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Beyond Identification: HF RFID and NFC for Digital Twins

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12/02/2022

MILCOM IEEE ComSoc IEEE Communications Society IEEE

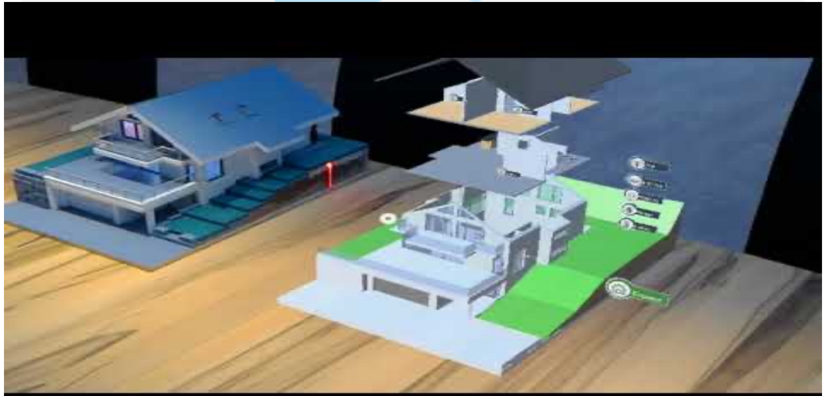
Outline

- Background: Digital world
- Digital Twins
  - Enabling technologies
  - System architecture
  - Applications
- **Wireless sensing using HF RFID and NFC**
  - **Motivation and requirements for digital twin**
  - **Communication and networking protocols**
  - **Research challenges and solutions**
- **Future research directions**

Example: digital twin for smart home

- A virtual model of the home can be built with exactly everything inside
- With AR/MR/VR headsets, you can live in the virtual or mixed world
- Everything at home is tagged to track their locations and status
- Application:
  - If you buy a new TV, you can simulate the best location for it; you can also simulate the electricity bill
  - If you buy a new jacket, you can simulate what are the best outfits for you
  - Provide suggestions for dinner dishes based on what you have at home

Is a Smart Home a digital twin? Tim Aikin



HoloLens KNX SmartHome Physical Twin vs. Virtual Twin

Example: digital twin of soldiers

- Internet of everything around soldiers' body
  - Weapon, supplies, health status monitoring, identification devices
- Simulation of battles
  - Building a 'digital twin' of the Ukraine conflict (https://www.aerosociety.com/news/building-a-digital-twin-of-the-ukraine-conflict/)
  - Estimate battle consumptions and optimize the supply chain

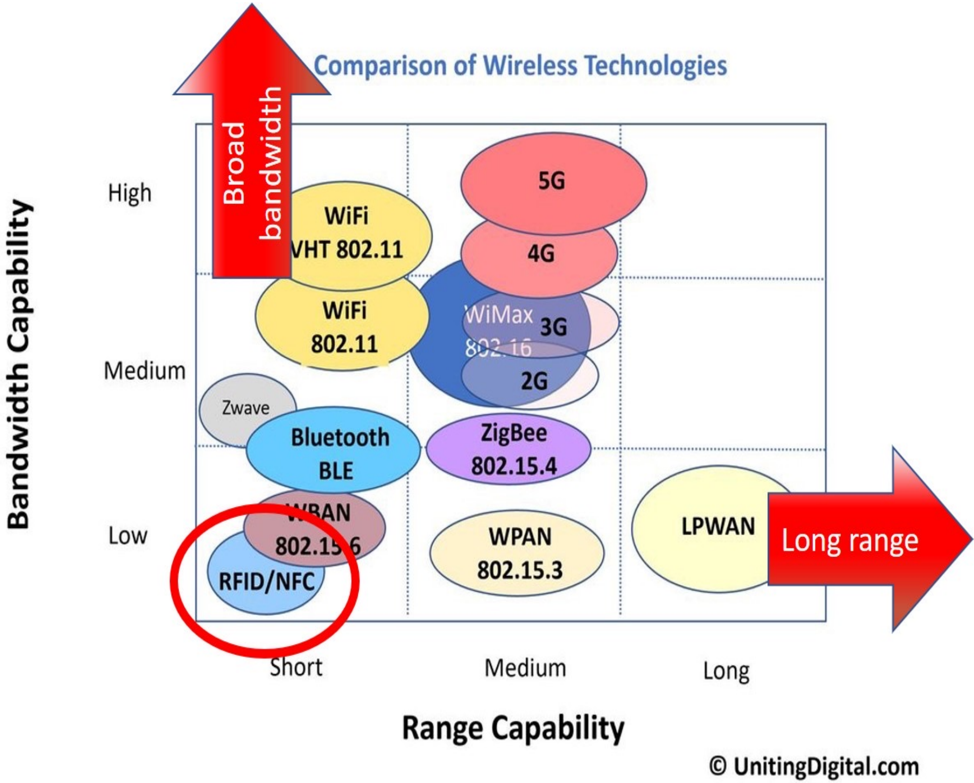
U.S. Army

openPR.com

Digital Twin requires a large number of sensors in a small area

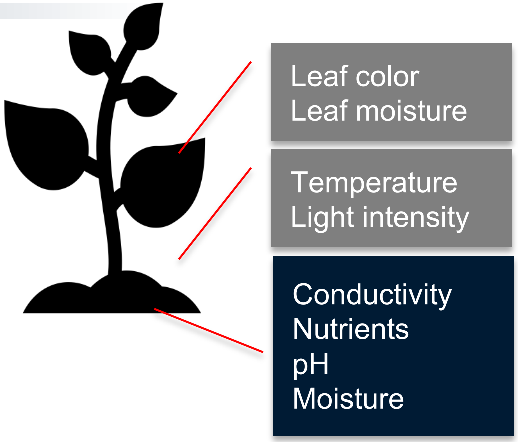
Motivation

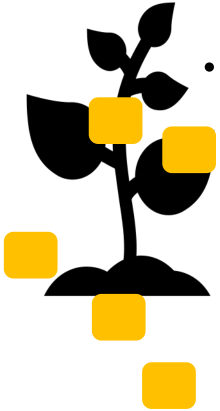
- Internet of everything is a challenging task
- No single wireless solution can network everything
- To internet everything, it requires:
  - Low cost
  - Low weight
  - Low power
  - Non-intrusive
  - Low interference to other applications
- Meet **digital twin** requirements



Long-range or short-range?

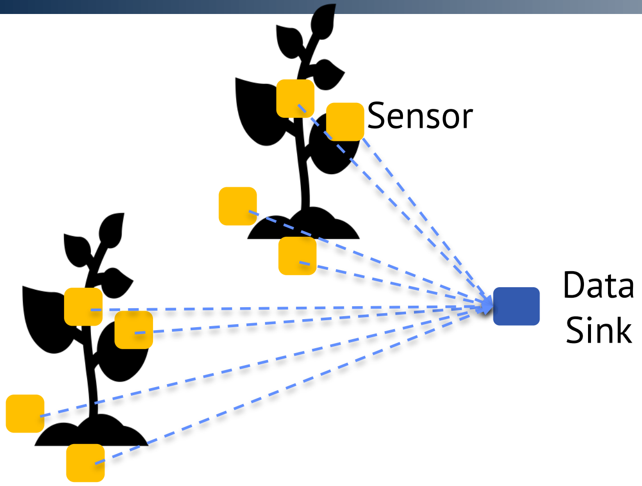
- Digital twin sensing focuses on a small area with a large number of sensors
  - Collect sufficient information to build the virtual representation
- Long-range communication performs well in connecting spatially isolated sensors
  - LoRaWAN, Sigfox, NB-IoT
  - Cellular networks, satellite communication, UAVs
- Short-range communication performs well in ultra-dense IoT environments

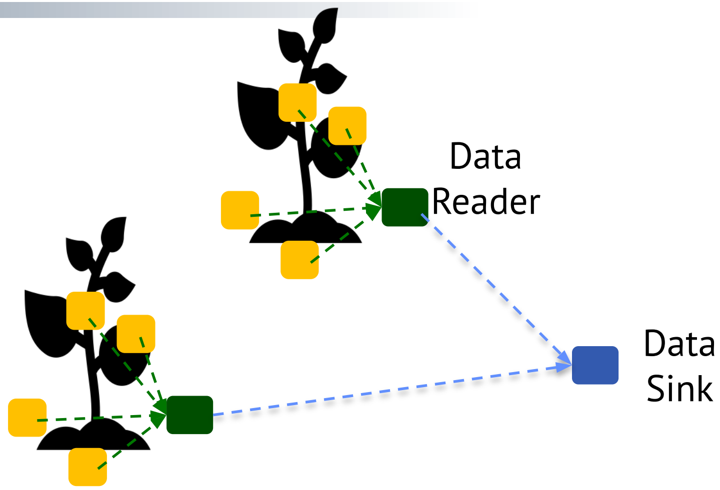




- Requirements:
  - Tiny
  - Low-cost
  - Low-power

Short-range communication: pros & cons





- Long-range
  - High transmission power
  - Battery
  - Nonnegligible weight & size
  - Interference

- Short-range & Long-range
  - Optimized transmission power
  - Tiny sensors
  - Limited interference

Near Field Communication

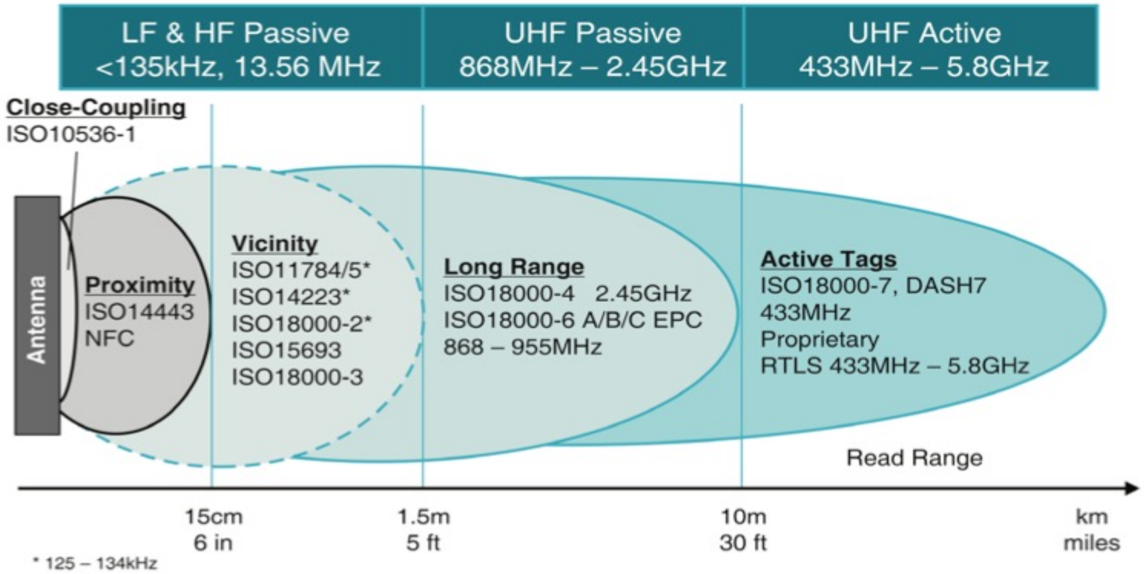
- NFC (near field communication) is designed for very close proximity (<10 cm) ⟶ short communication range
- It uses the ISM frequency band 13.56 MHz ⟶ long wavelength
- In most cases, it does not require battery-powered tags ⟶ battery-free
- NFC Forum is the governing body of the standard and a compliance program that ensures the reliability and interoperability of connections

Image: medium

HF RFID and NFC

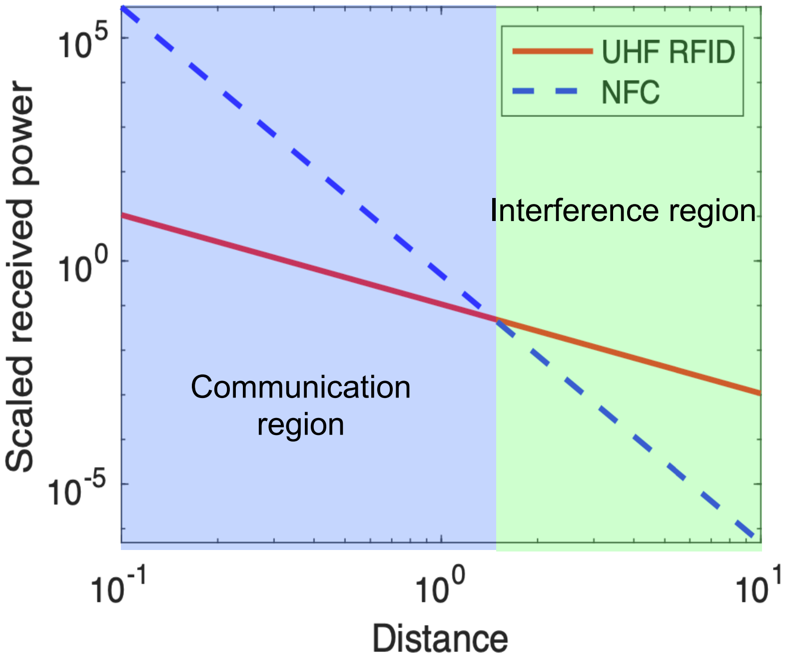
Navigating your way through the RFID jungle, Klemens Sattlegger and Uli Denk, Texas Instruments

