Energy-Efficiency and Security in Hardware-Constrained Wireless Communications

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New York University

BalkanCom 2024

June 4, 2024

NYU | TANDON SCHOOL OF ENGINEERING

NYU WIRELESS

Background

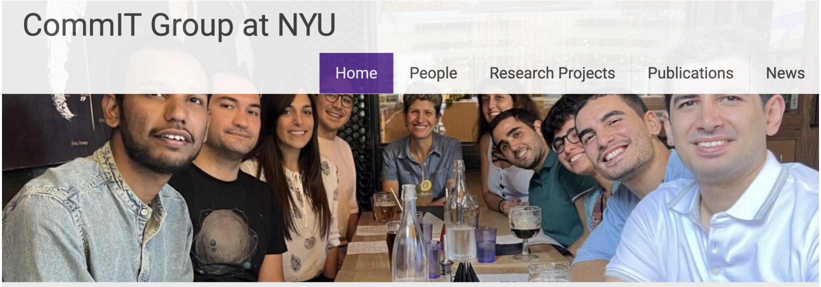
- ECE Department, NYU Tandon School of Engineering.
- Member of NYU WIRELESS.

NYU WIRELESS

ANALOG DEVICES AHEAD OF WHAT'S POSSIBLE™	CROWN CASTLE	DELL Technologies
ERICSSON	interdigital.	MEDIATEK
NOKIA	NSF	QUALCOMM®
SHARP Be Original.	SONY	UMC

Research Group

- Theoretical foundations and practice oriented applications:
  - Wireless and networking.
  - Security and privacy.
  - Compression.



CommIT Group at NYU

Today: Energy and Security in Hardware-Constrained NextG


Abbas Khalili


Serhat Bakirtas


Jim Buckwalter


Matthieu Bloch

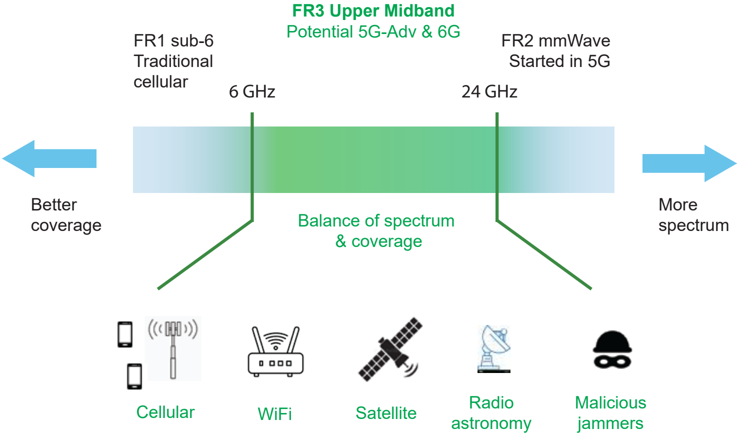

Sundeep Rangan


Ozlem Yildiz


Hamed Rahmani

Upper Mid-Band

- 5G: MmWave frequencies.
- NextG: Upper mid-band.



S. Kang et al., "Cellular Wireless Networks in the Upper Mid-Band," *IEEE Open Journal of the Communications Society*, 2024.

Upper Mid-Band for NextG Wireless

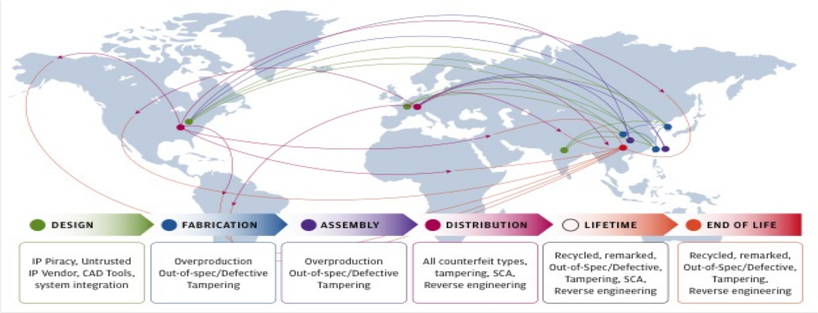
- Opportunities
  - Wide bandwidth.
  - High data rates.

Upper Mid-Band for NextG Wireless

- Opportunities
  - Wide bandwidth.
  - High data rates.
- Challenges:
  - Share spectrum with incumbents.
  - ⇒ High power consumption.
  - Large antenna arrays.
  - Wide bandwidh.

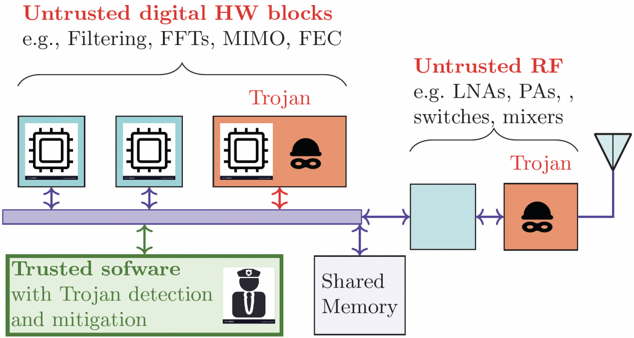
Resilient NextG Wireless Built Using Unsecure Hardware

- Disaggragated radio access and core network.
- Global supply chain.



