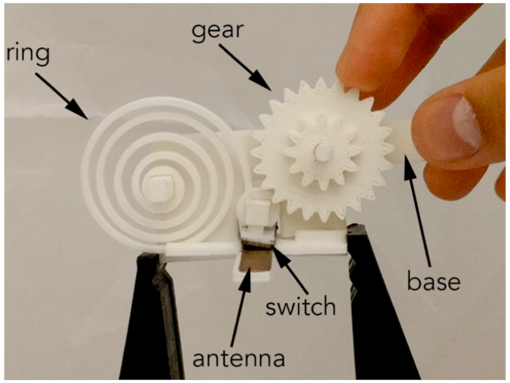
Incorporation into wearable's

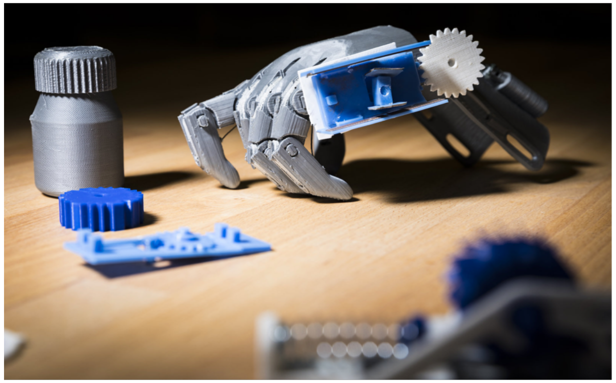




Incorporation into printed objects







Thank you

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