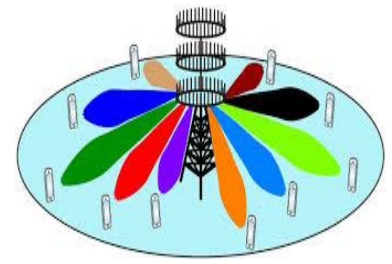
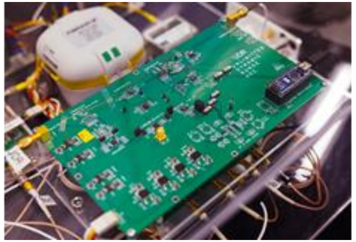
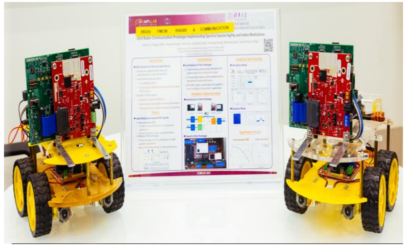

Future Communication and Sensing Systems

Nimrod Glazer

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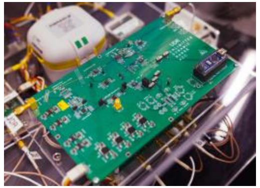
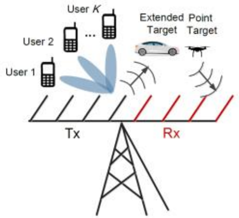
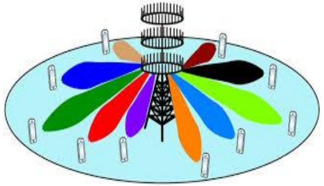
Signal Acquisition Modeling Processing and Learning

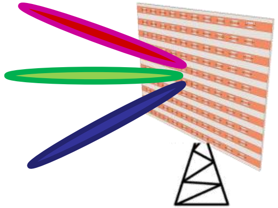
Future Trends Outlines

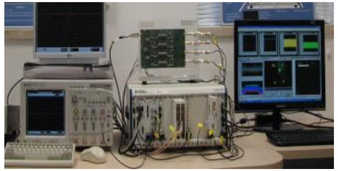
- Near-field Communication for 6G
- Joint radar comm
- Task-based quantization
- Automotive radar
- Power Efficient Hardware

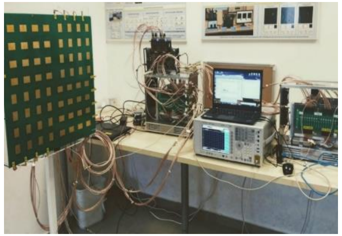


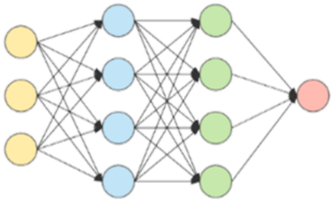


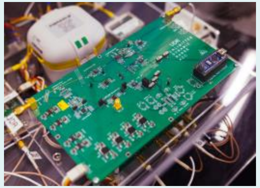


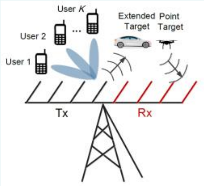


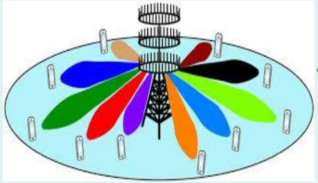


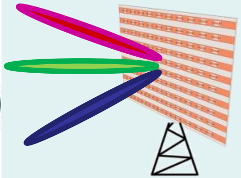












Near-Field Communication for 6G

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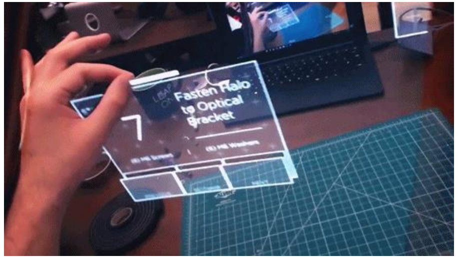
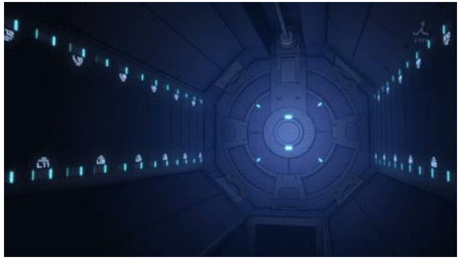
Emerging Applications for 6G Communication

- Fifth-Generation (5G) involves an increased scope of communication scale from within humans to among countless human beings, machines and things

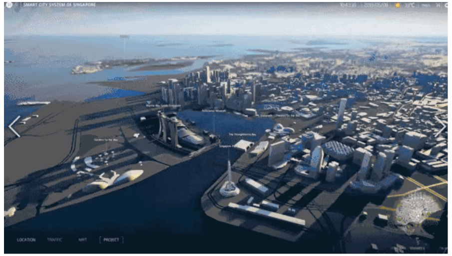
- The evolution from 5G to 6G will further fuse the digital worlds and real worlds
  - Emerging new applications: Extended Reality, Holographic Video, Digital Replica, and Intelligent Transport and Logistics



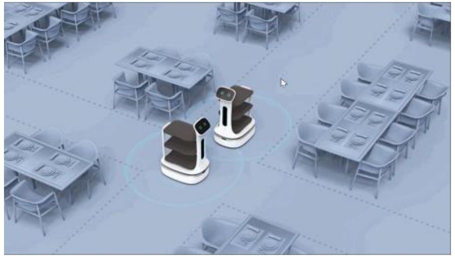
Extended Reality



Holographic Video



Digital Replica

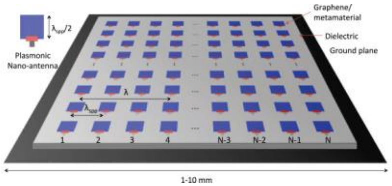


Intelligent Transport and Logistics

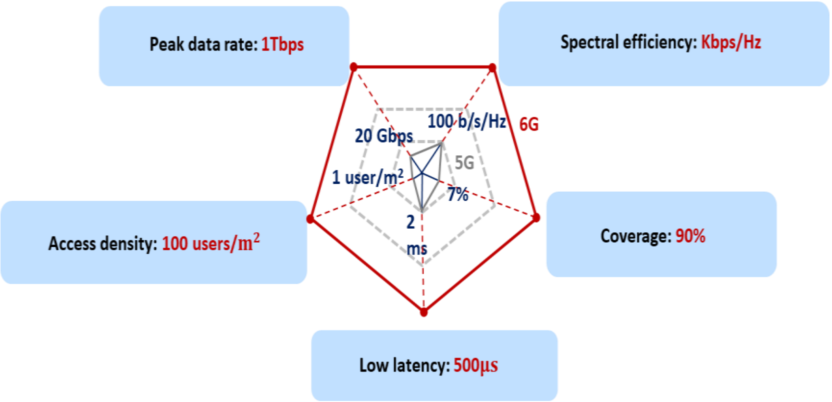
[1] ITU FG-NET-2030, "Network 2030-A Blueprint of Technology, Applications and Market Drivers towards the Year 2030 and Beyond," *https://www.itu.int/en/ITUT/ focusgroups/net2030/Documents/ White_Paper.pdf*, document ITU-T FG-NET-2030, ITU, Geneva, Switzerland, May 2019.