Hardware Trojans in NextG Wireless

⇒ Detect and mitigate hardware Trojans in NextG transceivers.



This Talk

- Information and communication theory incorporating hardware constraints.
- Approach:
  - Start with abstract formulation, information theoretic bounds.
  - Incorporate/explore practical constraints.
  - Provide design guidelines.

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- Low resolution quantization.
  - Receiver: Analog to digital conversion (ADC).
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- Covert communications by a Trojan.
- Impact of pilot scaling attacks.

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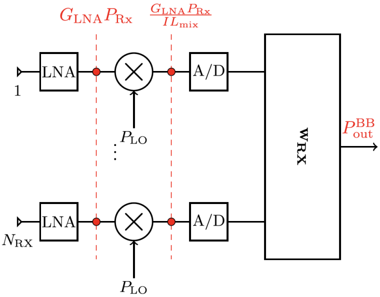
MIMO Receiver

- Classical MIMO receiver.
    - Fully digital.
    - High resolution ADC.
- What about NextG?

Fully Digital Receiver



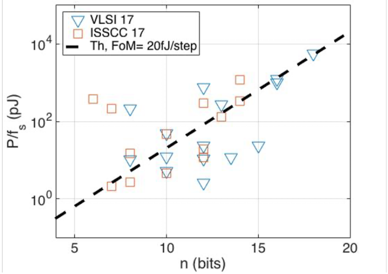
S. Dutta et.al., "A Case for Digital Beamforming at mmWave," IEEE TW, 2020.

- One ADC per antenna, N_{RX} antennas
- NextG systems use large number of transmit and receive antennas

⇒ Linear power consumption with N_{RX}.

High Resolution ADCs

- $P/f_s = \text{FoM} \times 2^n$
  - f_s: Sampling frequency.
  - FoM : Figure of merit.
  - n : ADC resolution.



B. Murmann, "ADC Performance Survey 1997—2017."

⇒ Exponential power consumption with resolution, b.

⇒ Linear power consumption with bandwidth, f_s.

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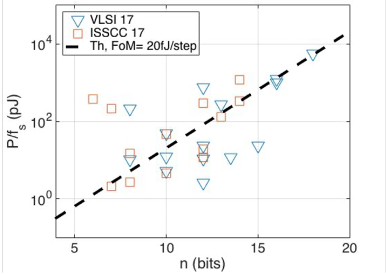
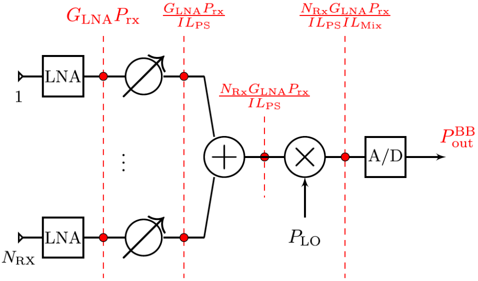


⇒ Exponential power consumption with resolution, b.

⇒ Linear power consumption with bandwidth, f_s.

⇒ May need low resolution ADCs and/or receiver architectures different than fully digital.

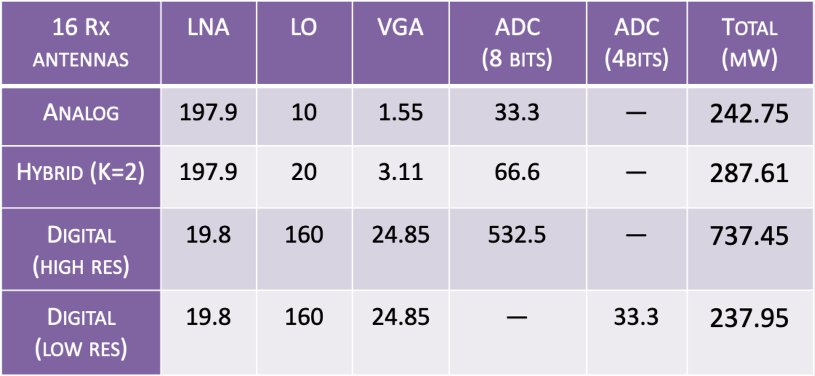
Analog Receiver



S. Dutta et.al., "A Case for Digital Beamforming at mmWave," IEEE TW, 2020.

- Analog receiver: One ADC.
- Hybrid receiver.
- How do the power consumption of different architectures compare?

Receiver Front-end Power Consumption



16 Rx antennas	LNA	LO	VGA	ADC (8 bits)	ADC (4bits)	Total (mW)
Analog	197.9	10	1.55	33.3	—	242.75
Hybrid (K=2)	197.9	20	3.11	66.6	—	287.61
Digital (high res)	19.8	160	24.85	532.5	—	737.45
Digital (low res)	19.8	160	24.85	—	33.3	237.95

S. Dutta et.al., "A Case for Digital Beamforming at mmWave," IEEE TW, 2020.

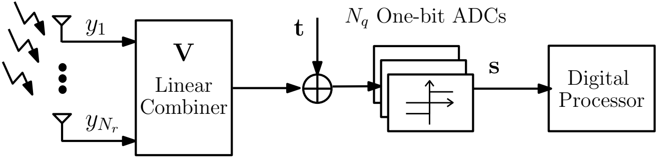
Low Resolution ADCs

- Several papers on analog/hybrid/digital receivers.
- We present an information theoretic formulation.