- The ISO14443, ISO15693, and ISO18092 are widely used NFC protocols, which are the focus of this presentation



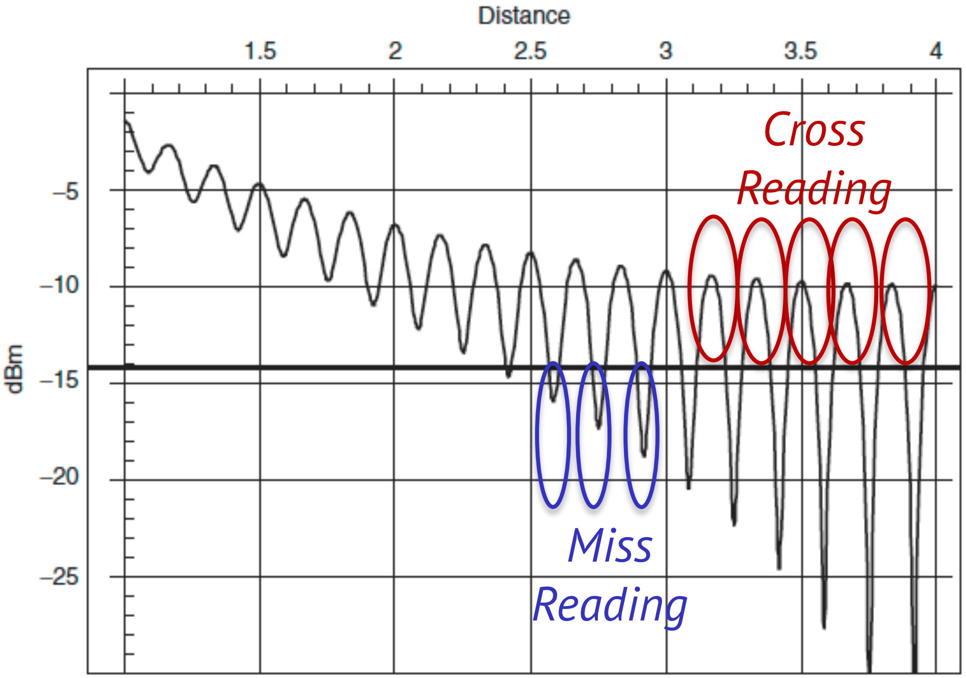
Long-range vs Short-range

- Communication vs Interference
- Long-range communication covers a large area
  - Creates more interference
  - UHF signals fall off as $\frac{1}{d^2}$
- Short-range communication covers a small area
  - Allow more simultaneous communications
  - HF RFID/NFC signals fall off as $\frac{1}{d^6}$



Why not UHF RFID?

- It is not reliable for ultra-dense applications
  - – Miss readings
  - – Read tags outside of range
  - – E.g., range is 3m, sensitivity is -14 dBm
- Reflections, blockages, etc.



Finkenzeller, Klaus. *RFID handbook: fundamentals and applications in contactless smart cards, radio frequency identification and near-field communication*. John wiley & sons, 2010.

HF RFID and NFC at 13.56 MHz

- 13.56 MHz is an ISM band (Industrial, Scientific and Medical)
- Long wavelength
  - Use magnetic induction instead of electromagnetic radiation
  - Use the near field of electromagnetic waves for communication
  - High penetration efficiency; not affected by surrounding environments
  - Stable wireless channel

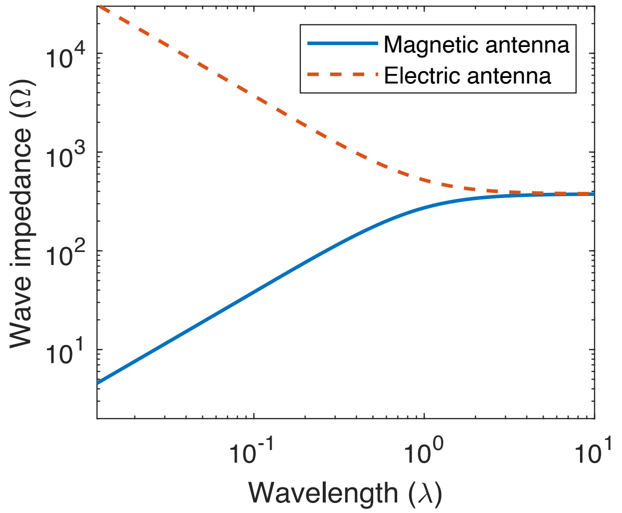
ISM Band Frequencies
6.765 - 6.795 MHz
13.553 - 13.567 MHz
26.957 - 27.283 MHz
40.66 - 40.70 MHz
83.996 - 84.004 MHz
167.992 - 168.008 MHz
433.05 - 434.79 MHz
886 - 906 MHz
2.400 - 2.500 MHz
5.725 - 5.875 MHz
24.0 - 24.25 GHz
61.0 - 61.5 GHz
122 - 123 GHz
244 - 246 GHz

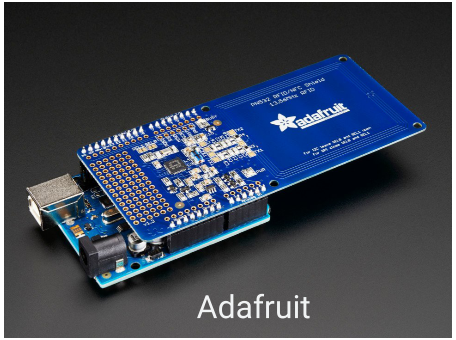
Image: pasternack

Why magnetic coils?

- Wave impedance $\frac{Electric\ field}{Magnetic\ field}$
  - In the far field, it is a constant
  - In the near field, magnetic coils generates more magnetic fields

- Magnetic fields fall off fast with high penetration efficiencies
  - Magnetic fields are less affected by materials' electric conductivity and permittivitiy
  - Network everything in a small area



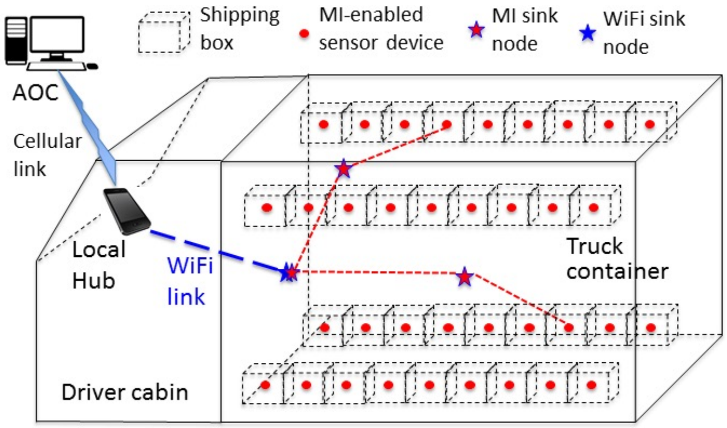


Adafruit

MikroElektronika

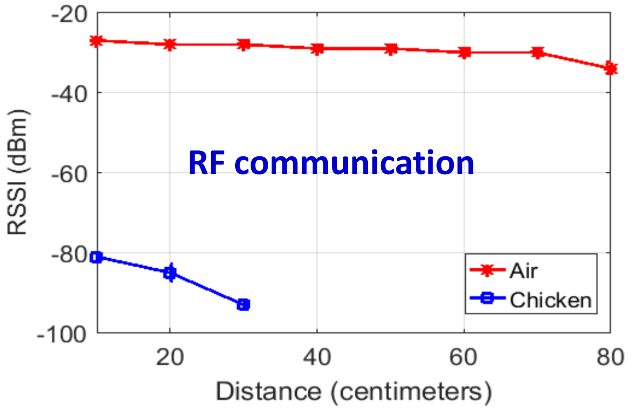
Food supply chain sensing/communication

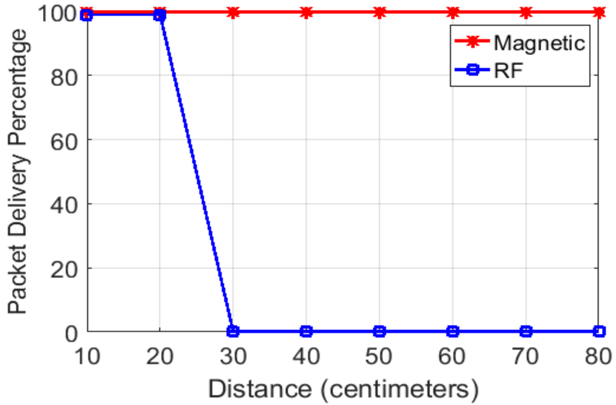
- All packages of perishable products equipped w/ a sensing node
  - Sensor nodes have one or more sensors
  - Detect crucial aspects of product quality via direct or proxy sensing
- Sensed quality communicated to Analytics & Operations Center (AOC) for further analytics and action



NFC for tissue medium

Amitangshu Pal, and Krishna Kant, “MagLoc: A magnetic induction based localization scheme for fresh food logistics”, Elsevier Internet of Things, 2022.





Penetration loss

Product	NFC loss	UHF loss
Bottle water	0 dB	15 dB
Can coke	2 dB	11 dB
Boxed milk	2 dB	12 dB

Zhao, Renjie, et al. "NFC+ breaking NFC networking limits through resonance engineering." Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication. 2020.

Examples of NFC tags

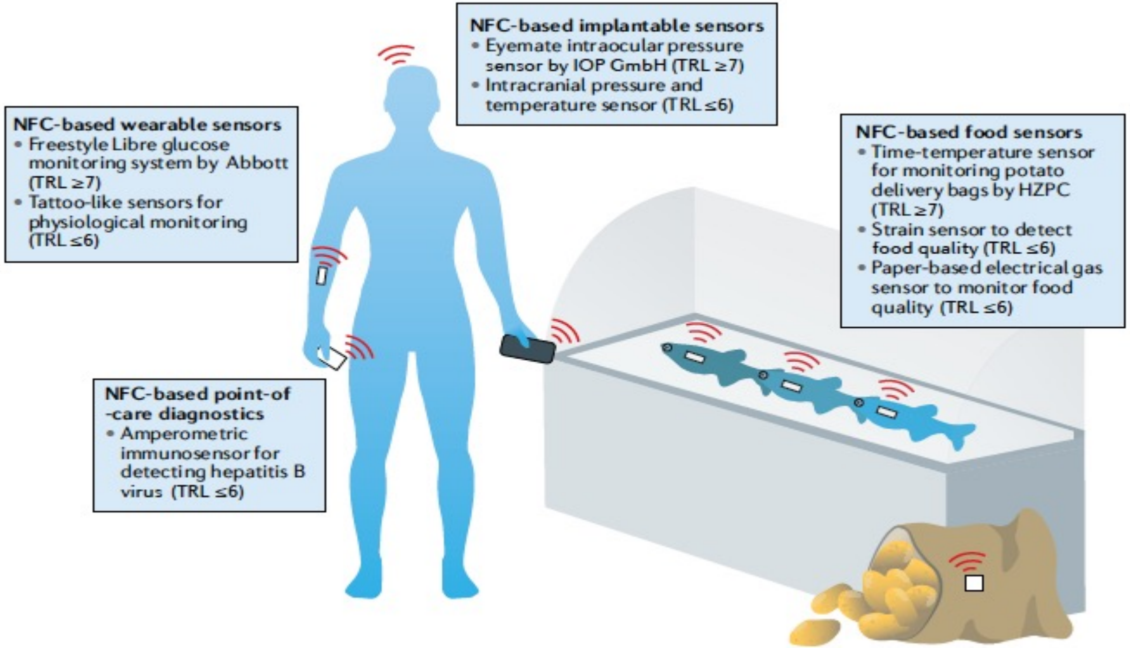
Existing NFC tags

Stretchable textile NFC tags, washable NFC tags, etc.

- Clothes, washable tags, etc.
- Track locations and monitor status

Examples of NFC tags

Olenik, S., Lee, H. S., & Güder, F. (2021). The future of near-field communication-based wireless sensing. *Nature Reviews Materials*, *6*(4), 286-288.