Key Performance Indicators (KPI) of 6G

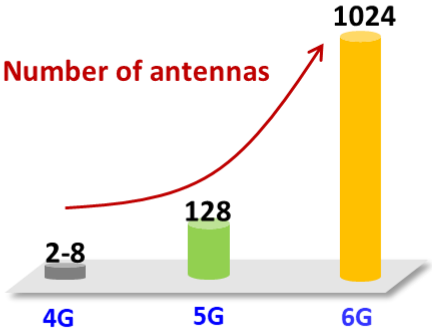
100× peak data rate

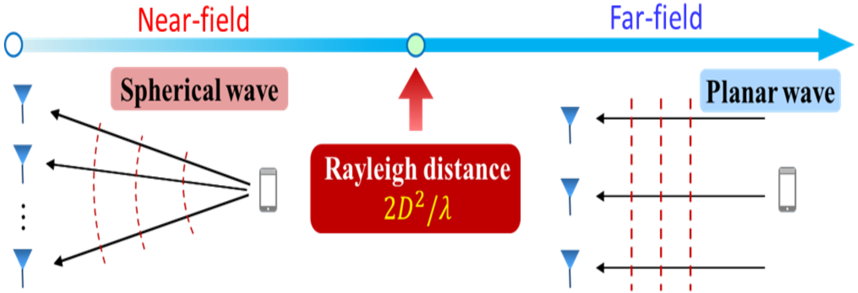


1024 ×1024 elements for THz band (0.06-10THz) [3]



10× spectral efficiency





> 5G with massive MIMO: Users are located in the far-field region

> 6G: Users are more likely located in the near-field region

Table I. Rayleigh distance [m]

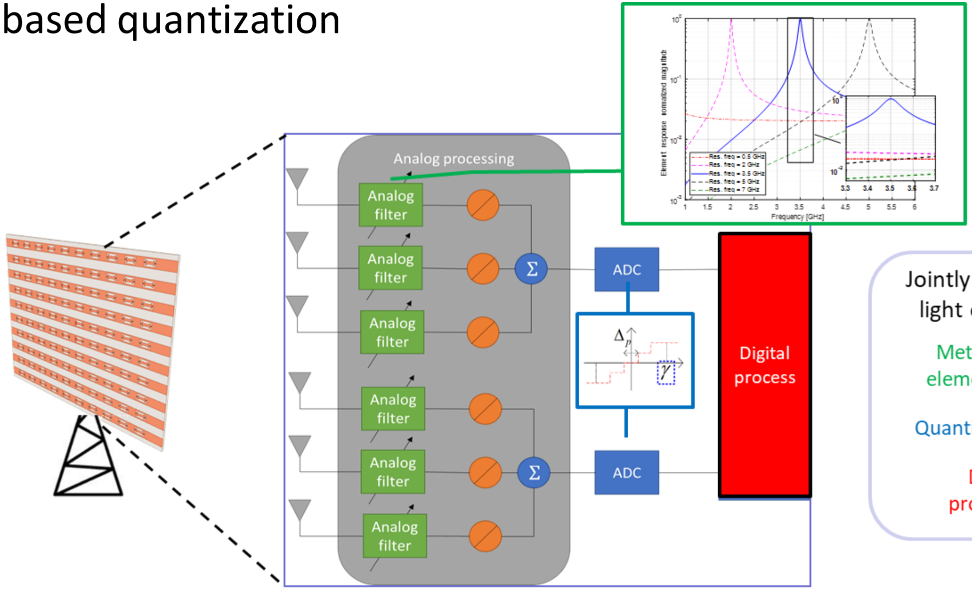
	0.1 m	0.5 m	1 m	3 m
2.6 GHz	-	4.3	17	156
28 GHz	1.9	47	187	\
100 GHz	6.7	167	667	\
142 GHz	9.5	237	947	\

[1] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The Road Towards 6G: A Comprehensive Survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334-366, Feb. 2021.
[2] I. F. Akyildiz, and J. M. Jornet, "Realizing ultra-massive MIMO (1024 ×1024) communication in the (0.06–10) terahertz band," *Nano Commun. Netw.*, vol. 8, pp. 46-54, Jun. 2016.

Metasurface Antennas with Low-Bit ADCs

- Exploit analog precoding for task-based quantization
- Frequency selectivity
- Suitable for wideband signaling

Enables low-bit wireless communications

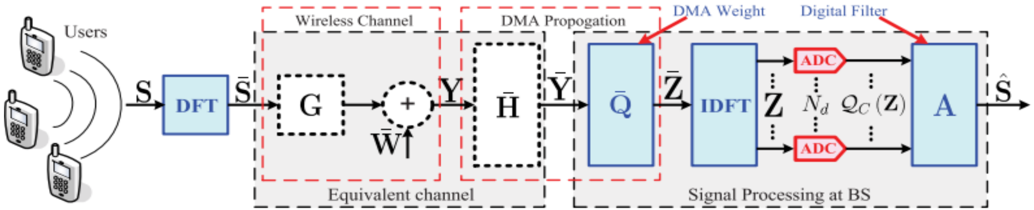


Jointly optimize in light of the task

Metamaterial element setting

Quantizer support

Digital processing

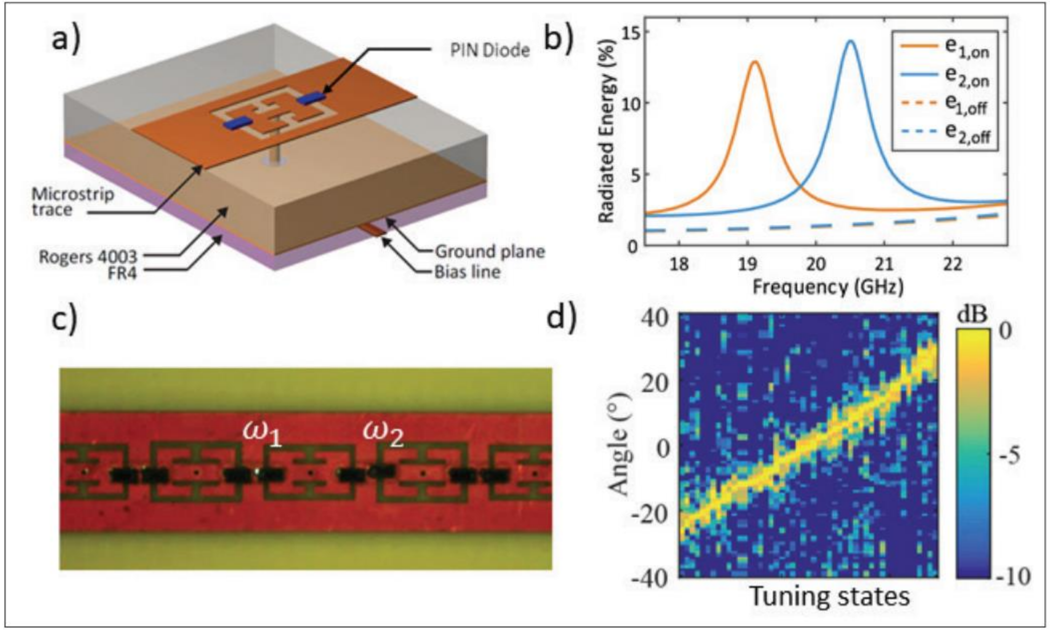


[1]. Wang, N. Shlezinger, Y. C. Eldar, S. Jin, M. F. Imani, I. Yoo, D. R. Smith, "Dynamic Metasurface Antennas for MIMO-OFDM Receivers with Bit-Limited ADCs", IEEE Transactions on Communications, vol. 69, issue 4, pp. 2643-2659, April 2021

DMA with reduced numbers of Radio Frequency (RF) chains

- Reliably communicate with reduced numbers of Radio Frequency (RF) chains
- Exploit inherent analog signal processing flexibility
- Frequency-Selective Analog Beamforming

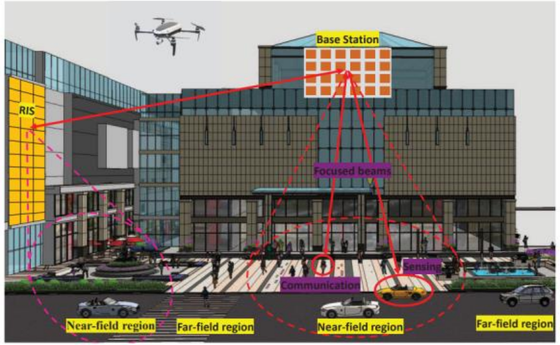
Reduces number of frequencies



[1]. N. Shlezinger, G. C. Alexandropoulos, M. F. Imani, Y. C. Eldar, and D. R. Smith, "Dynamic Metasurface Antennas for 6G Extreme Massive MIMO Communications", IEEE Wireless Communications Magazine, vol. 28, issue 2, pp. 106-113, April 2021

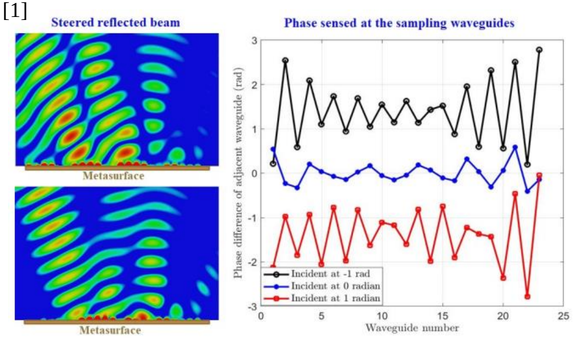
Hybrid Reflecting and Sensing RIS (Reconfigurable Intelligent Surfaces)