MIMO system with a given (small) number of one-bit ADCs:

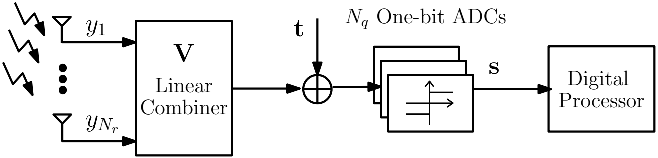
1. What is the maximum achievable rate?
2. Which receiver achieves this rate?

One-shot Hybrid Receiver



- N_r : Number of receiver antennas.
- N_q : Number of quantizers.
- $\mathbf{V}$: Analog combiner matrix $(N_q \times N_r)$.
- $\mathbf{t}$: Threshold vector.
- $\mathbf{s} = \mathrm{sign}(\mathbf{V}\mathbf{y} + \mathbf{t})$: Quantized signal.

One-shot Hybrid Receiver



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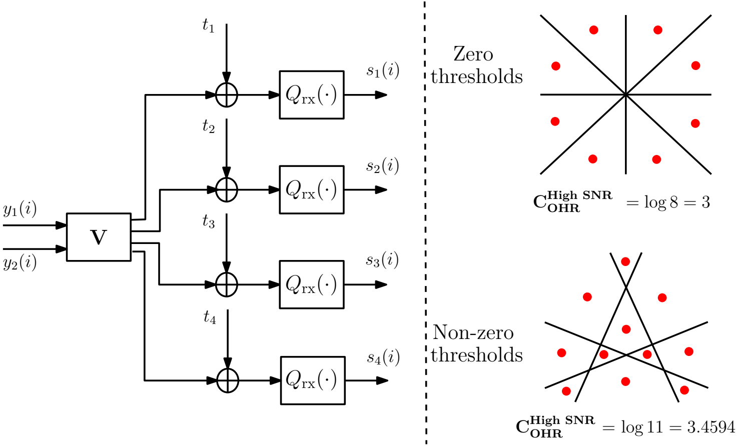
- $\mathbf{s} = \text{sign}(\mathbf{V}\mathbf{y} + \mathbf{t})$: Quantized signal.
- C_{OHR}: For a given N_q, maximum achievable rate, maximized over all input distributions, $\mathbf{t}$, and $\mathbf{V}$.

Example: MIMO One-shot

- $N_t = N_r = 2$ and $N_q = 4$.
- Each **ADC** corresponds to a **hyperplane** partitioning the signal space of dimension N_r.



$\mathbf{C}_{\mathbf{OHR}}^{\mathbf{High\ SNR}} = \log 8 = 3$

$\mathbf{C}_{\mathbf{OHR}}^{\mathbf{High\ SNR}} = \log 11 = 3.4594$

High SNR Capacity

[Khalili et. al, ISIT'18], [Khalili et. al., TCOM'22].

- High SNR capacity: Log of maximum number of regions

$$\log\left(\sum_{k=0}^{\text{rank}}\binom{N_q}{k}\right) \le C_{\mathsf{OHR}} \le \log\left(\sum_{k=0}^{N_r}\binom{N_q}{k}\right)$$

⇒ When $N_q \le N_r \Rightarrow C$ grows linearly with N_q
⇒ When $N_q > N_r \Rightarrow C$ grows logarithmically with N_q

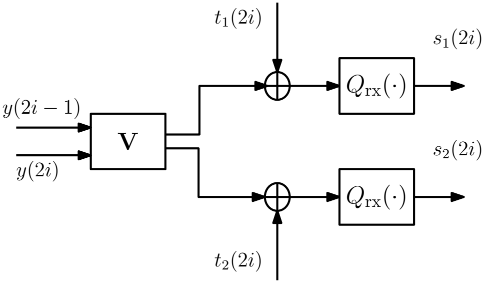
- Does not always achieve N_q bits per channel-use

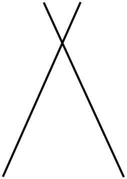
Question: Can we increase the signal dimension and the number of hyperplanes **without** increasing the number antennas or ADCs?