- Near-field communication-based sensors in health care and food quality monitoring

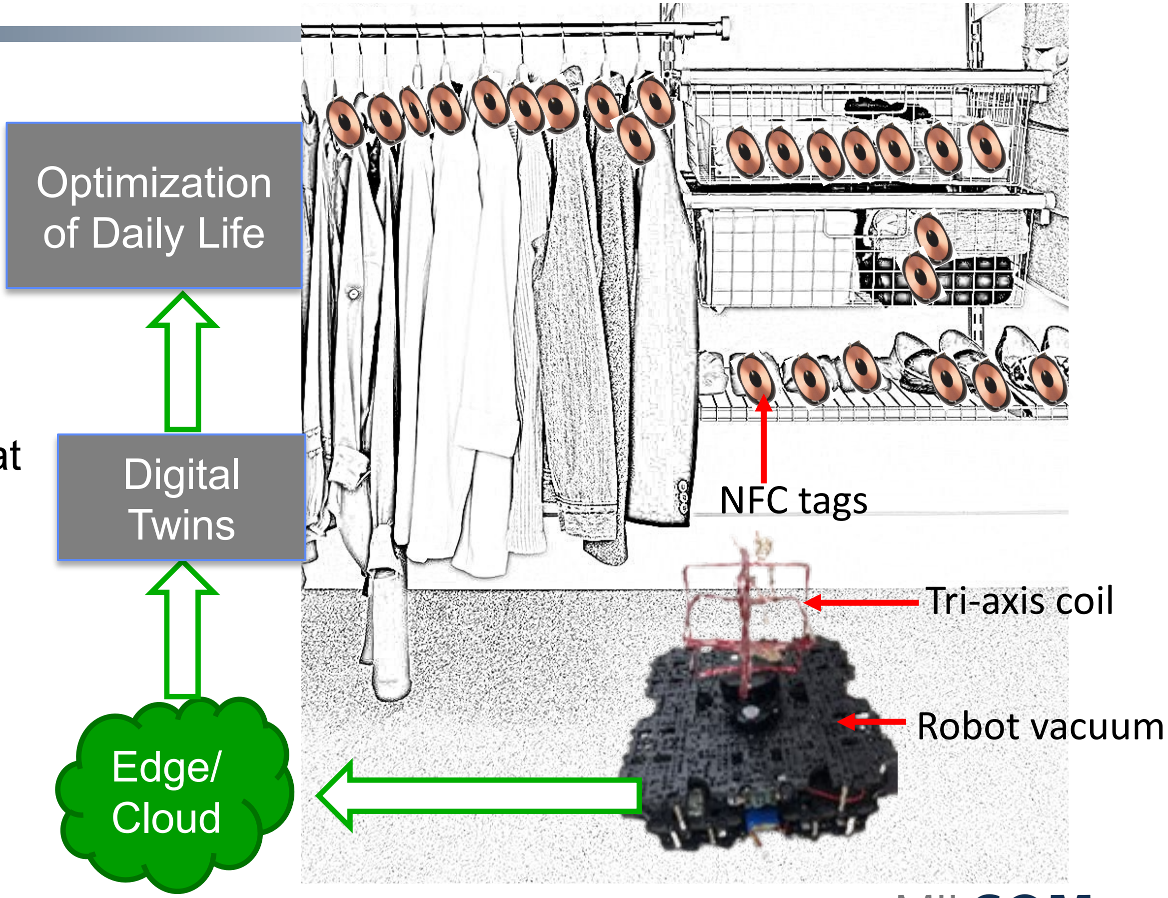
NFC tags for Internet of Clothing

- Imagine a world in which your t-shirt tells you its carbon footprint
- Your sweater tells you how to recycle it
- Your jacket lets you review it, and then shares that with your social networks
- Your handbag lets you join a loyalty program and unlock celebrity content
- Your football jersey is your ticket to the game and lets you pre-order drinks with a special offer

https://evrythng.com/the-internet-of-clothing-how-smart-products-will-transform-fashion/

HF RFID/NFC-based Digital Twin

- Ultra-dense internet of everything
- Mobile robot collect sensing data
  - Location
  - Status
  - Objects/clothes/food, etc. at home
- Create digital twins based on sensed data
- Optimize daily life based on simulations/optimizations



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Fundamentals of NFC

- NFC is based on 13.56 MHz, HF passive RFID/contactless card technology and provides a bidirectional link between devices
- NFC offers three operating modes: Peer-to-Peer, reader/writer and card emulation
- Peer-to-Peer mode:
  – Either devices can initiate the communication and share data, like cellphones
- Reader/Writer mode:
  – An NFC reader/writer can read data from and write data to NFC/RFID contactless smartcards
- Card Emulation mode:
  – NFC devices behave like a smartcards
- Besides communication, there is a wireless charging mode
  – Power transfer of up to 1W using NFC connection

ISO standards

ISO Standard	Proximity cards		Vicinity card
	14443A	14443B	15693
Frequency	13.56 MHz		
Modulation (reader to tag)	ASK 100%, Modified Miller	ASK 10%, NRZ	ASK 10% or 100%, PPM
Modulation (tag to reader)	106kbps, ASK 100%, Manchester	106kbps, BPSK, NRZ-L	ASK Manchester 6.62 kbps to 211.8 kbps
	212, 424, 848 kbps, BPSK, NRZ-L		
Subcarrier frequency	847.5 kHz		211.8 kHz, 423.75 kHz
Read or write range	Up to 10 cm		Up to 1m
	2 cm	10 cm	20 cm
Bandwidth	1.7 MHz		1 MHz
Q factor	Around 8		13.6
Current	1 mA	25 mA	Around 220 mA
TX output power	>50mW		>200mW

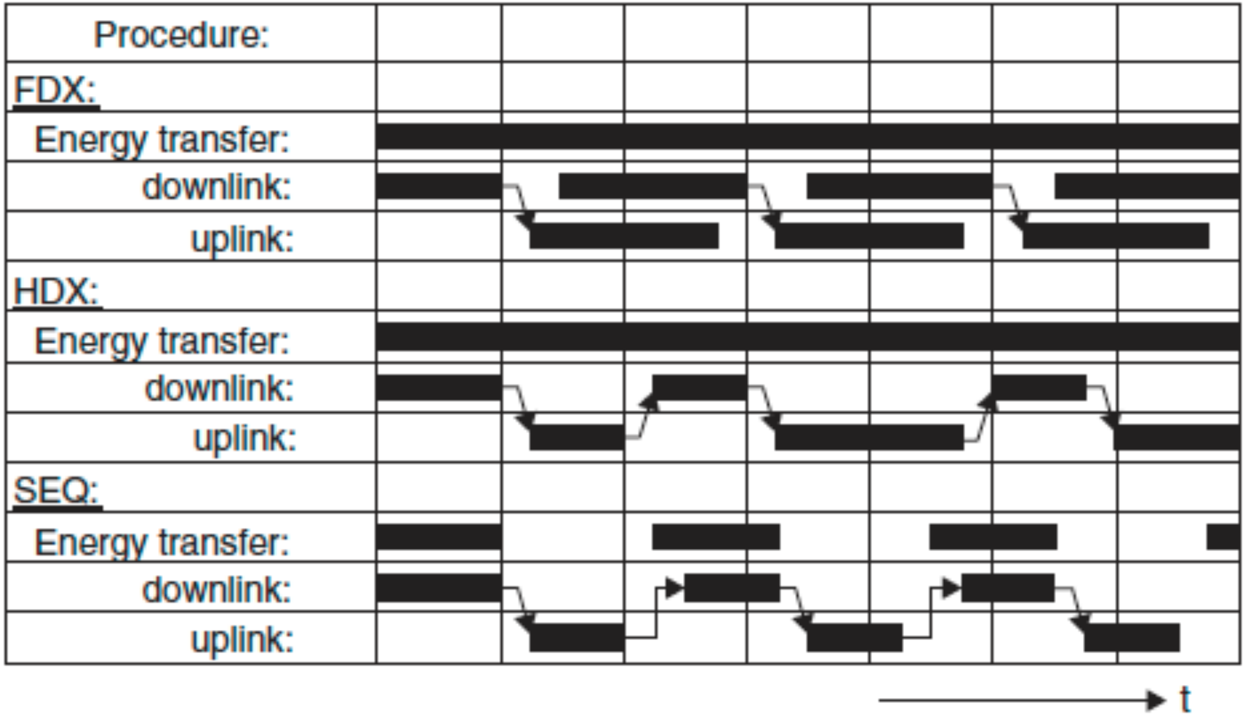
Range

System	Baud rate (kBd)	Subcarrier frequency (kHz)	Carrier frequency (MHz)	Range (m)
ISO 14443	106	847	13.56	0.1
ISO 15693	26.48	484	13.56	0.3
ISO 15693	6.62	484	13.56	0.7
Long-range system	9.0	212	13.56	1.0

RFID systems with a field strength of up 60 dB uA/m measured at a distance of 10 m, can be operated on the classical ISM frequency 13.56 MHz.

Communication modes

- FDX: full-duplex
- HDX: half-duplex
- SEQ: sequential systems



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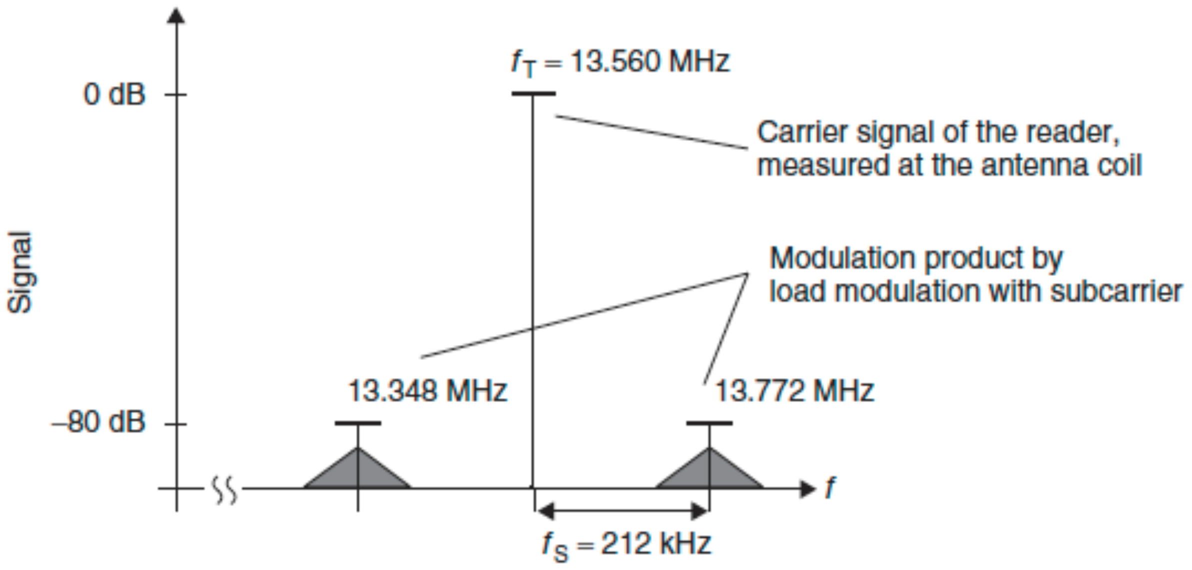
Subcarrier



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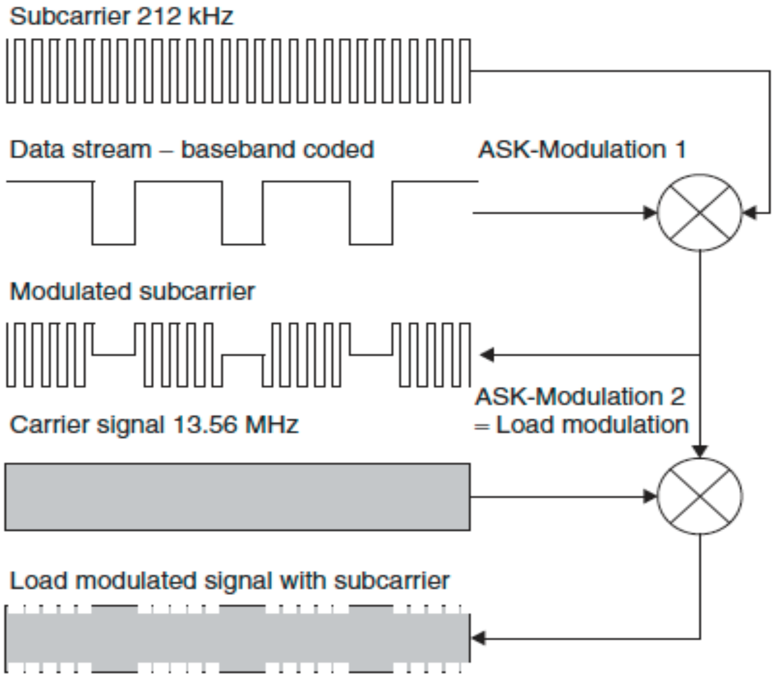
Modulation



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HF RFID & NFC for Digital Twins: Challenges

Existing HF RFID and NFC cannot be directly used because of the following challenges:

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Short-communication range	Although short-communication ranges is desired for internet of ultra-dense things, a 10cm range cannot allow automatic networking
Misalignment reduces communication range	Magnetic coils are sensitive to misalignment
The materials of HF RFID and NFC tags need to be improved	Rigid metal/plastic tags cannot be used everywehere New materials: textile, paper, etc.
HF RFID and NFC sensing	Localization, material, fluid content & level, orientation
Security & Privacy	