> Challenges
  > No signal processing ability
  > Only cascaded channel is available
  > Large number of channel coefficients

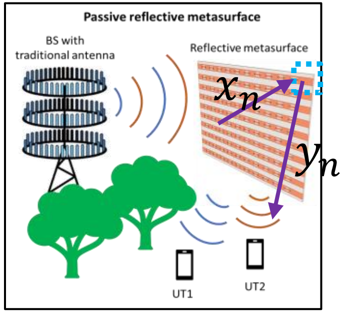


From Far-field Beam Steering to Near-field Beam Focusing

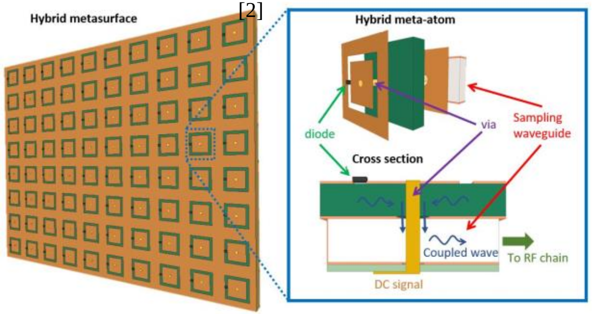
[1]

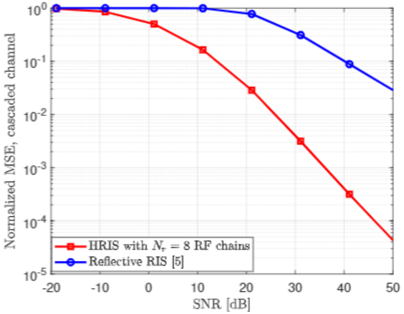


Simultaneous reflection and sensing



[2]





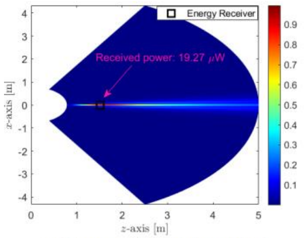
[1]. G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang and Y. C. Eldar, "Hybrid Reconfigurable Intelligent Metasurfaces: Enabling Simultaneous Tunable Reflections and Sensing for 6G Wireless Communications", Submitted to IEEE Transactions on Signal Processing, April 2021.

[2]. H. Zhang, N. Shlezinger, G. C. Alexandropoulos, A. Shultzman, I. Alamzadeh, M. F. Imani and Y. C. Eldar, "Channel Estimation with Hybrid Reconfigurable Intelligent Metasurfaces", Submitted to IEEE Transactions on Communications, June 2022.

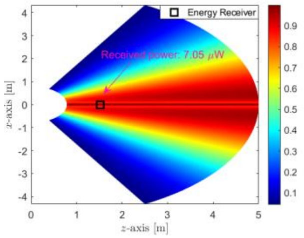
[3] H. Zhang, N. Shlezinger, F. Guidi, D. Dardari, and Y. C. Eldar, "6G Wireless Communications: From Far-field Beam Steering to Near-field Beam Focusing", Submitted to IEEE Wireless Communications, March 2022.

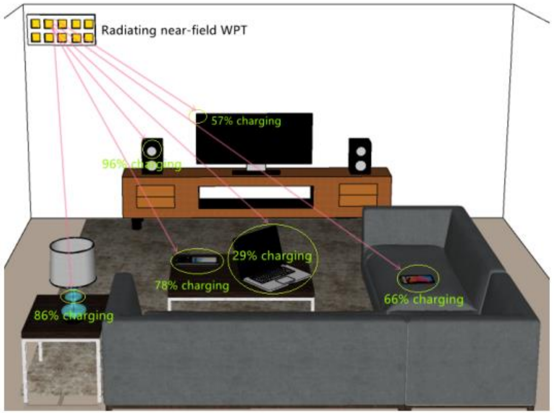
Multi-User Wireless Power Transfer (WPT) Systems

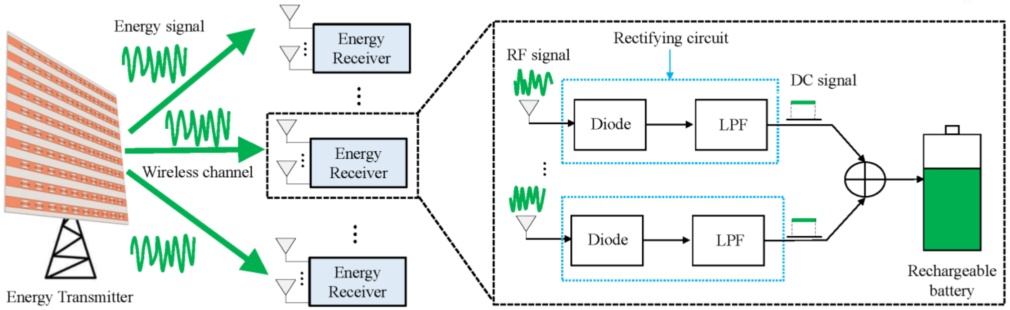
- Current wireless charging devices
  - Inductive coupling or Electro magnetics
  - Short distance
- Near field RF charging
  - Leveraging Near field and Beam focusing
  - Extends the power distances
  - Support of multi devices

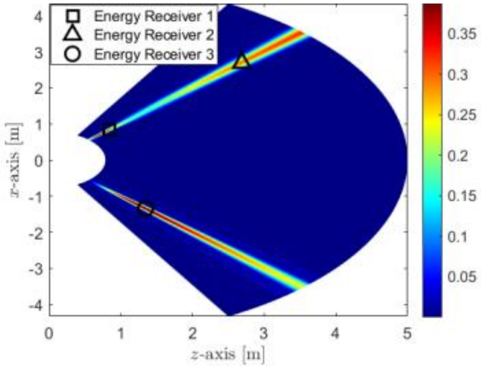


(a) Single energy receiver located at the near-field region

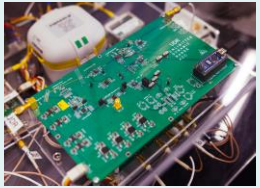
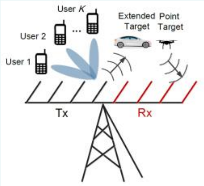


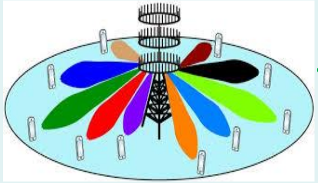
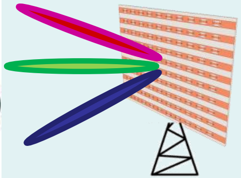






[1]. H. Zhang, N. Shlezinger, F. Guidi, D. Dardari, M. F. Imani, and Y. C. Eldar, "Near-field Wireless Power Transfer for 6G Internet-of-Everything Mobile Networks: Opportunities and Challenges", to appear in IEEE Communications Magazine.

Joint radar comm

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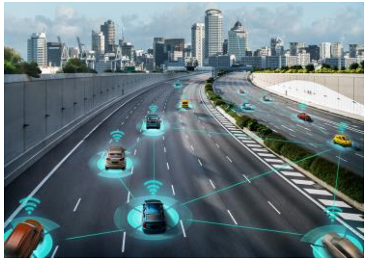
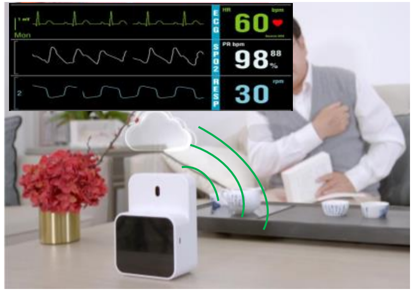
Integrated Sensing and Communication

- Enabling many new technologies such as connected cities, connected vehicles, and remote health caring
- Perceptive Networks: Sensing as a Service
  - Sensing aided resource management
  - Traffic monitoring
  - Weather observation
  - Human activity recognition
  - Smart home and smart city applications





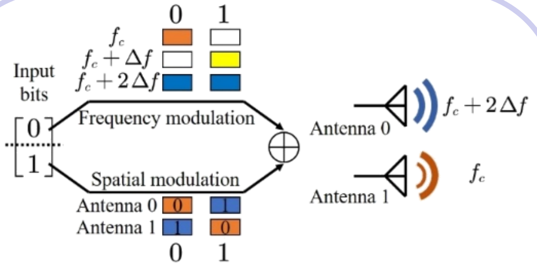
ISAC: Convergence of sensing and communication to efficiently utilize congested resources