Example: Proposed Blockwise Receiver

SISO channel:

- Analog block length $\ell = 2$
- $N_t = N_r = 1$, and $N_q = 2$





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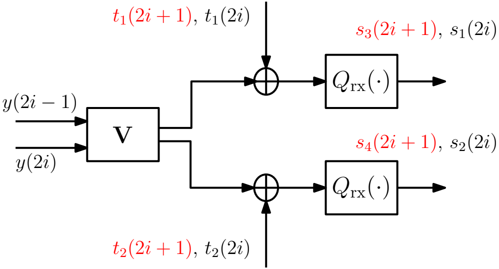

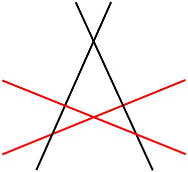

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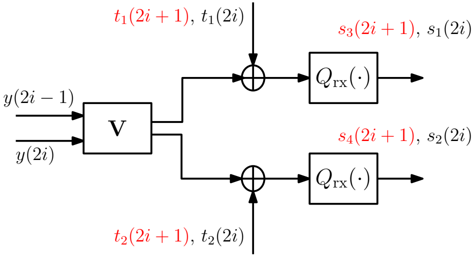

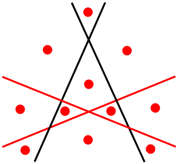

$\mathbf{C}_{\mathbf{BAR}}^{\mathbf{High\ SNR}} = \frac{1}{2}\log 11 = 1.7297$

- Without joint processing $C = \log 3 = 1.58$.

Observations

- Proposed blockwise analog processing virtually preserves the one-bit ADCs and uses them at once.
- For analog processing block length of $\ell = 2$:
    - Virtual number of receive antennas: $2N_r$.
    - Virtual number of ADCs: $2N_q$.
- For general ℓ:

$$\frac{1}{\ell}\log\left(\sum_{k=0}^{\ell\text{rank}}\binom{\ell N_q}{k}\right) \le C_{\mathsf{BHR}}^{\mathsf{High\ SNR}} \le \frac{1}{\ell}\log\left(\sum_{k=0}^{\ell N_r}\binom{\ell N_q}{k}\right)$$

Key Observations

- Geometric approach to characterize the high SNR capacity of receivers with low resolution ADCs.
- Two new receiver architectures that improve the high SNR rate:
  - Blockwise hybrid receiver.
  - Adaptive threshold receiver (optimal performance).

  [Khalili, Shirani, Erkip, Eldar, TCOM'22]

Key Observations

- Geometric approach to characterize the high SNR capacity of receivers with low resolution ADCs.
- Two new receiver architectures that improve the high SNR rate:
  - Blockwise hybrid receiver.
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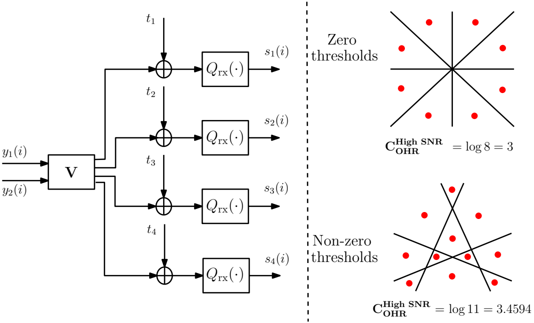
  [Khalili, Shirani, Erkip, Eldar, TCOM'22]
- What about optimized design/performance at finite SNR?

One-shot Hybrid Receiver

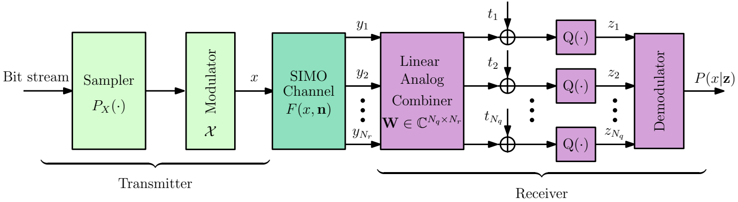
- High SNR capacity.



- Finite SNR.
  - Optimal input constellation and hyperplane placement.
  - Deep learning based solution.

SIMO with Low Resolution ADCs

[Khalili, Erkip, Asilomar'22]



Transmitter:

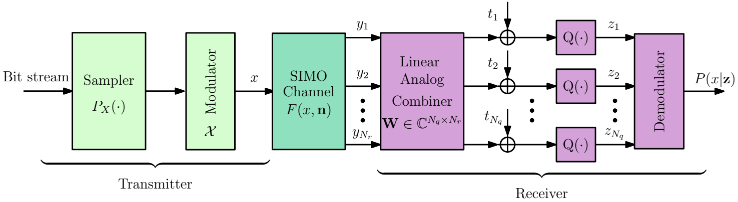
- x: Transmitted symbol.
- $P_X(\cdot)$: Input probability distribution.
- $\mathcal{X}$: Modulator.

Receiver:

- $\mathbf{W}$: Linear analog combiner.
- $\mathrm{Q}(\cdot)$: b-bit ADC.
- $\mathbf{t}$: ADC thresholds.