The need of long-range HF RFID & NFC

- 10 cm communication range can only allow touch-and-go applications
  - It is mainly due to security issues; a short communication range can physically protect devices from attacks

- Extend the communication range from 10 cm to any range up to 1.5 m can allow many more digital twin applications

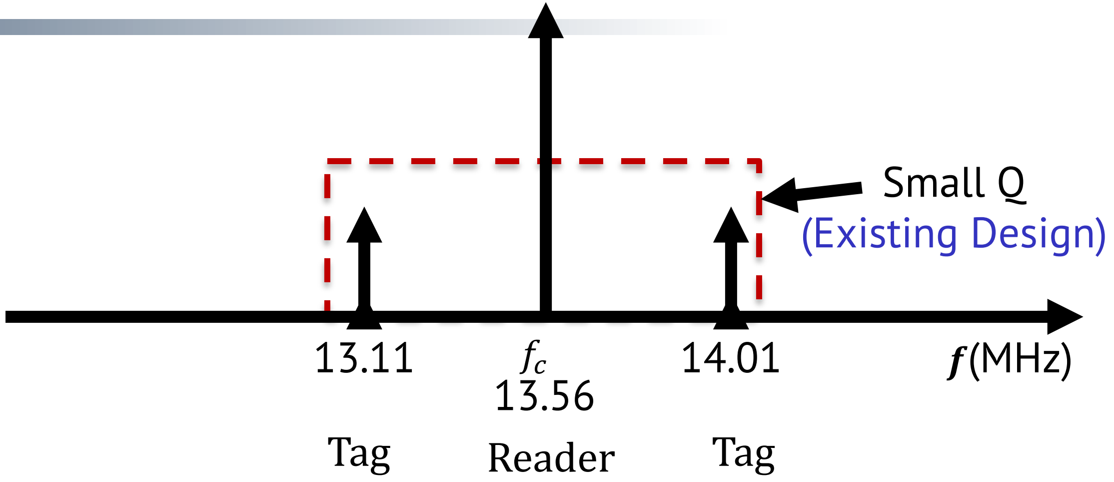
- Existing works extend the range using various solutions
  - Signal processing

    Zhao, Renjie, et al. "NFC+ breaking NFC networking limits through resonance engineering." Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication. 2020.
  - Novel antenna design

    Guo, Hongzhi, Zhi Sun, and Chi Zhou. "Practical design and implementation of metamaterial-enhanced magnetic induction communication." *IEEE Access* 5 (2017): 17213-17229.

Review of ISO15693

- Key technologies that fundamentally limit the communication range
  - Full duplex communication without self-interference cancellation
  - Low-quality factor coils that trade off between bandwidth and communication range



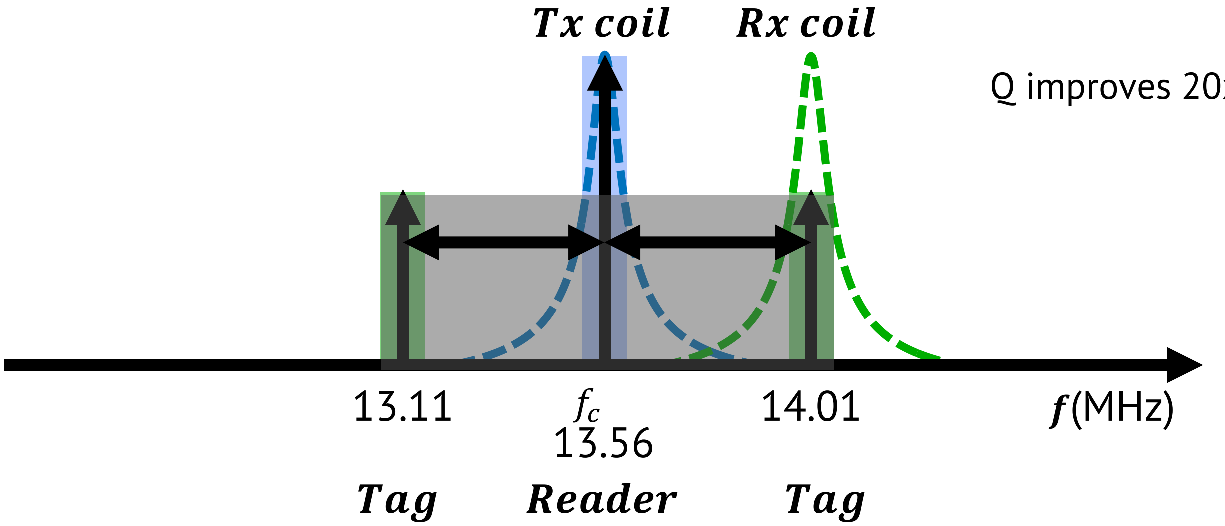
Reader's coil has to use a small Q to have a large bandwidth that can cover transmitted signals and reflected signals.

$$Q = \frac{f_0}{BW} = \frac{13.56\ MHz}{0.484 \times 2\ MHz} \approx 14$$

Full-duplex NFC with SIC

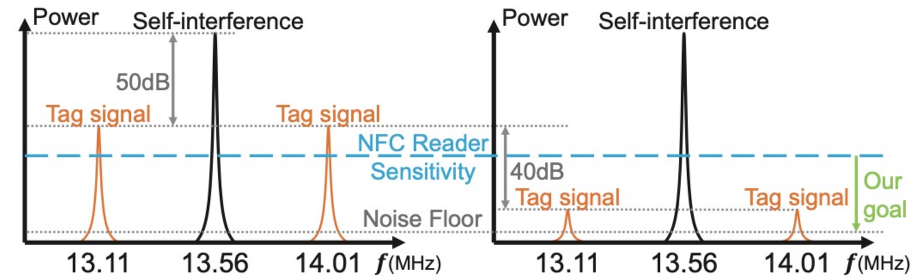
Zhao, Renjie, et al. "NFC+ breaking NFC networking limits through resonance engineering." Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication. 2020.

- NFC+ uses separated transmitting coil and receiving coil
  - Design self-interference cancellation (SIC) to reduce self-interference

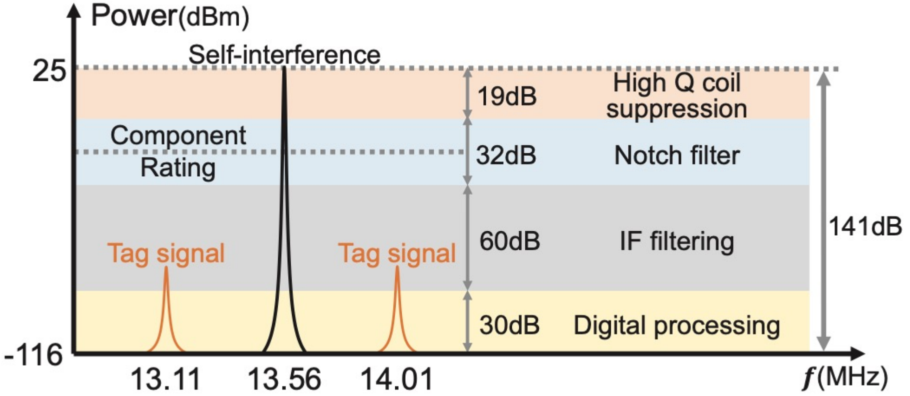


Self-interference cancellation

- As the distance between the tag and reader increases, the self-interference problem becomes more challenging
- Multiple stages of self-interference cancellation are used
  - High Q coil suppression, notch filter, IF filtering, digital signal processing,
  - Overall, 141 dB



(a) Received signal strength when tag is 10cm away. **(b) Received signal strength when tag is 1m away.**



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High-Q coils

- **Transmit coils**
  - The reader-to-tag downlink transmission using pulse position modulation with 9.44 us pulse width
  - The bandwidth for reader-to-tag link is 1/9.44 us = 106 kHz
  - Transmit coil quality factor $Q = \frac{f_0}{BW} = \frac{13.56\ MHz}{0.106\ MHz} \approx 128$

- **Receive coils**
  - The tag performs FSK modulation at 6.7 kbps with a 423 kHz or 484 kHz subcarrier
  - The required bandwidth is (484-423)+2×6.7 = 74.4 kHz
  - Receive coil quality factor $Q = \frac{f_0}{BW} = \frac{14.01\ MHz}{0.0744\ MHz} \approx 188$

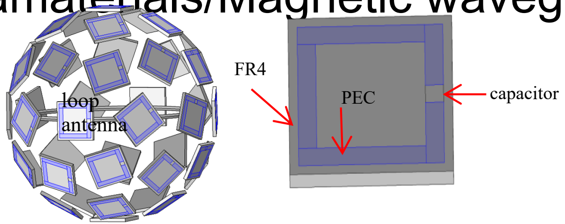
- High-Q transmit and receive coils increase the communication range longer than 1.6 times

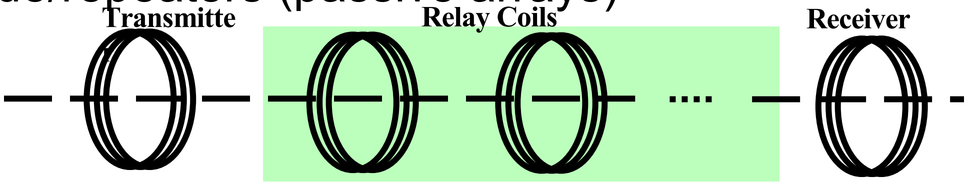
Novel coil antenna design

- Coil arrays
  - Magnetic MIMO（active arrays）

Jadidian, Jouya, and Dina Katabi. "Magnetic MIMO: How to charge your phone in your pocket." *Proceedings of the 20th annual international conference on Mobile computing and networking*. 2014.

  - Metamaterials/Magnetic waveguide/repeaters (passive arrays)





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Security & Privacy	

Arbitrary orientation of tag coils

- HF RFID and NFC tags can be randomly orientated since they are attached to physical objects without specific requirements

- Magnetic beamforming is widely used to power up HF RFID and NFC tags

Zhao, Renjie, et al. "NFC+ breaking NFC networking limits through resonance engineering." Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication. 2020.

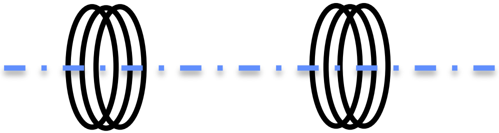
- Magnetic blind beamforming does not require channel estimation; which can be used for battery-free tags

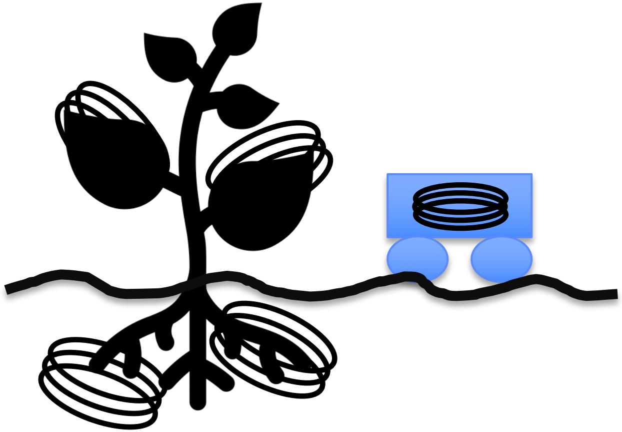
Wang, Jingxian, et al. "Locating everyday objects using nfc textiles." Proceedings of the 20th International Conference on Information Processing in Sensor Networks (co-located with CPS-IoT Week 2021). 2021.

Ofori, Albert Aninagyei, and Hongzhi Guo. "Magnetic Blind Beamforming for Battery-Free Wireless Sensor Networks." *IEEE Transactions on Green Communications and Networking*6.3 (2022): 1819-1832.