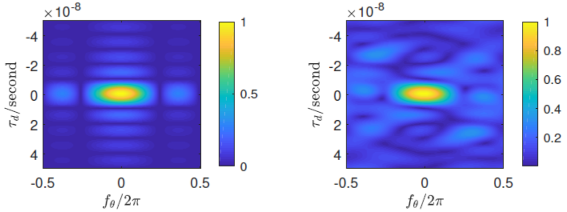
https://isac.committees.comsoc.org/

Index Modulation for DFRC

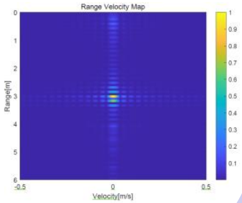
> Collaboration with the groups of Profs. Tianyao Huang

- MAJoRCom: Multi-carrier Agile Joint Radar Communications
  - Use only radar waveforms
  - Embed information in the frequency and antenna allocation
- SpaCoR: Spatial Modulation Based Communication-Radar
  - Orthogonal transmissions with distinct bands and antennas
  - Toggle antenna selection
- FRaC: FMCW-based joint radar-communications
  - Higher bit rate than MAJoRCom, through an extra level of phase modulation





(a) Full Antenna Array (b) SpaCoR

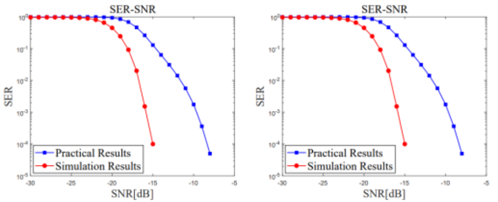


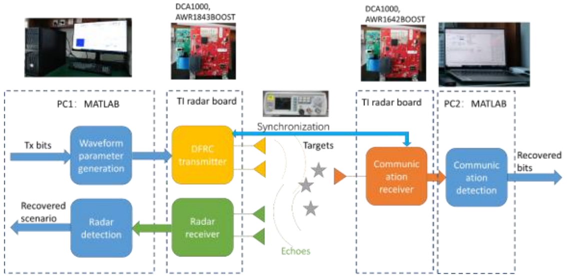
FMCW-Based Joint Radar and Communications: Index Modulation

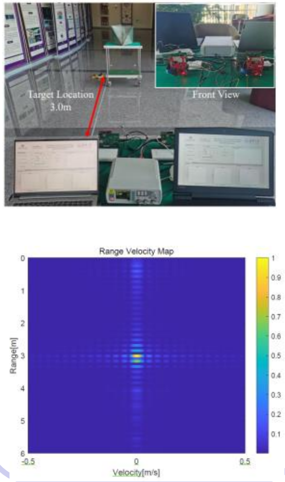
> Ma et al. 21

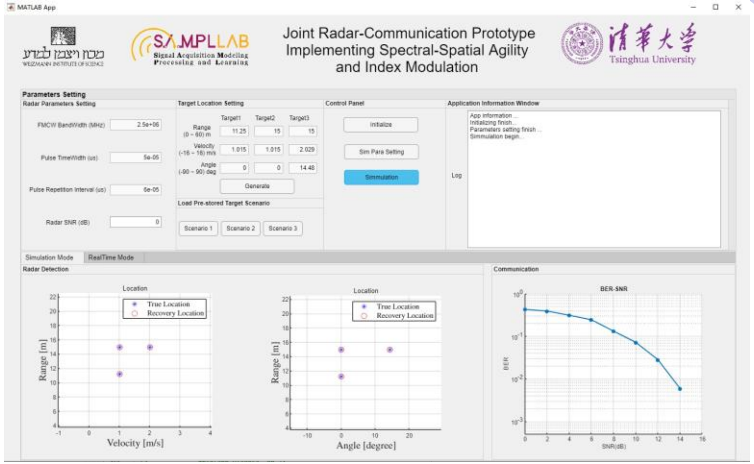
- Based on FMCW modulation
  - Commercial automotive radars
- Eliminate the limitation of sampling rate
- Obtain acceptable performance of both radar and communications in a time-division mode

Higher bit rate than MAJoRCom, through an extra level of phase modulation







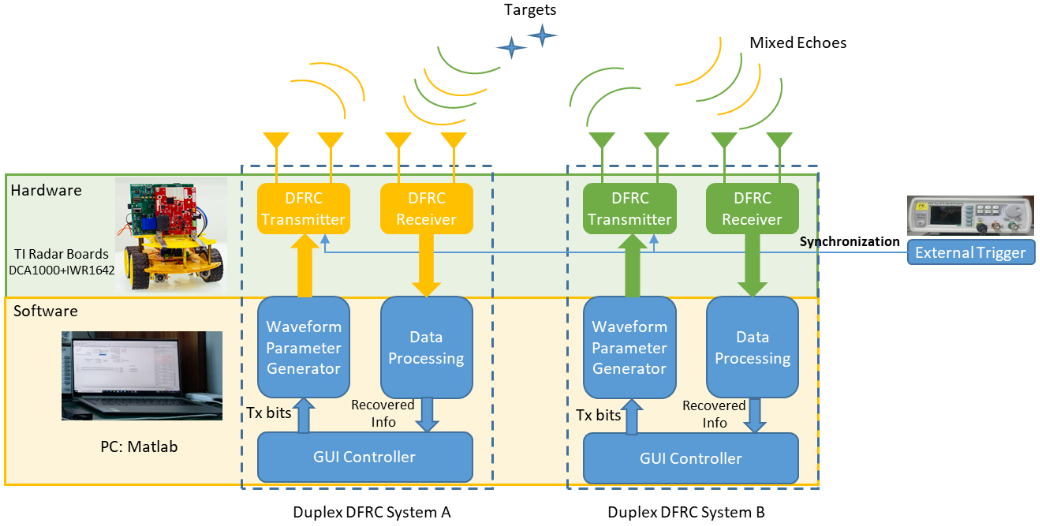


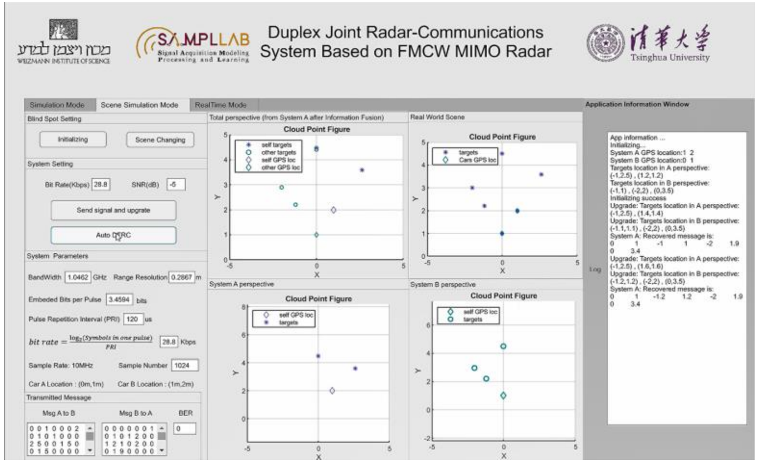
Duplex FRaC: FMCW-based joint radar-communications

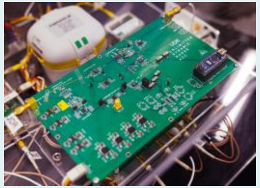
> Collaboration with the groups of Profs. Tianyao Huang

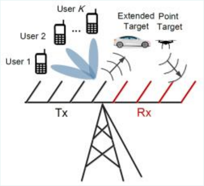
Radar Waveform-Based DFRC System + **Full-duplex DFRC System**

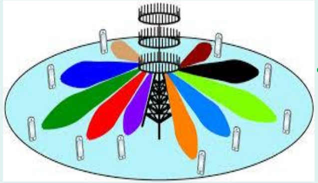
- > Full-duplex spectral-spatial Index modulation
  - > Real-time Information sharing and detection
- > Low-cost commercial automotive radars