SIMO with Low Resolution ADCs

[Khalili, Erkip, Asilomar'22]



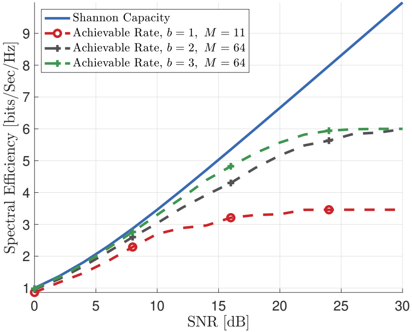
Objective:

Under average transmit power P, maximize achievable rate

$$\max_{P_X(x),\mathcal{X},\mathbf{W},\mathbf{t},\mathrm{Q}(\cdot)} I(X;Z)$$

$$\text{subject to} \quad \mathbb{E}|X|^2 \le P$$

Achievable Rates

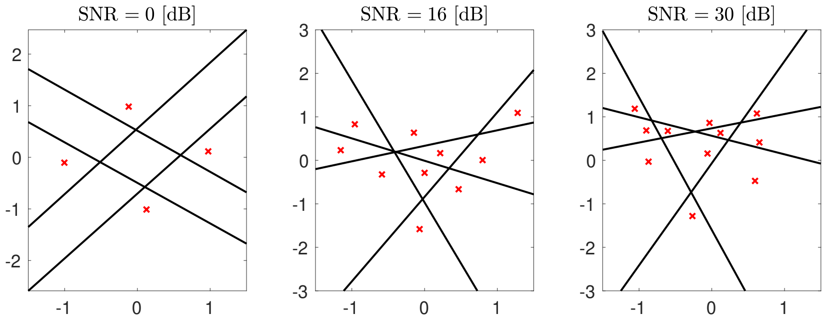


- $N_t = N_r = 1, N_q = 4$.
- b: No. of bits per quantizer.
- M: Modulation order.

⇒ Optimal high SNR rate.

⇒ Near Shannon capacity at low and intermediate SNRs.

Learned Constellations



- $N_q = 4$ quantizers, each $b = 1$ bits.
- Symmetric constellations.
- Modulation order increases as SNR is increased.

This Talk

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- Low resolution quantization.
  - Receiver: Analog to digital conversion (ADC).
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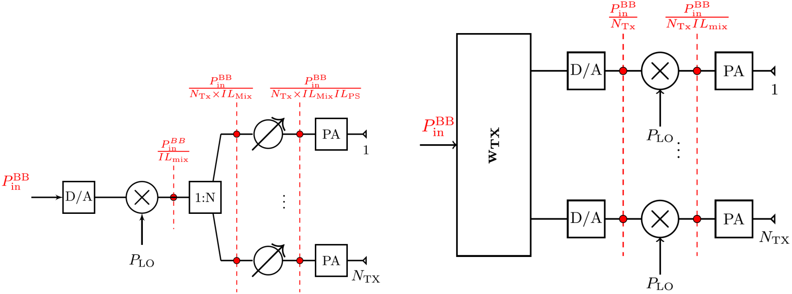
- Other RF components.

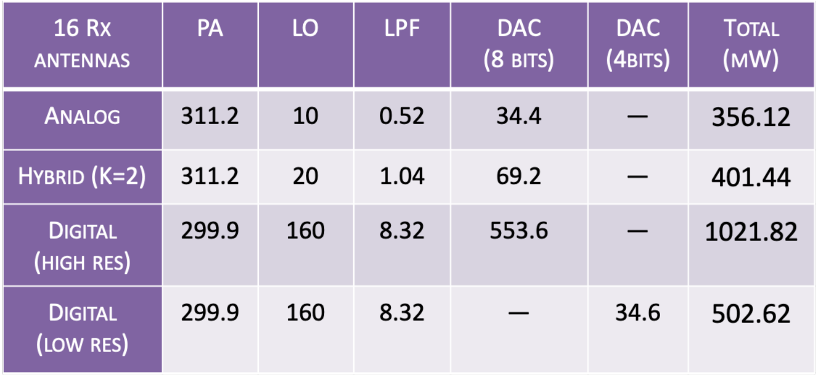
(2) How do we mitigate the impact of hardware Trojans in NextG networks?
  - Covert communications by a Trojan.
  - Impact of pilot scaling attacks.

Analog versus Digital Transmitter



S. Dutta et.al., "A Case for Digital Beamforming at mmWave," IEEE TW, 2020.

Transmitter Front-end Power Consumption

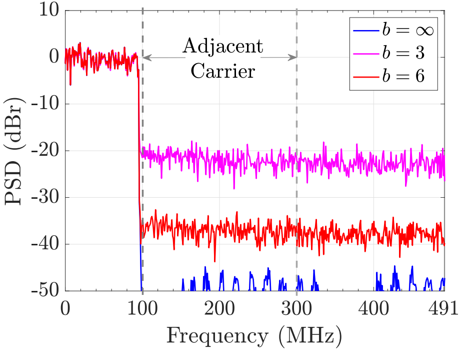


16 Rx Antennas	PA	LO	LPF	DAC (8 bits)	DAC (4bits)	Total (mW)
Analog	311.2	10	0.52	34.4	—	356.12
Hybrid (K=2)	311.2	20	1.04	69.2	—	401.44
Digital (high res)	299.9	160	8.32	553.6	—	1021.82
Digital (low res)	299.9	160	8.32	—	34.6	502.62

S. Dutta et.al., "A Case for Digital Beamforming at mmWave," IEEE TW, 2020.

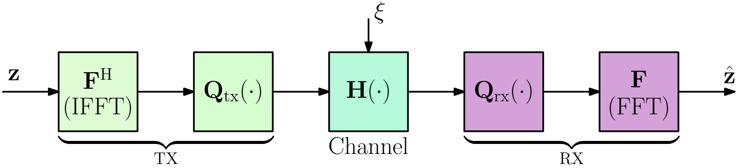
Effect of Low-resolution DACs

- Rate loss.
- Spectral contamination: Quantization noise leaks into adjacent bands.