Misalignment losses

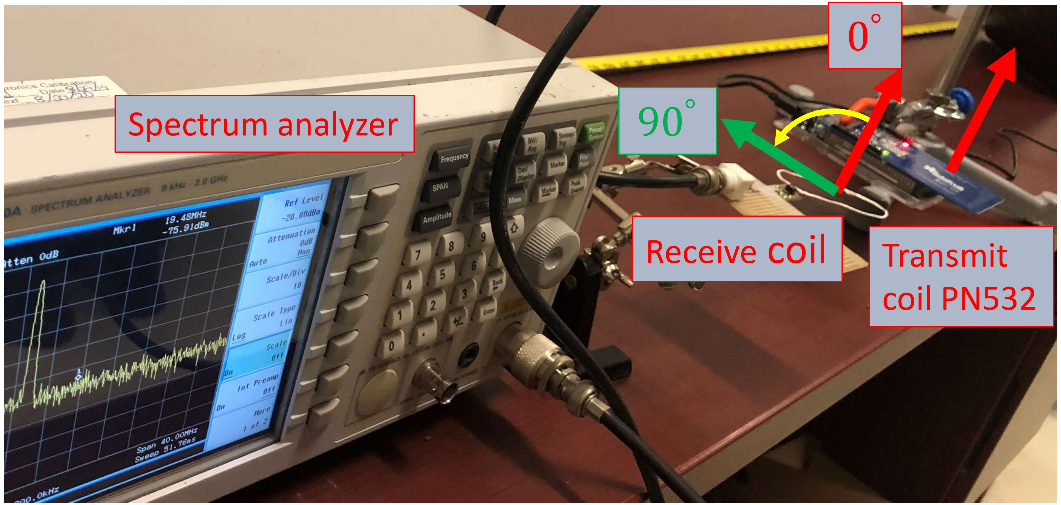
- NFC uses coils, which have to be aligned in orientation
- Agriculture sensors attached to leaves & roots may change orientation
  - Growth is a dynamic process
- Sensor coils have arbitrary orientation
  - Alignment, if possible, is labor-intensive

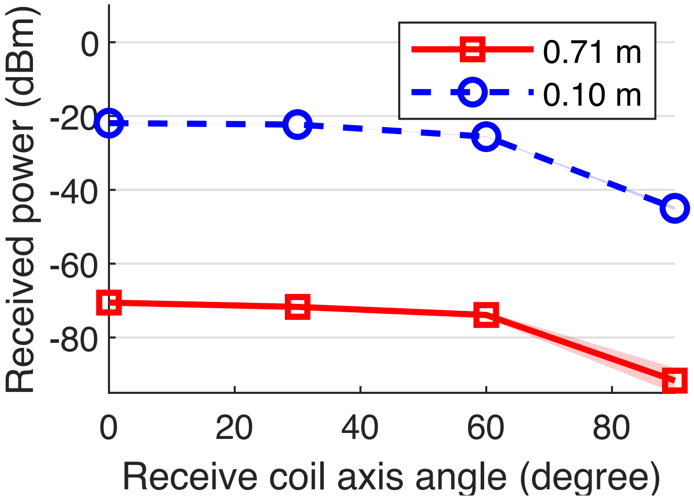




Evaluation of misalignment losses

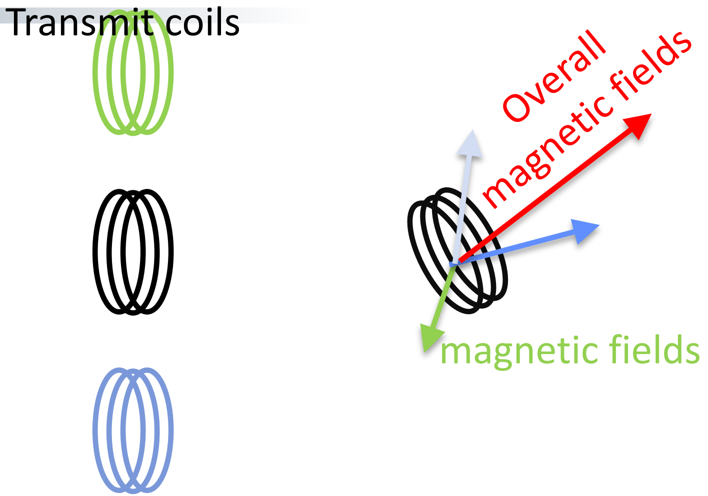
- Misalignment losses 20 - 30 dB
- It is challenging to maintain the alignment of coils

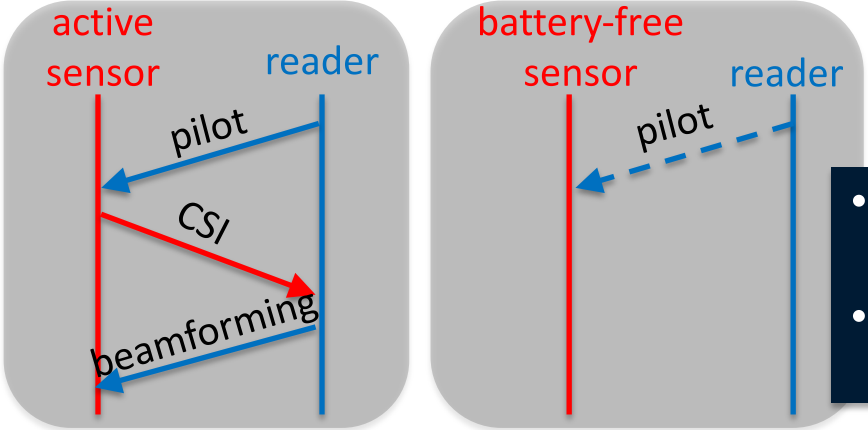




Misalignment losses & magnetic MIMO

- Use multiple transmit coils to increase diversity
  – Optimally allocate transmission power
  – Require channel estimation
- Battery-free sensors cannot estimate channel without power

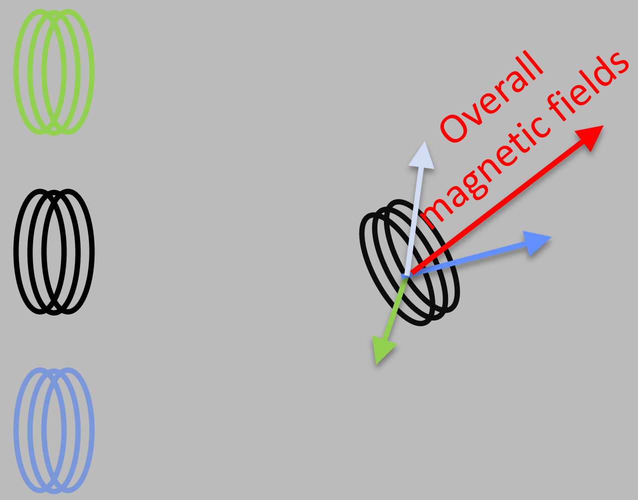




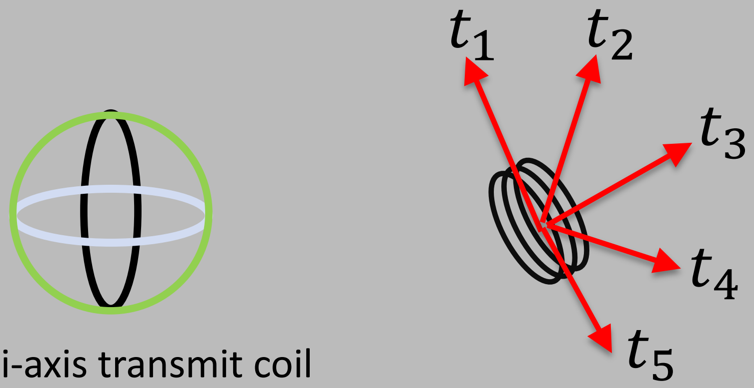
- Reader wakes up sensors using beamforming
- Reader needs sensors' responses to design beamforming signals

Magnetic blind beamforming

- Magnetic blind beamforming without channel information
  - Rotate the magnetic field directions
  - At least one or a few will work



Transmit coils



Tri-axis transmit coil

A. Ofori & H. Guo, IEEE TGCN 2022

Beamforming current vector design

$$\underset{\boldsymbol{i}\in\mathbb{C}^3}{\text{minimize}} \parallel t\boldsymbol{u} - \boldsymbol{h} \parallel^2$$

$$s.t.\ \boldsymbol{i}^T\boldsymbol{C}^T\boldsymbol{C}\boldsymbol{i} = t^2 \leftarrow \text{magnetic field at the receiver}$$

$$\boldsymbol{i}^T\boldsymbol{R}\boldsymbol{i} \leq 2P_{max} \leftarrow \text{transmission power is limited}$$

$$\boldsymbol{i}^T\boldsymbol{C}^T\boldsymbol{u}\boldsymbol{u}^T\boldsymbol{C}\boldsymbol{i} > \frac{V_{th}^2}{\omega^2(\mu_r\mu_0 N_r \pi a_r^2)^2} \leftarrow \text{induced voltage}$$

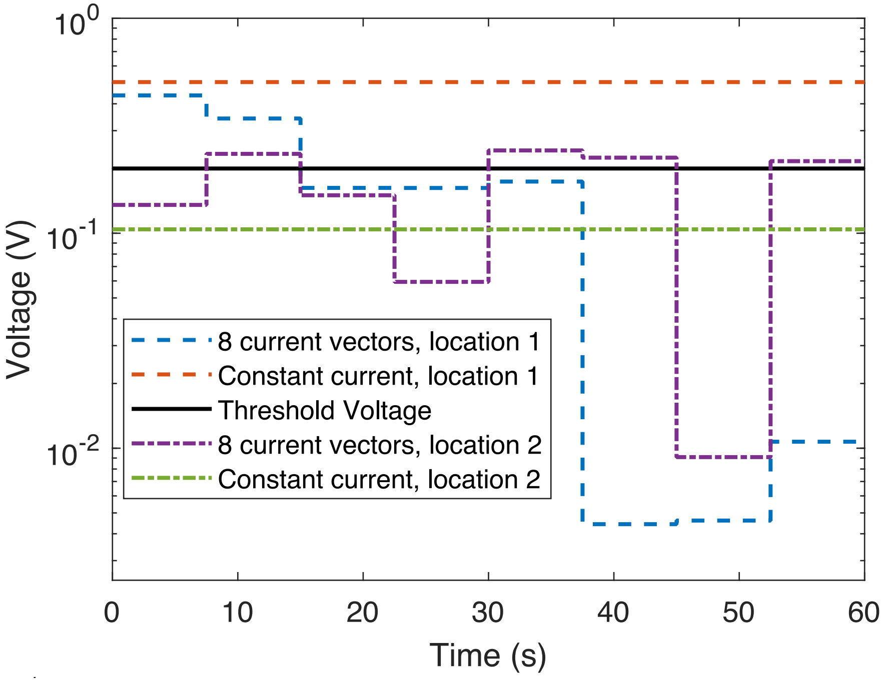
- Define an optimization problem to find the optimal current vectors for the tri-axis coil
- In the near field, if rotating magnetic field at one location, it also rotates at other locations
- In the far field, it is different and complex

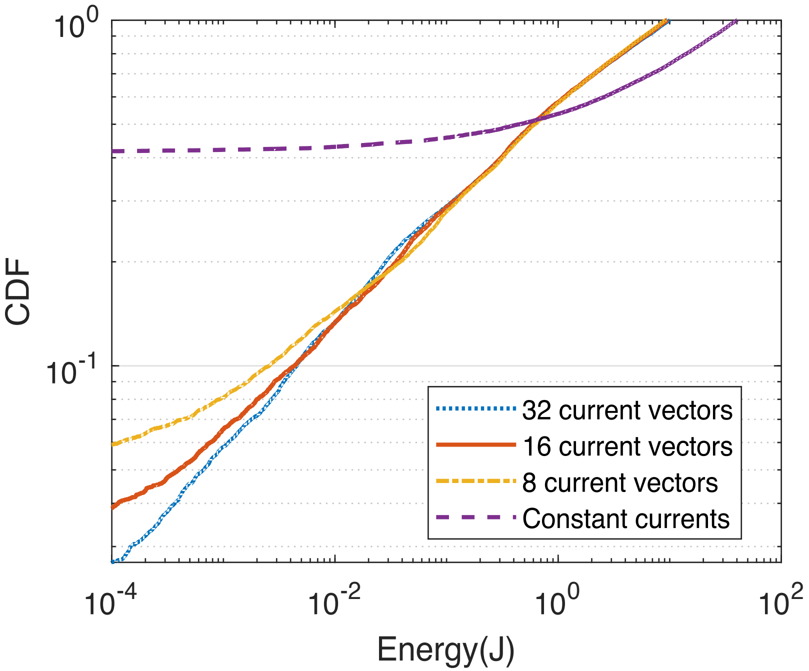
1. Assume sensor location & orientation
2. Solve a semidefinite relaxation problem
3. Obtain the optimal current vectors
4. Study the impacts of sensor location & number of beamforming vectors

Next current vector

Numerical performance

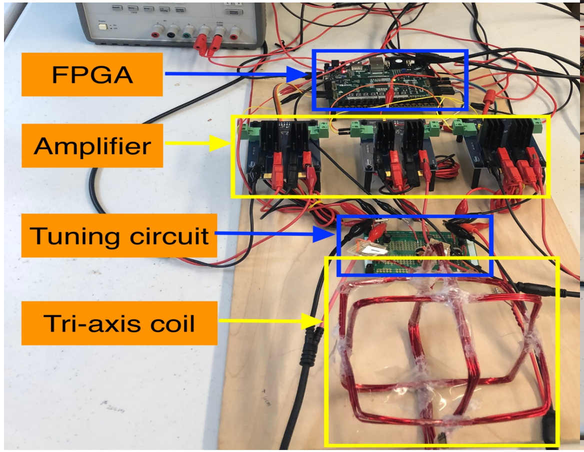
- A constant current vector can have very different performances
- Rotating magnetic fields has guaranteed performances