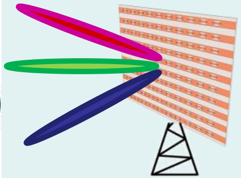












Task-based quantization

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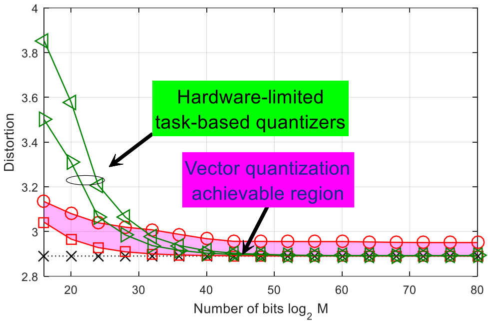
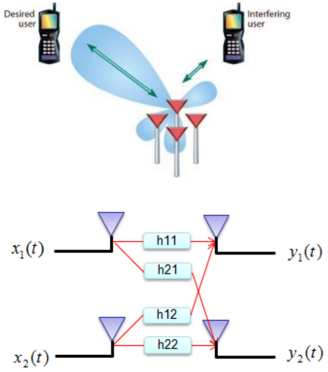
Task-Based Hardware-Limited Quantization

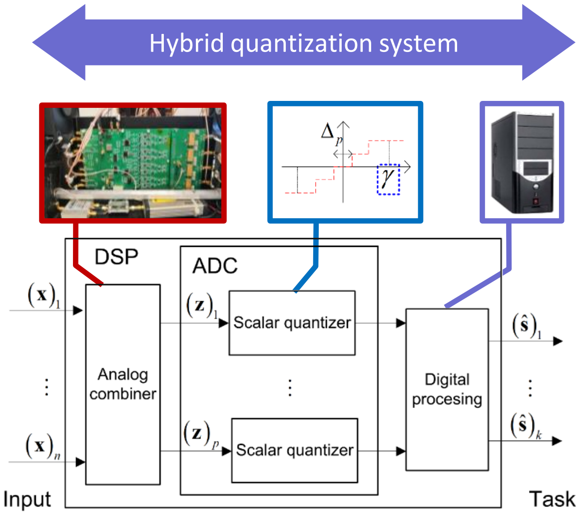
> Shlezinger, Eldar, Rodrigues 19-21
> Neuhaus et. al 21-22

- Optimal quantization typically using vector quantizers
- ADCs are usually serial scalar quantizers
- Signals are often acquired for a task:
  - Channel estimation
  - Source localization…





Exploit task to reduce number of bits and simplify hardware



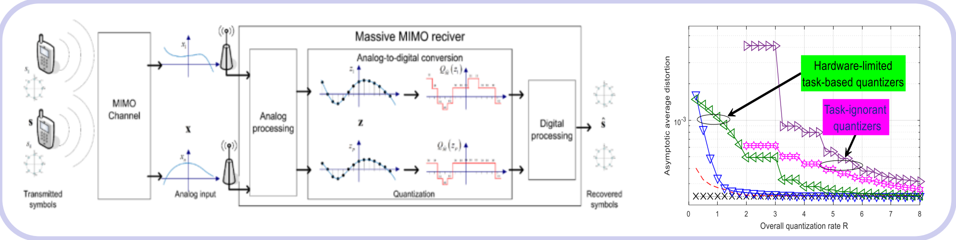
Jointly optimize in light of the task

Analog combining	Quantizer support	Digital processing

Tools: Majorization theory, dithering, water filling

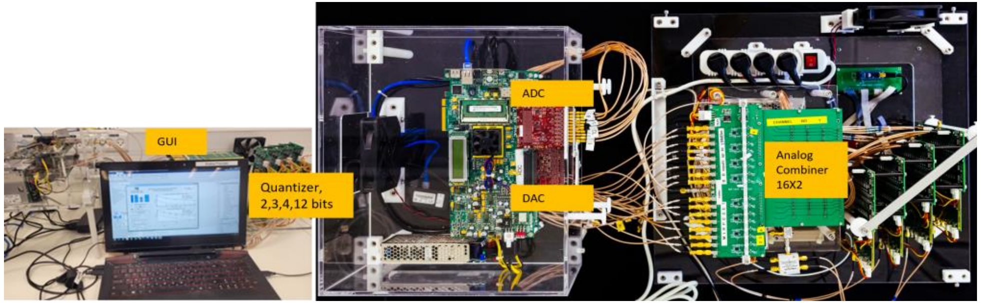
Task-based Quantization for Multi-user Implementation

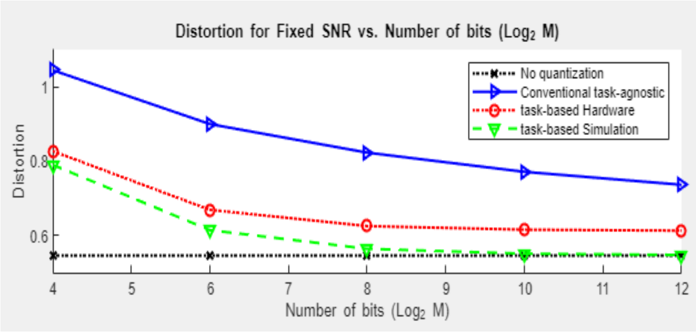
- Utilize task information
- Combined system design
- Quantizing the signal with lower bits
- Reduces 16 MIMO receivers to 2 RF chains

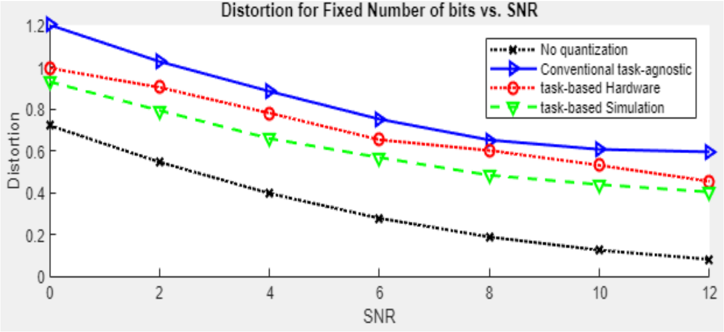


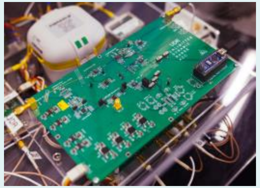
Jointly optimize as a task-based quantizer!

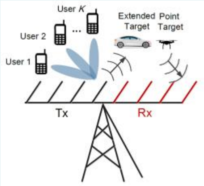
Hardware Prototype

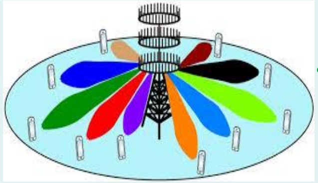


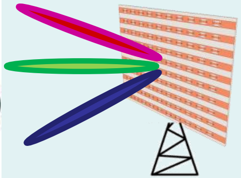












Automotive radar

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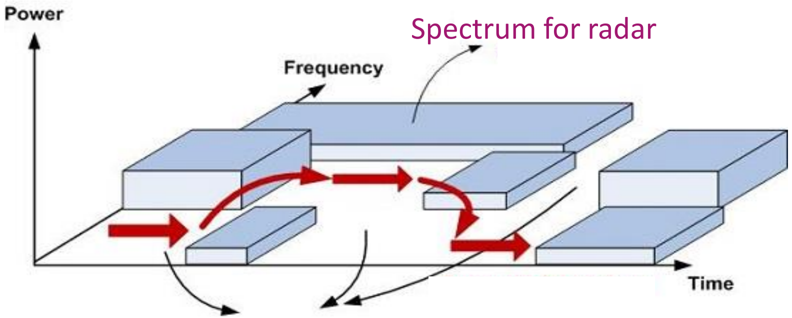
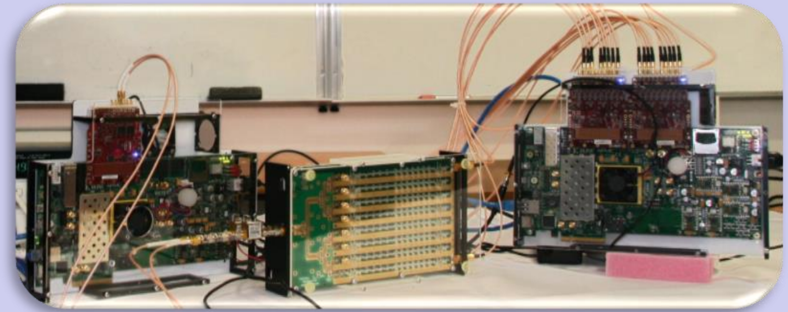
Spectrum Sharing: Cognitive Radio + Radar