PSD of the linear modulator used for transmitting a 400 MHz channel centered at 28 *GHz in a 5G NR system sample rate* $f_{\text{samp}} = 983$ *Ms/s. The PSD is shown for various number of bits* (b) *in the DAC.*

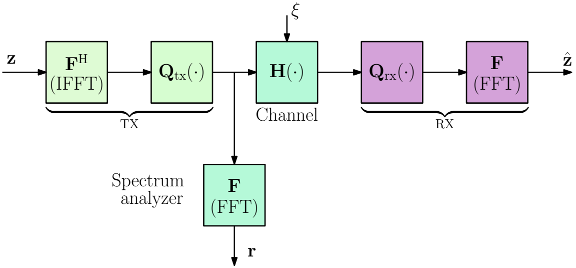
OFDM Transceiver with Low Resolution DAC and ADC



[Dutta, Khalili, Erkip, Rangan, TCOM'23]

- SISO channel
- $\mathbf{z} \in \mathbb{C}^N$: Vector of transmit symbols (e.g., frequency domain)
- $\mathbf{F} \in \mathbb{C}^{N \times N}$: Unitary matrix (e.g., FFT matrix)
- $\mathbf{u} = \mathbf{F}^{\mathsf{H}}\mathbf{z}$: Modulated signal (e.g., time domain)
- $\mathbf{Q}_{\mathrm{tx}}, \mathbf{Q}_{\mathrm{rx}}$: DAC and ADC at the transmitter and receiver side
- $\mathbf{H}(\mathbf{x}, \boldsymbol{\xi})$: Mapping representing the channel
- $\boldsymbol{\xi}$: Channel noise independent of the input

Spectral Power Distribution



- $\mathbf{r}$: Output of the spectrum analyzer (e.g., frequency domain)
  - $\mathbf{r}$ has to conform to the spectrum mask
- *Precise linear additive noise model* to capture the effect of DAC and ADC.
  - $r = \alpha_{\mathrm{tx}} z + w_{\mathrm{tx}}, \quad w_{\mathrm{tx}} \sim \mathcal{C}N(0, \tau_{\mathrm{tx}} \overline{P})$
  - $\widehat{z} = \alpha_{\mathrm{rx}} z + w_{\mathrm{rx}}, \quad w_{\mathrm{rx}} \sim \mathcal{C}N(0, \tau_{\mathrm{rx}} \overline{P})$,
  - Validity proved in the wideband regime.

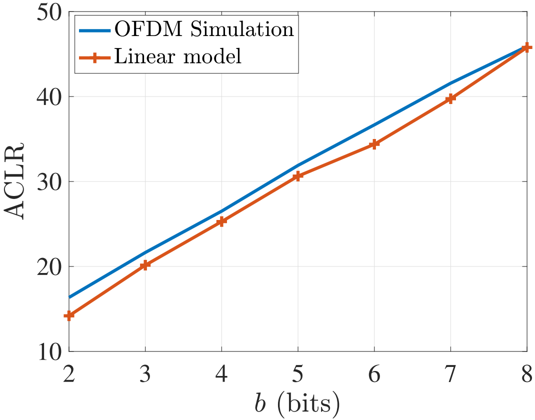
Adjacent Carrier Leakage Ratio

- Adjacent carrier leakage ratio (ACLR):

$$\text{ACLR} = 10\log_{10}(\nu_1/\nu_2).$$

- ν_1 : Transmitted power in the main sub-band
- ν_2 : Leaked power into the second sub-band

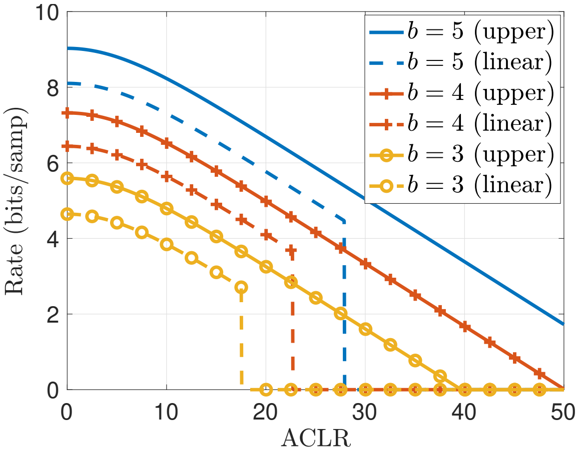
Accuracy of the Linear Model



ACLR with a finite DAC resolution (b) for a 200 MHz 3GPP NR OFDM transmitter compared with the proposed Linear model.

- Theoretical model accurately predicts the ACLR.