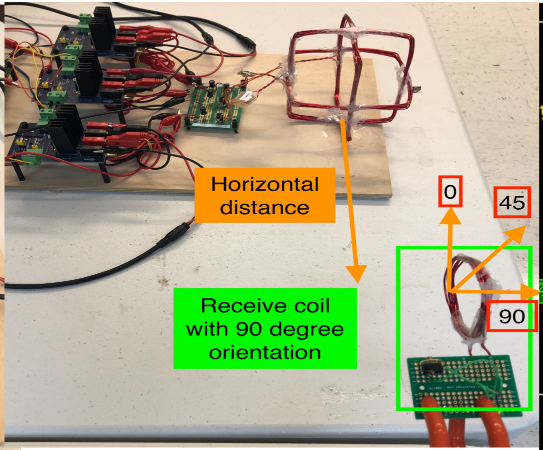


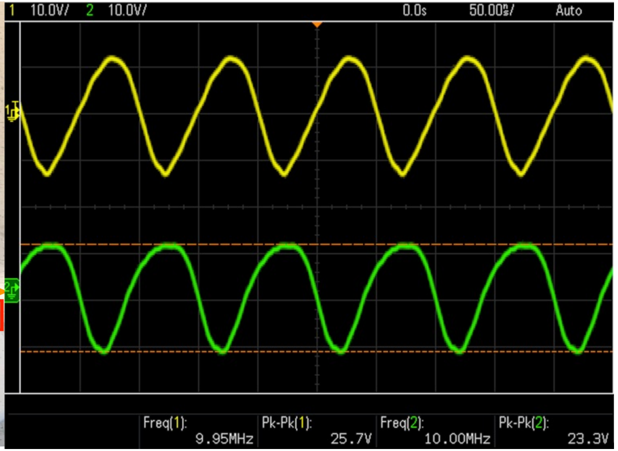


Proof-of-concept testbed

- In the near-field, there is no phase shift due to propagation
- Only two phases: coaxial or coplanar
- Voltage switching amplifier is used to control phase and amplitude







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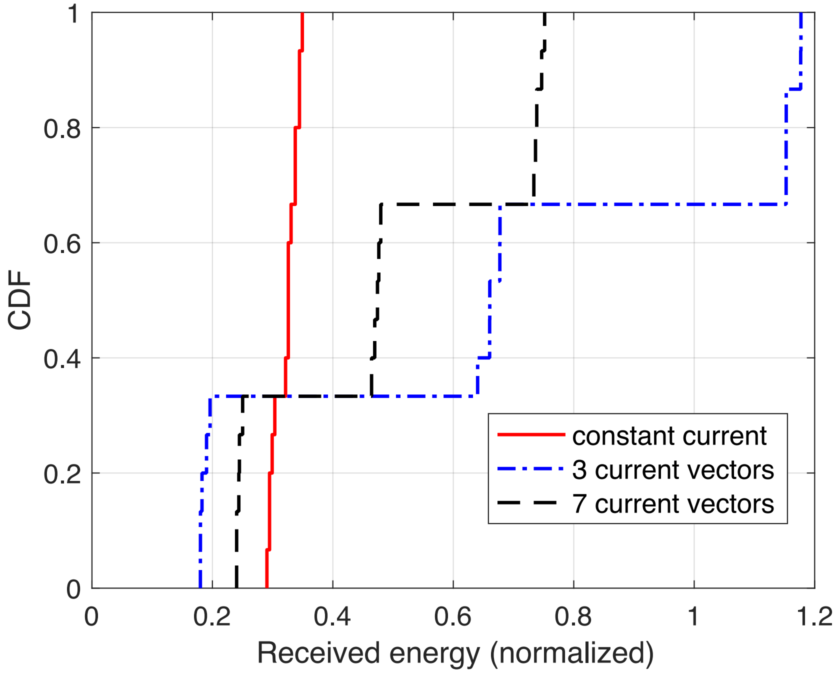
Results

- Measured received voltage in the small coil placed on one side of the transmit tri-axis coil

- Rotating current vectors induce different voltages



HF RFID & NFC for Digital Twins: Challenges

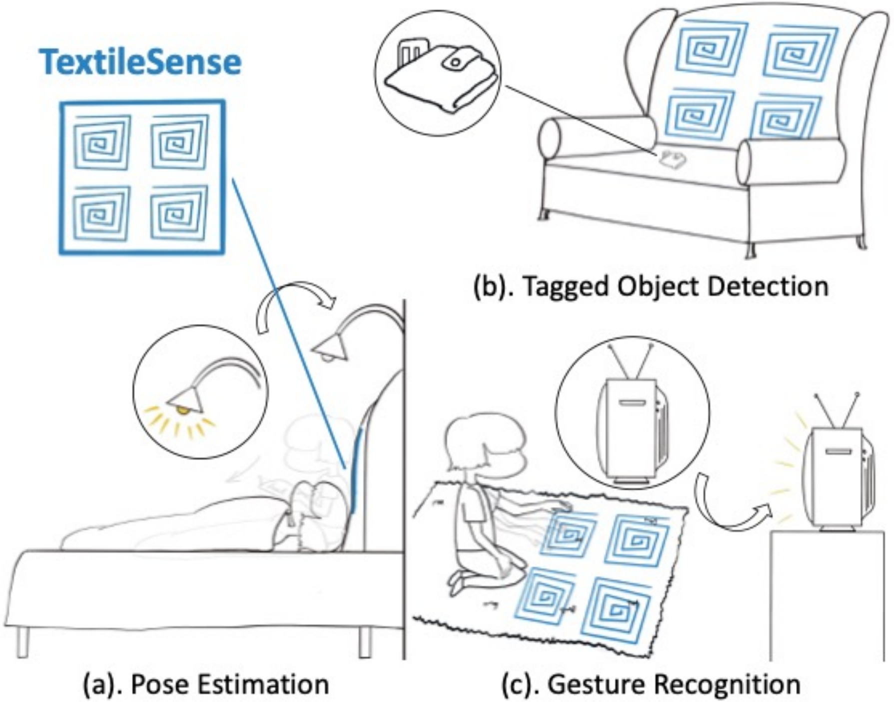
Existing HF RFID and NFC cannot be directly used because of the following challenges:

Existing HF RFID and NFC cannot be directly used because of the following challenges:

Short-communication range	Although short-communication ranges is desired for internet of ultra-dense things, a 10cm range cannot allow automatic networking
Misalignment reduces communication range	Magnetic coils are sensitive to misalignment
The materials of HF RFID and NFC tags need to be improved	Rigid metal/plastic tags cannot be used everywehere New materials: textile, paper, etc.
HF RFID and NFC sensing	Localization, material, fluid content & level, orientation
Security & Privacy	

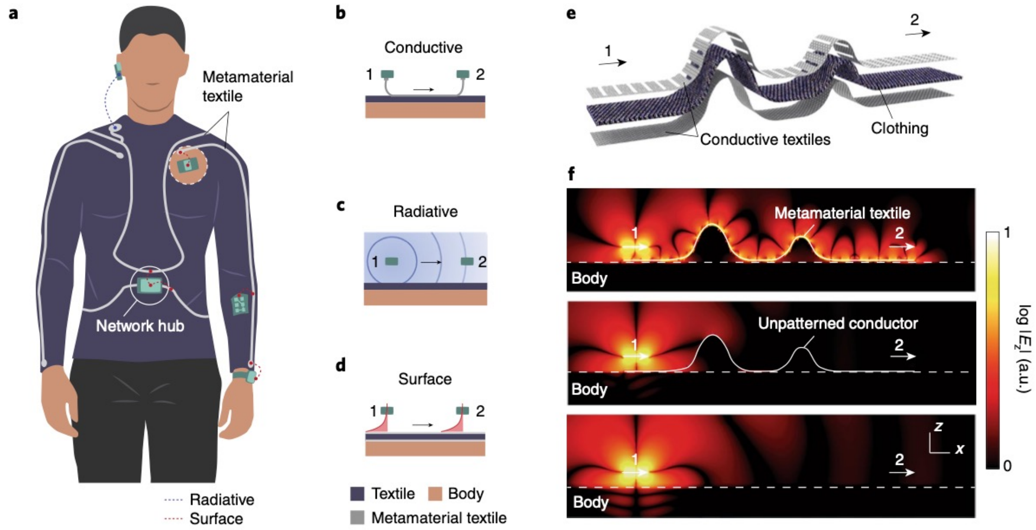
HF RFID and NFC tag materials

- Traditional tags
- Washable tags
- Textiles tags



Wang, Jingxian, et al. "Locating everyday objects using NFC textiles." Proceedings of the 20th International Conference on Information Processing in Sensor Networks (co-located with CPS-IoT Week 2021). 2021.

Textiles tags



Tian, Xi, et al. "Wireless body sensor networks based on metamaterial textiles." *Nature Electronics* 2.6 (2019): 243-251.

HF RFID & NFC materials design considerations

- Robustness
  - Tags do not deformation much (bending, twisting, and stretching)
  - Serve digital twin applications for the lifetime of a physical object
- Cost
- Size
  - Depends on application, e.g., the size of an object
- Health/implants
  - Bioresorbable tags for infection or other surgical recovery monitoring
- Environmental consideration
  - Disposable

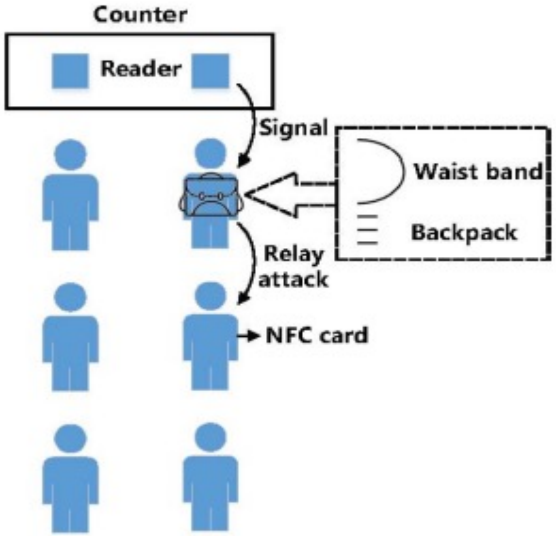
Olenik, S., Lee, H. S., & Güder, F. (2021). The future of near-field communication-based wireless sensing. *Nature Reviews Materials*, *6*(4), 286-288.

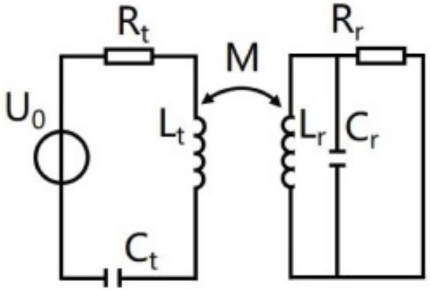
NFC security

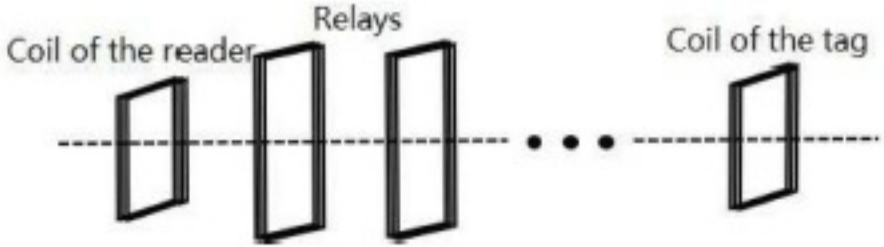
- NFC uses a short communication range to avoid eavesdropping
- Public key encryption/decryption are used, but NFC normally has limited computation resources and cannot support complex encryption/decryption
- It experiences the following attacks
  - Relay attack
  - Powerful eavesdropping
  - Cloning

Relay attack

Sun, Y., Kumar, S., He, S., Chen, J., & Shi, Z. (2020). You foot the bill! Attacking NFC with passive relays. *IEEE Internet of Things Journal*, *8*(2), 1197-1210.