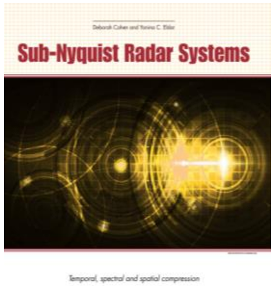
- Find frequency white spaces to transmit communication signals
- Use remaining spectrum for radar signals
- Challenges:
  - Fast and efficient spectrum sensing
  - Transmit radar signals with limited bandwidth
- Solution based on Sub-Nyquist sampling

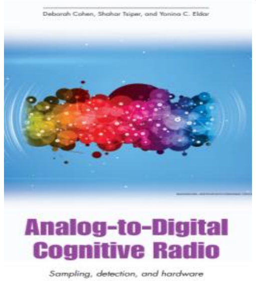


Spectrum for radar

Spectrum holes for communications

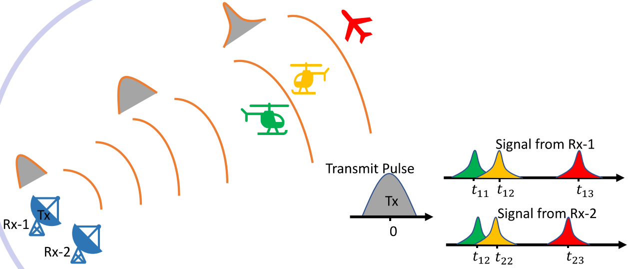






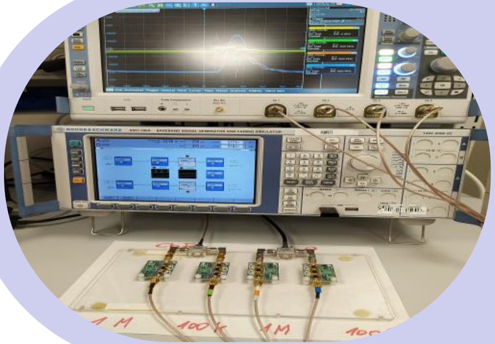
Radar With Unknown Pulse Shape

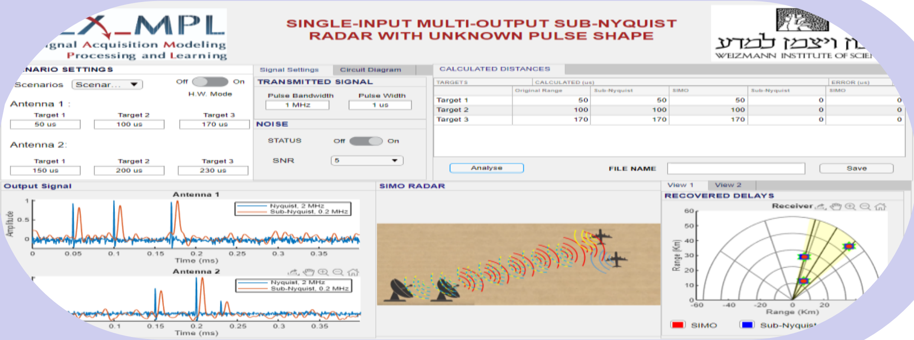
> Mulleti et. al 20



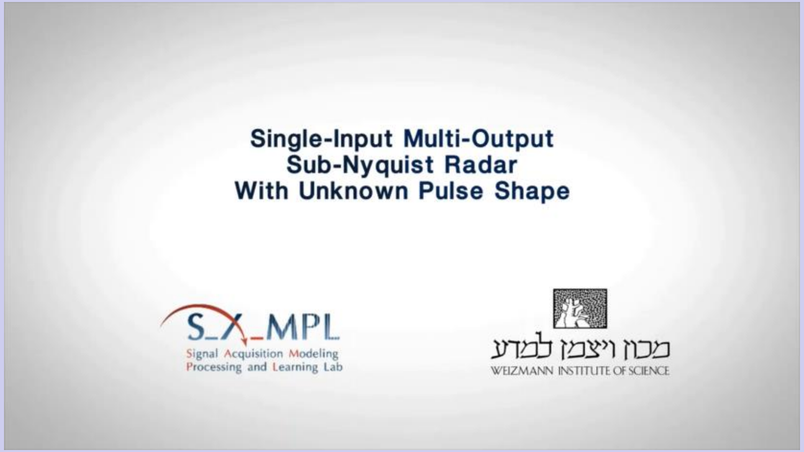
- In practice the pulse shape can be distorted and unknown
- We propose the use of multiple receivers (at least 2) to recover the targets and pulse
- Each Rx operates at a sub-Nyquist rate

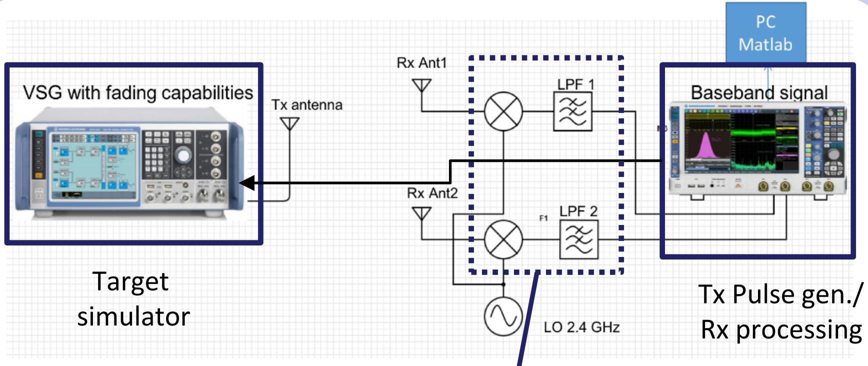
Signal recovery from samples at 10 times lower than Nyquist

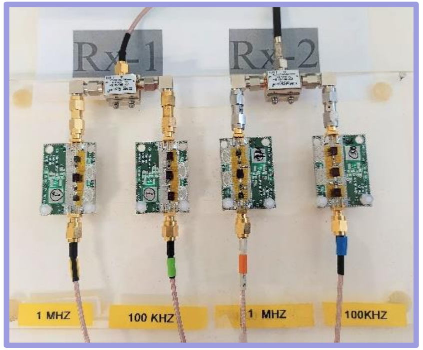




Radar With Unknown Pulse Shape (Cont.)

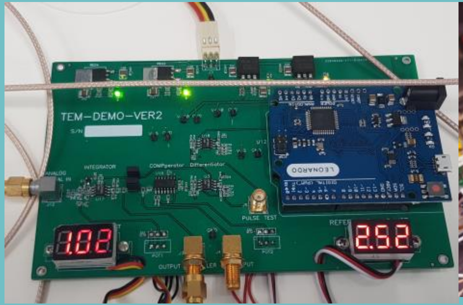


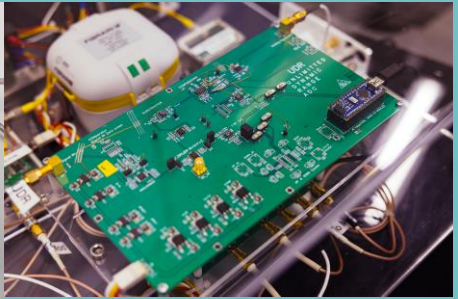




Lowpass filters for Rx

Allows for low power, low BW radar detection in complicated settings like automotive radar





Power Efficient Hardware

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Signal Acquisition Modeling Processing and Learning

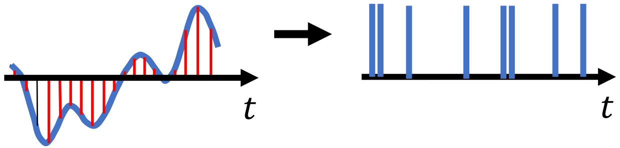
Timing Based Sensing

> Lazar and Toth, 04
> Adam, Scholefield, and Vetterli 20
> Naaman, Mulleti, Eldar 22

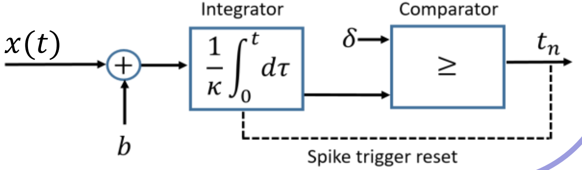
Change the information recorded!