High-SNR Rate versus ACLR

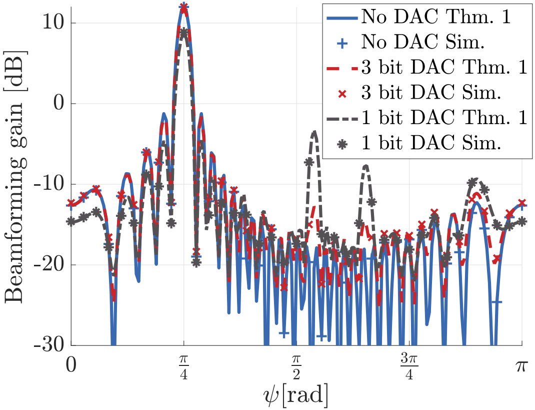


Solid lines show the upper bounds on the achievable rate and the dashed lines show the achievable rate predicted by the linear model.

MIMO: Spatial Power Distribution

[Khalili, Erkip, Rangan, ISIT'22]

- Transmit array directed at $\pi/4$: $\mathbf{P}_1 = \frac{1}{N_t}\mathbf{e}(\frac{\pi}{4})\mathbf{e}(\frac{\pi}{4})^{\mathsf{H}}$
- Beamforming gain at direction ψ: $(\mathbf{e}(\psi)^{\mathsf{H}}\mathbf{S}_1\mathbf{e}(\psi))$



Key Observations

- Linear model rigorously captures the effect of low resolution quantization on
    - Achievable rate of the system.
    - Achievable power spectrum, including out of band (OOB) emissions.
    - Spatial power distribution.
- Low resolution DAC $\Rightarrow$ OOB emission cannot be reduced below a threshold.

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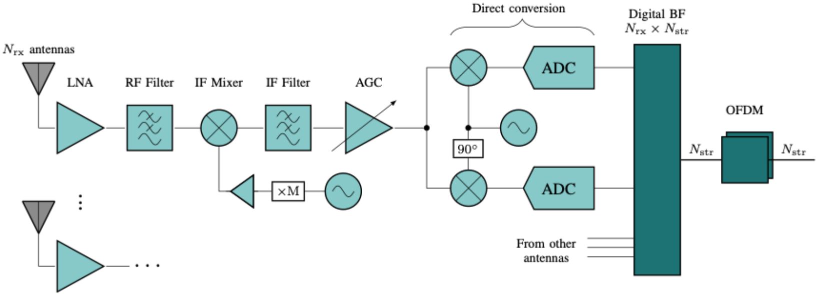
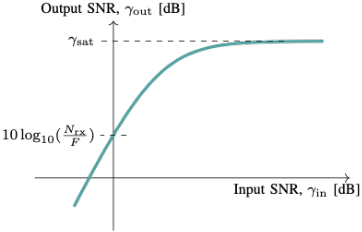


- Many components, e.g. mixer, are nonlinear.
    - "Knobs," e.g. LO power, to control the linear range.
    - Higher power ⇒ larger linear range.

Extension of the Linear Noise Model



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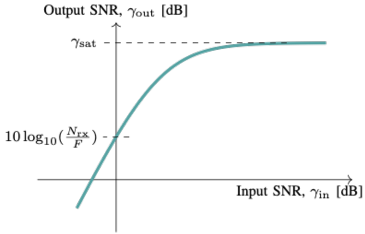
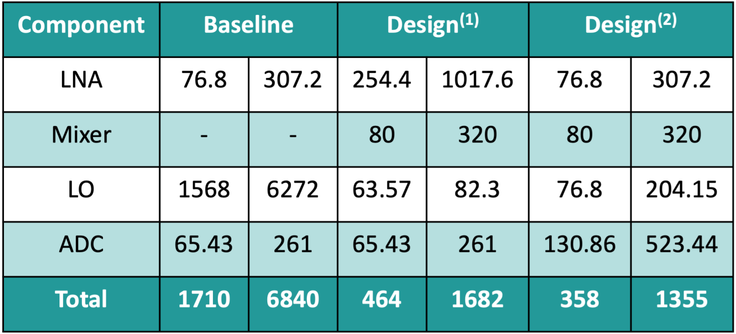


[Skrimponis, Hosseinzadeh, Khalili, Rodwell, Buckwalter, Erkip, Rangan, IEEE Access'21]

- End-to-end model using [Dutta, Khalili, Erkip, Rangan, TCOM'23].
- Validated in practical systems using circuit and system level simulations.
  - Various design options for key RF components including the LNA, mixer, LO and ADC in 140 GHz.
- Allows for power optimized designs for the same achievable rate.

Power Savings



Component	**Baseline**		**Design$^{(1)}$**		**Design$^{(2)}$**	
LNA	76.8	307.2	254.4	1017.6	76.8	307.2
Mixer	-	-	80	320	80	320
LO	1568	6272	63.57	82.3	76.8	204.15
ADC	65.43	261	65.43	261	130.86	523.44
Total	**1710**	**6840**	**464**	**1682**	**358**	**1355**

- Power consumption estimates (in mW) for the baseline and two optimized designs.
- *70-80% power savings.*

This Talk

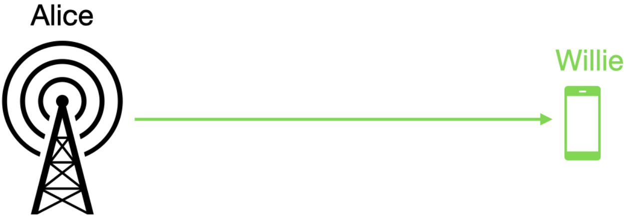
(1) How do we manage power consumption in NextG networks?