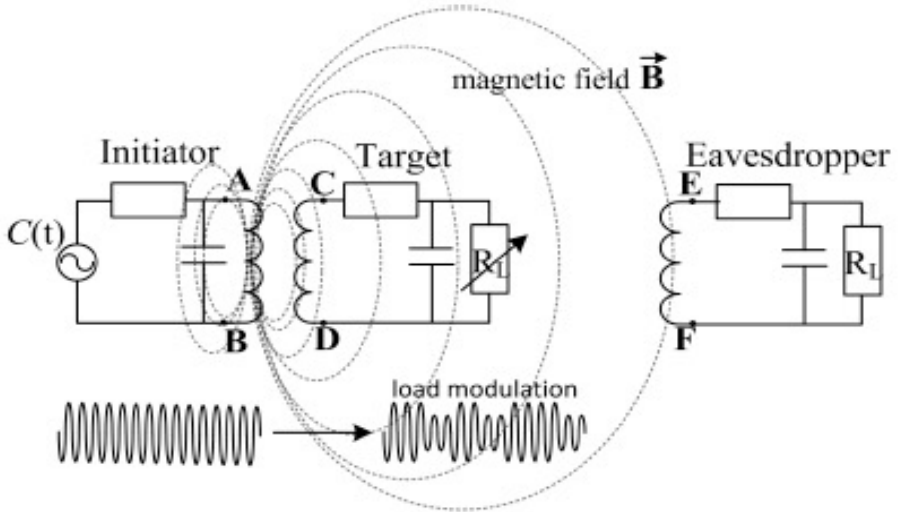


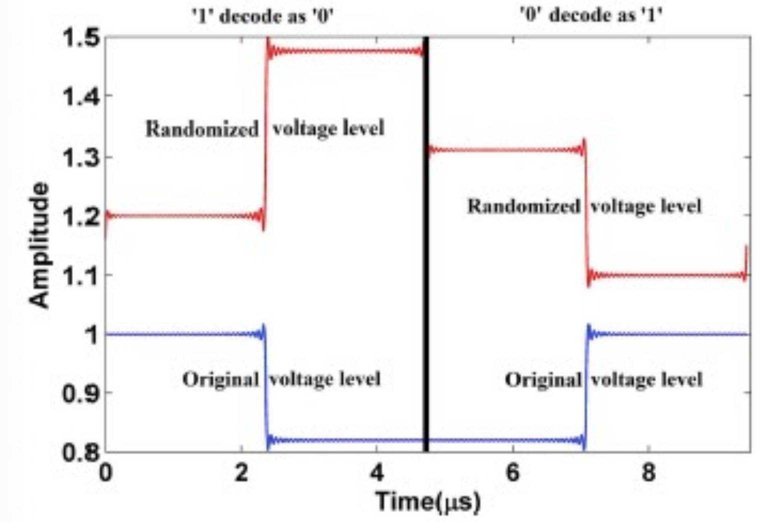
- NFC uses magnetic coils as antennas
- Extra relay in between the tag and the

Eavesdropping

Jin, R., & Zeng, K. (2018). Secure inductive-coupled near field communication at physical layer. *IEEE Transactions on Information Forensics and Security*, *13*(12), 3078-3093.

- The initiator (reader) uses a randomized sinusoidal wave to power up the target (tag)
- The initiator has the knowledge of the randomized sinusoidal wave
- The eavesdropper does not have the knowledge

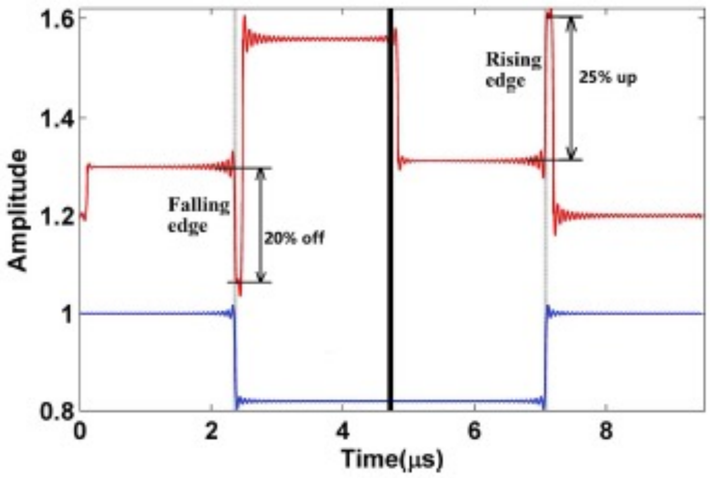


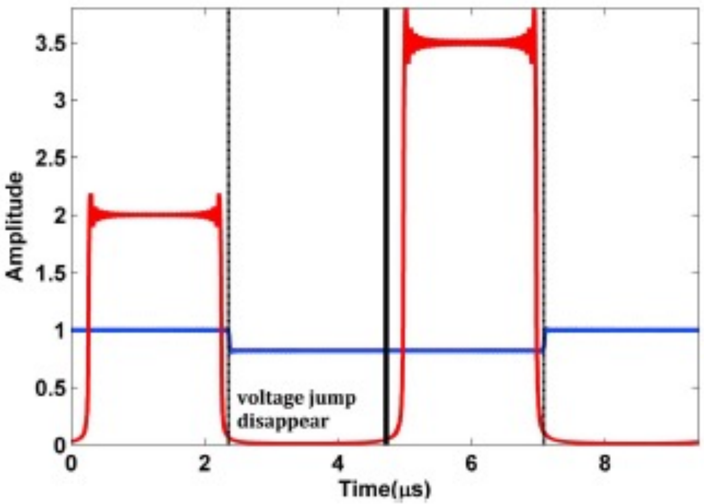


Eavesdropping

Jin, R., & Zeng, K. (2018). Secure inductive-coupled near field communication at physical layer. *IEEE Transactions on Information Forensics and Security*, *13*(12), 3078-3093.

- When existing synchronization offset, basic scheme is not secure. The eavesdropper can observe the voltage transition in the middle of a bit to compromise the bit
- The reader make the positive pulse shorter to remove the voltage jump





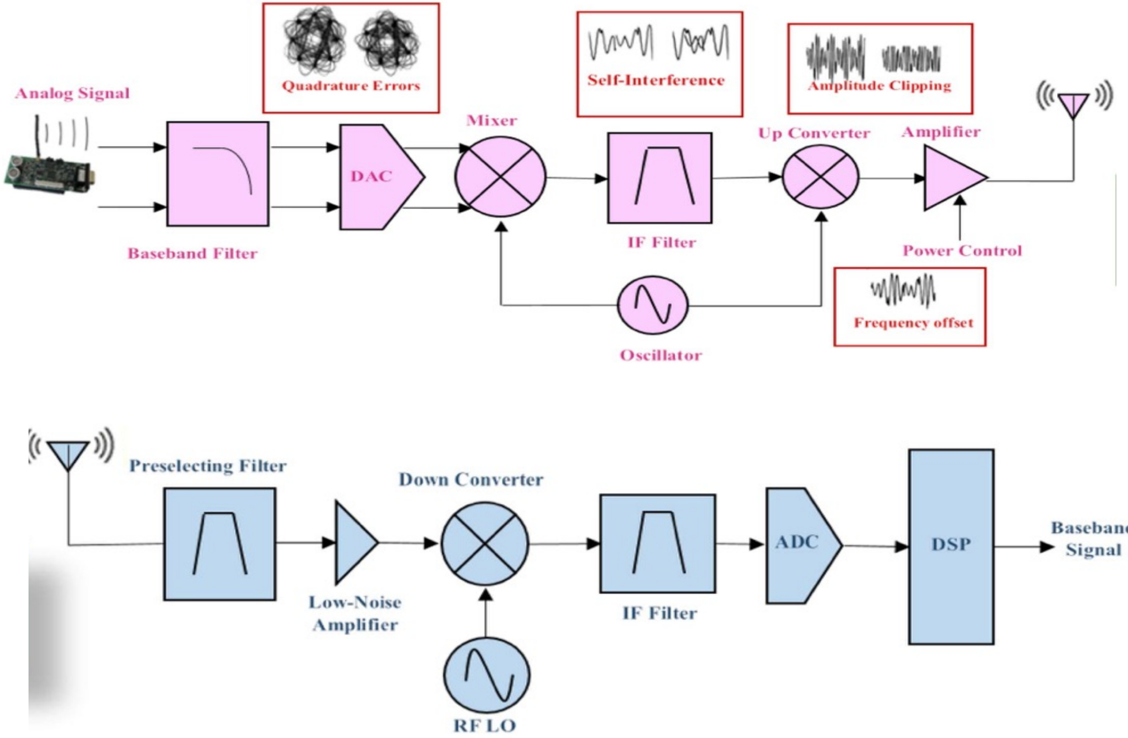
Cloning

- Cloning attack can generate a counterfeit NFC/RFID tag/card
  - Unauthorized access to buildings
  - Clothes, groceries, etc. with fake brand

- The real NFC/RFID tag/card is compromised, and the information stored is copied

RF fingerprint

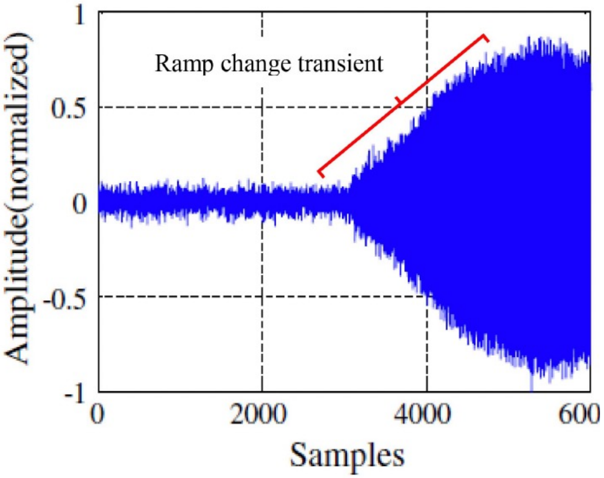
- RF fingerprint
  - Quadrature errors
  - Self-interference
  - Amplitude clipping
  - Frequency offset
- These fingerprints are universal
  - Does not depend on location and environment

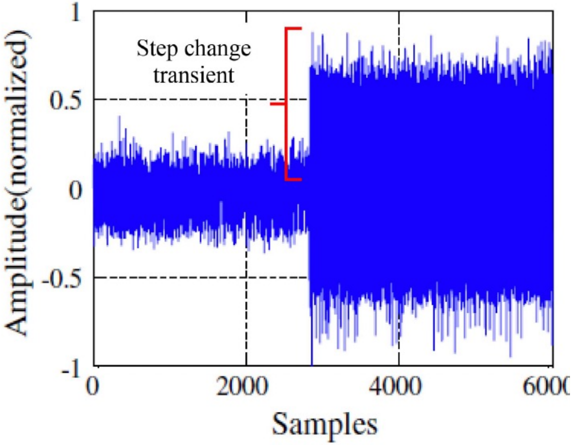


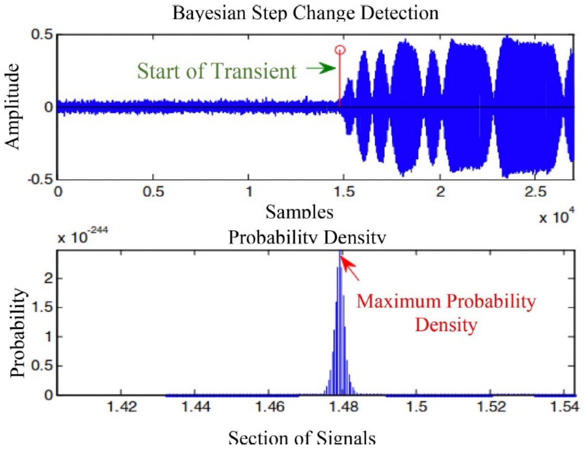
Soltanieh, N., Norouzi, Y., Yang, Y., & Karmakar, N. C. (2020). A review of radio frequency fingerprinting techniques. *IEEE Journal of Radio Frequency Identification*, *4*(3), 222-233.

Transient signals detection

- Bayesian step change detection
- Bayesian ramp change detection
- Phase change detection