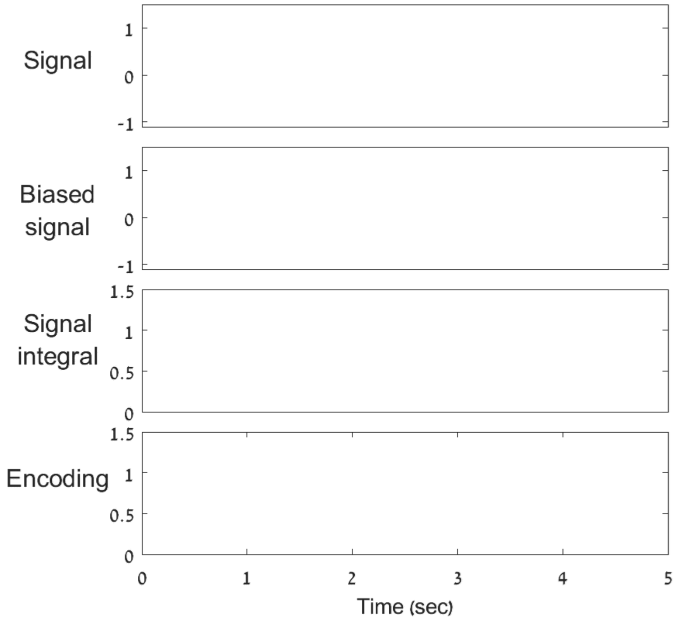
Time encoding machine:

Event-driven sensing approach
Quantizing timings



- No global clock is required:
  Low power consumption
- Increasing the signal's amplitude
  - Decreases timing quantization dynamic range
  - Decreases required number of bits per sample



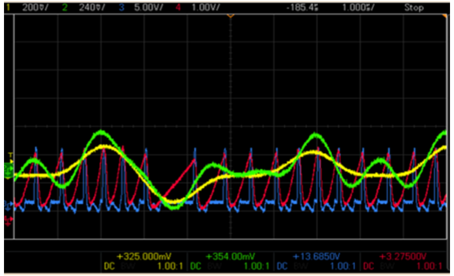


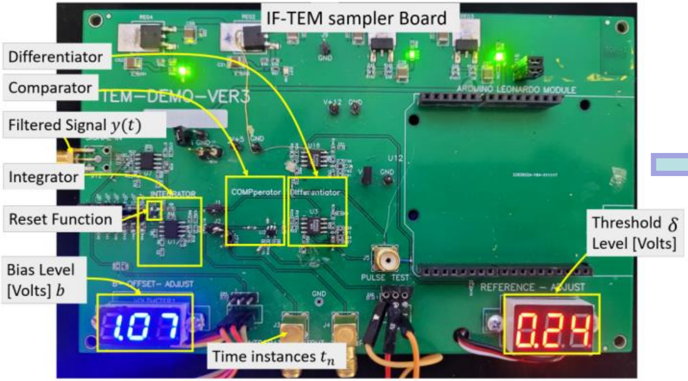
Reduce power and bits while leveraging low-cost, simple hardware