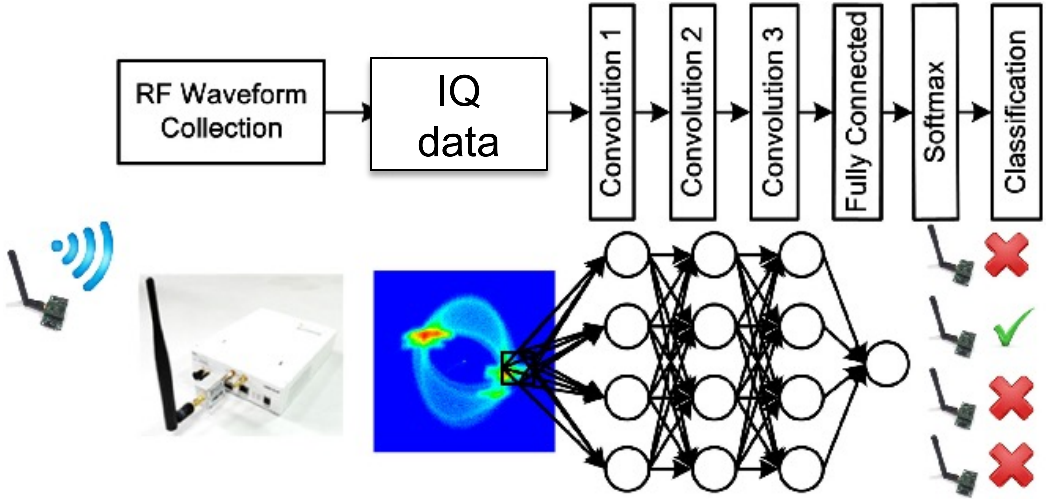






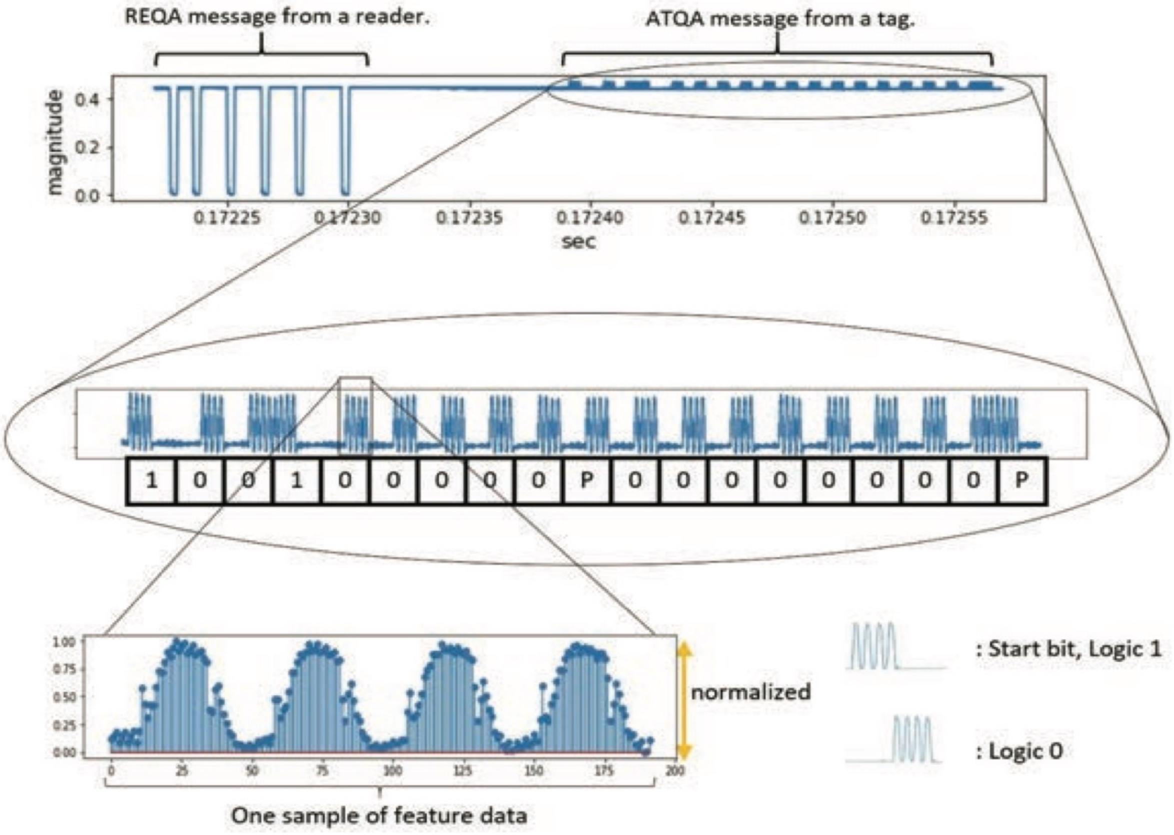
Deep learning model

- Typical procedure
  - Data collection, preprocessing, training, classification



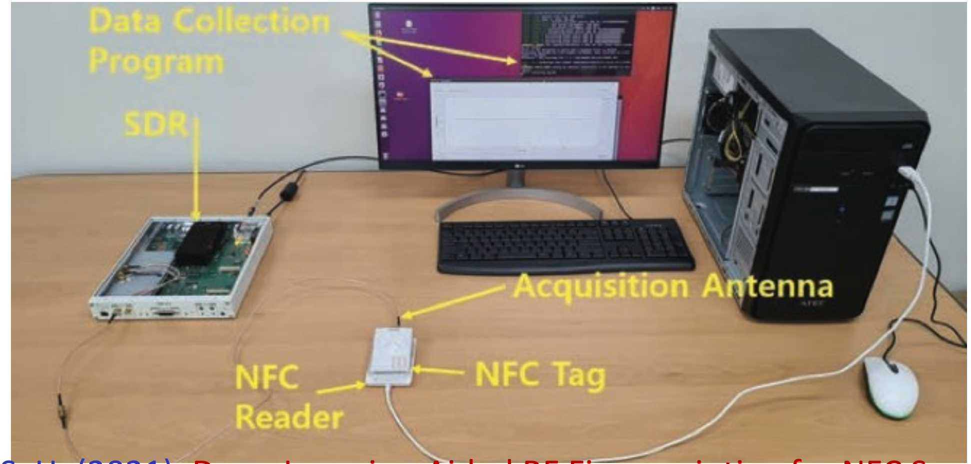
Example of signals

- ATQA message here has 19 bits
- Two P symbols among the logical values correspond to the parity bits for the first and last sets of 8 bits



Deep-learning RF fingerprinting

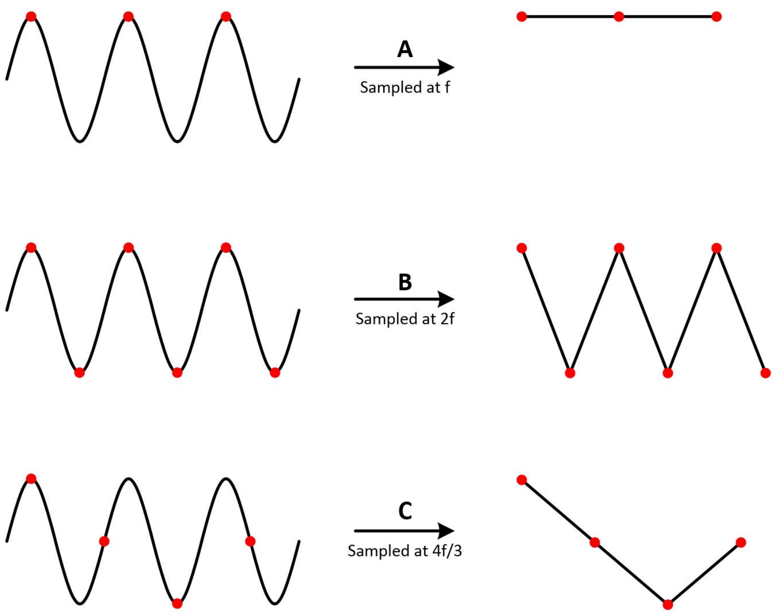
- End-to-End classification
  - Only based on IQ data and does not require domain knowledge
  - Challenge: how to collect pulses?
  - Software-defined radios are used as fast ADCs (analog to digital converters)



Lee, W., Baek, S. Y., & Kim, S. H. (2021). Deep-Learning-Aided RF Fingerprinting for NFC Security. IEEE Communications Magazine, 59(5), 96-101.

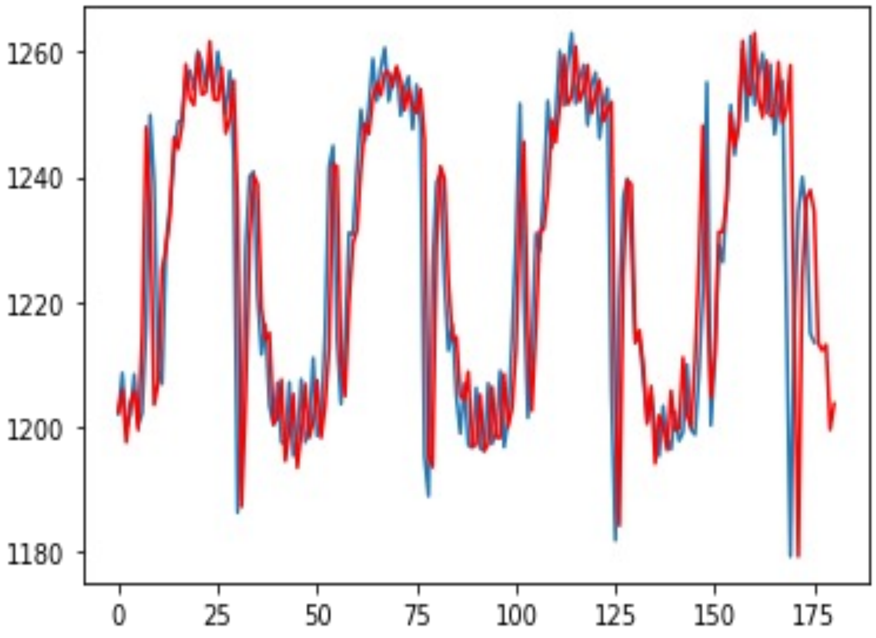
Sampling rate

- For a signal with frequency f, the sampling frequency should be no smaller than 2f
- Example: a 13.56 MHz signal requires at least 27.12 M samples/second to fully capture the signal spectrum
- Otherwise, we cannot fully reconstruct the signal

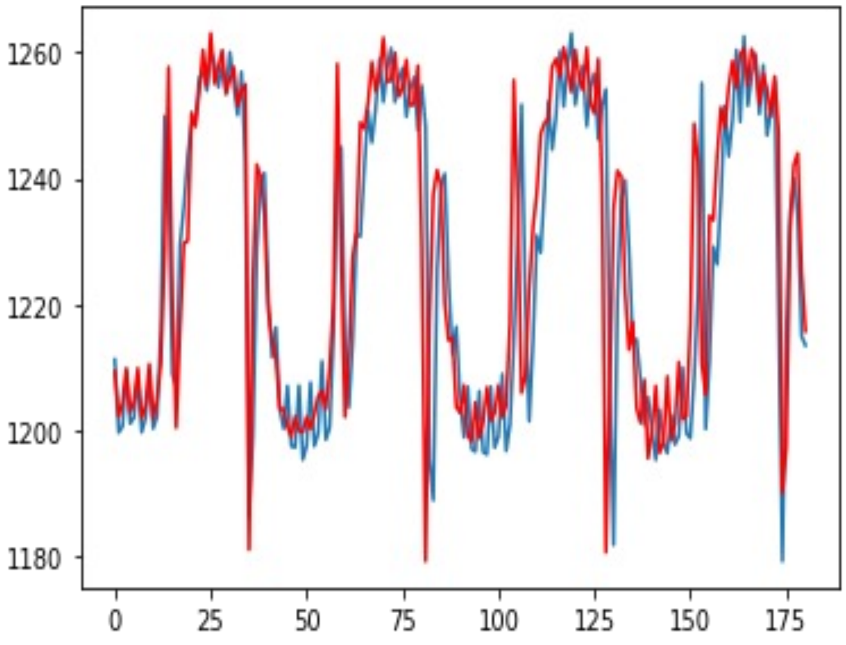


Signals example

- The same tag

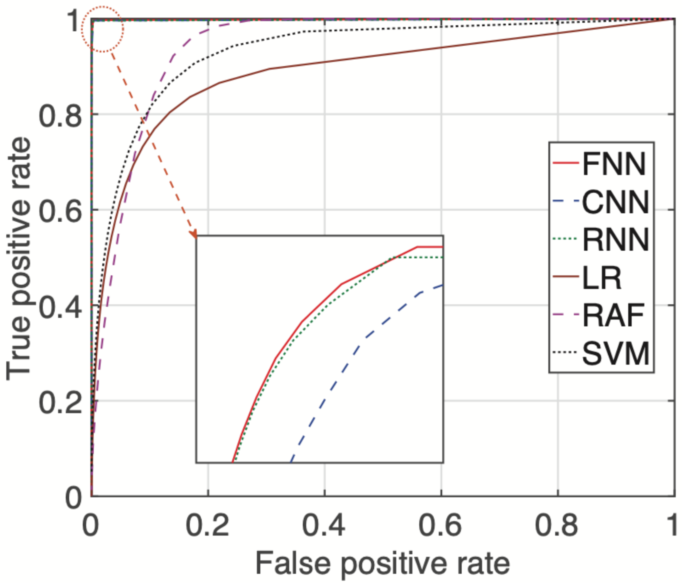


- Two different tags



Performance

Algorithm	Precision	Recall	Accuracy
FNN	0.9616	0.9616	0.9616
CNN	0.9498	0.9499	0.9499
RNN	0.9611	0.9609	0.9609
LR	0.3898	0.3547	0.3547
RAF	0.2955	0.3004	0.3004
SVM	0.3876	0.3938	0.3938



Outline

- Background: Digital world
- Digital Twins
  - Enabling technologies
  - System architecture
  - Applications
- Wireless sensing using HF RFID and NFC
  - Motivation and requirements for digital twin
  - Communication and networking protocols
  - Research challenges and solutions
- **Future research directions**

Future research directions

- Tiny long-range HF RFID/NFC tags/readers
  - Existing readers are high-power and large
- Ultra-dense deployment and operation of HF RFID/NFC tags
  - Consider mutual tag coupling and environmental coupling
- Coexistence with short-range high-security NFC tags
- HF RFID/NFC-based wireless sensing
  - Materials/food quality/liquid level/location
- Develop digital twin models based on HF RFID/NFC sensing data

Summary

Digital twin is an important tool to change the way that we interact with the world

Extended reality and **holographic-type communication** are used to observe digital twins

AI and cloud/edge computing can build digital twin models based on data

Internet of Everything monitors the physical world and collect data for digital twins

HF RFID & NFC use battery-free low-cost tags enable scalable wireless identification and sensing for Internet of Everything and support digital twin applications

Future research calls for long-range, high reliability, high security, and data incentive HF RFID & NFC systems