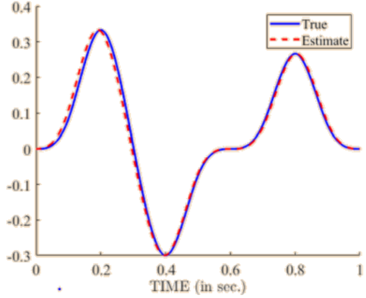
Timing Based Sensing implementation

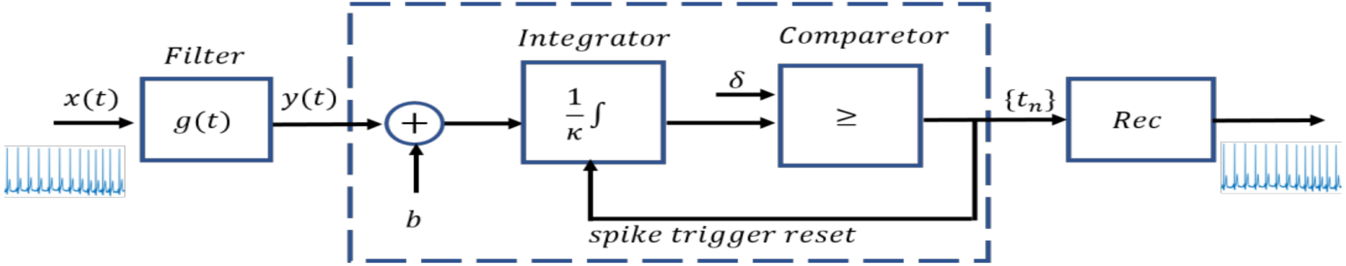
> Naaman, Eldar 21

Only 21 samples were used for reconstruction



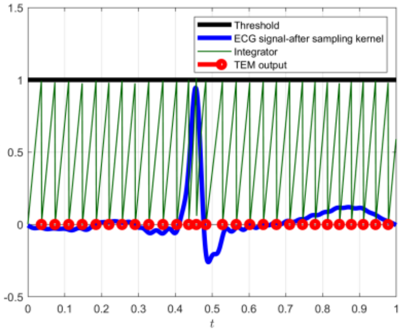




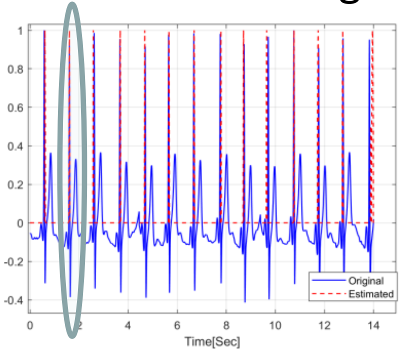


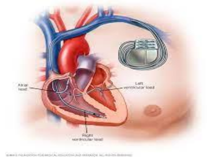
Timing Based Sensing Performance

ECG Input signal

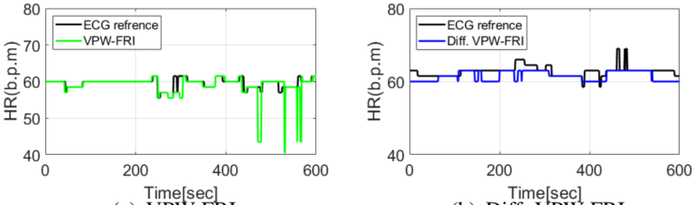


Reconstructed signal

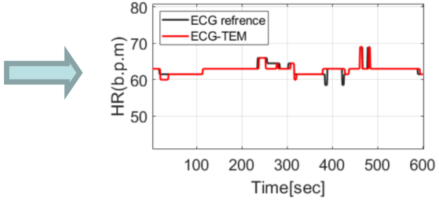




Decode methods

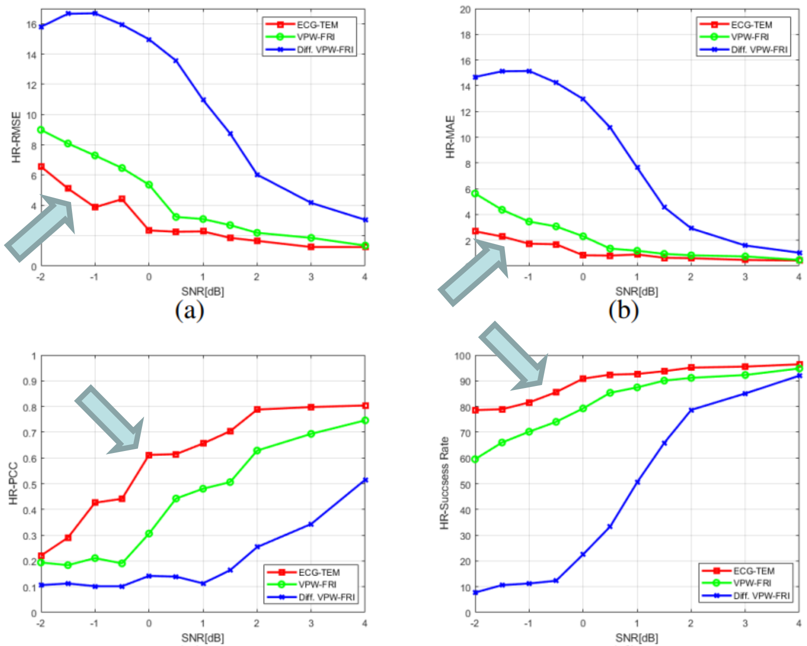


(a) VPW-FRI (b) Diff. VPW-FRI



(c) ECG-TEM

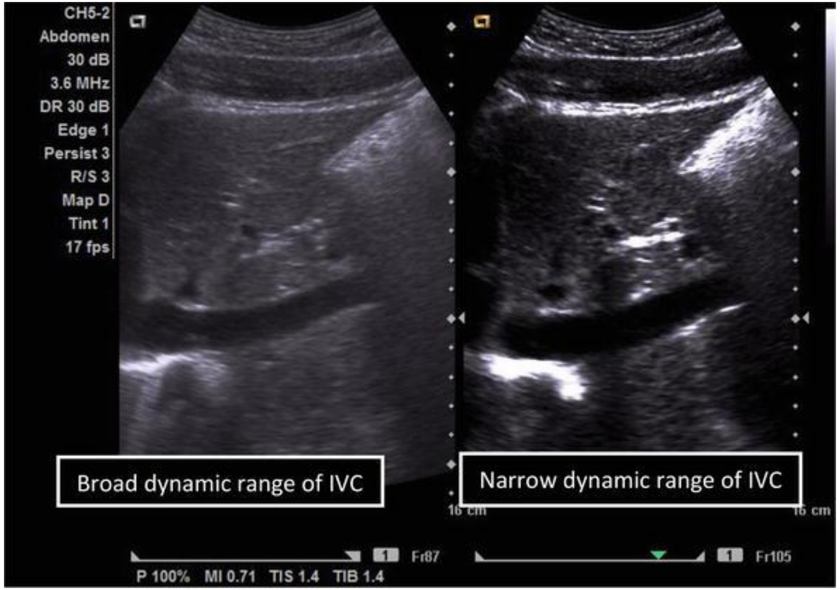
Comparison performance charts



(a) (b) (c) (d)

Can We Go Beyond the Dynamic Range Barrier?

- **Dynamic range** is defined as the difference between the maximum and minimum values of the displayed signal
- How do we go beyond the dynamic range of a signal without clipping while maintaining resolution?
- An example of a narrow vs. broad dynamic range in an ultrasound scan:

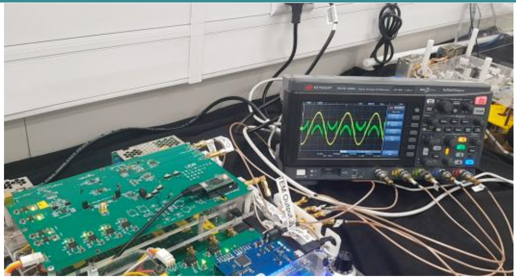


Yaw Amo Wiafe, et al.

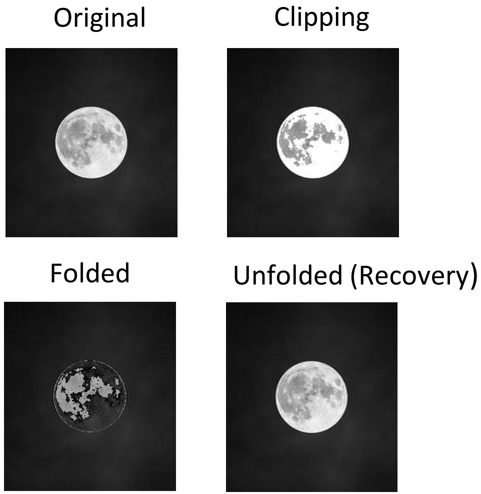
Modulo Sensing Can Go Beyond the Dynamic Range Barrier

> Conventional sensors
- Have a limited dynamic range – clipped when exceeds the sensor amplitude limit

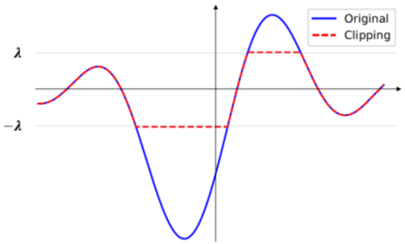
> Known solutions:
- Automatic Gain Control (AGC)
- Adapt the signal amplitude to the sensing capabilities
- Disadvantage:
  - Creates a momentarily clipping and reduces signal resolution



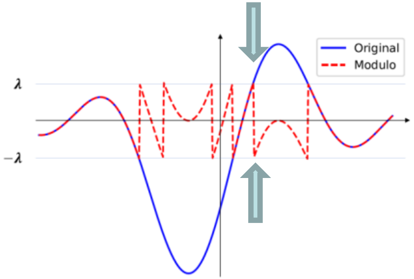
Modulo operation – fast adaptation to the signal



Conventional ADC



Modulo ADC

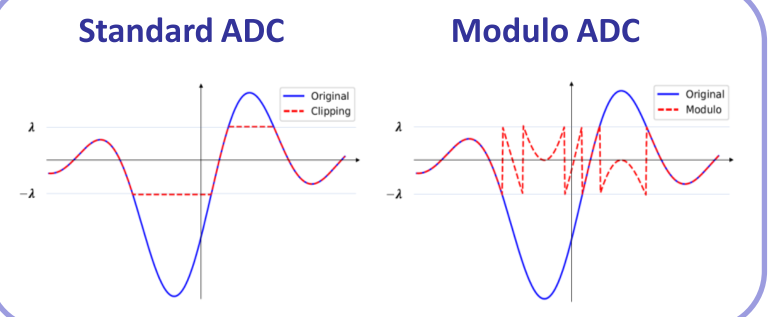


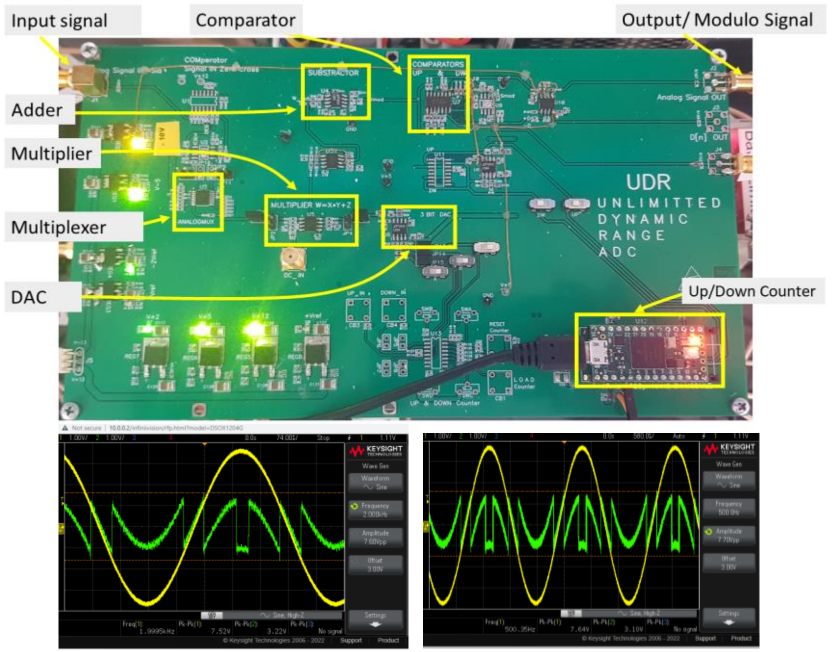
> Our solution
- Modulo sampling operation with faster improved dynamic range response
- Advantage: Clipping prevention within an extended range

Modulo Sampling: Overcoming Dynamic Range Restrictions

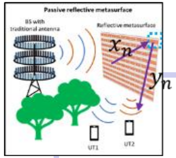
> Bhandari, Krahmer, Poskitt 21
> Romanov and Ordentlich 19
> Azar, Mulleti, Eldar 22

- Transmission medium or processing devices have limited dynamic range
- Clipping beyond dynamic range
- A modulo operation is used to limit dynamic range prior to transmission
- Signal structure e.g. correlation, sparsity, is used to recover the signal
- Signal can be recovered robustly



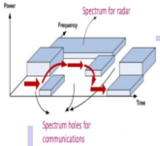


Future Communication and Sensing Systems

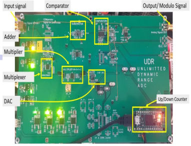


Near-Field Communication for 6G

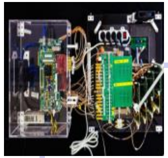
Joint Radar and Communication



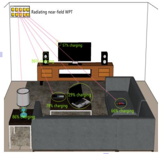
Automotive Radar



Power Efficient Hardware



Task-Based Quantization



Wireless Power Transfer (WPT) Systems

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thank you