- Low resolution quantization.
  - Receiver: Analog to digital conversion (ADC).
  - Transmitter: Digital to analog conversion (DAC).
- Other RF components.

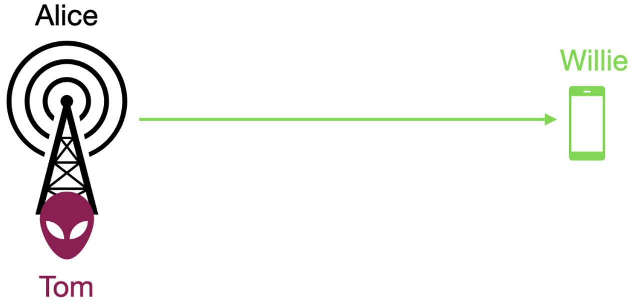
(2) How do we mitigate the impact of hardware Trojans in NextG networks?

  - Covert communications by a Trojan.
  - Impact of pilot scaling attacks.

Transmitter Hardware Trojan

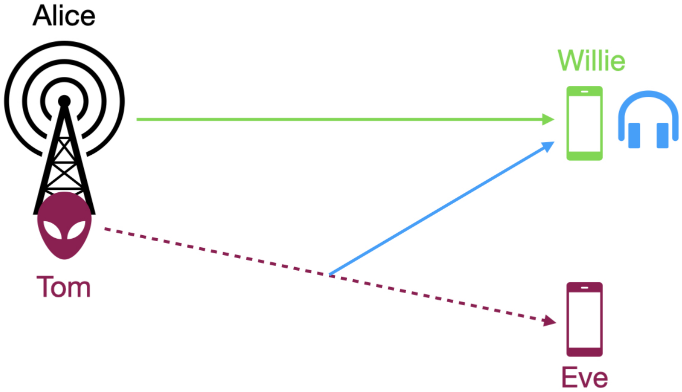


Transmitter Hardware Trojan



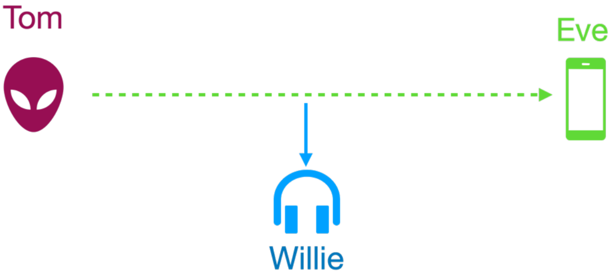
- *Tom* can disrupt Alice-Willie communication by jamming.
- Tom may have access to Alice's information, channel state etc.

Covert Communications of Hardware Trojans



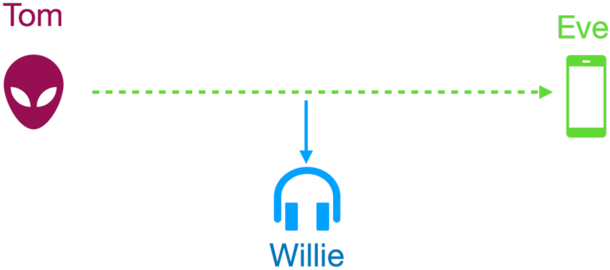
- Tom can also try to leak information by covertly communicating with Eve.
- Willie could act as the warden, trying to detect the covert communication.

Covert Communications: An Introduction



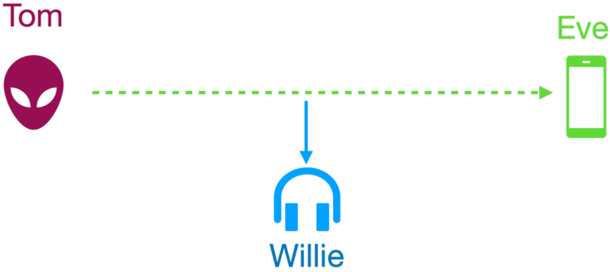
- Tom's goal: Transmit to Eve **reliably** and **covertly**.
  - *Covert:* Deniable, undetectable, low probability of detection.
- Willie's goal: Detect **if there is communication** between Tom and Eve.

Secure Communications: A Comparison



- Tom's goal: Transmit to Eve **reliably** and **securely**.
- Willie's goal: **Decode Tom's message**.
    - Willie is already aware of the communication.

Covert Communication: Willie's Hypothesis Test



- **Hypotheses:**
  - H_0: Only noise.
  - H_1: Noise + Tom-Eve communication.
- **Metrics of Interest:**
  - $\mathbb{P}_F$: Willie's type-I error / false alarm probability.
  - $\mathbb{P}_M$: Willie's type-II error / misdetection probability.

Covertness Criterion

- **Blind Test:** Independent of the his received signal,

  Willie decides $\begin{cases} H_0, & \text{with probability } p \\ H_1, & \text{with probability } 1-p \end{cases}$

  - $\mathbb{P}_F + \mathbb{P}_M = (1-p) + p = 1$ is always achievable.
- **Covertness Criterion:** $\mathbb{P}_F + \mathbb{P}_M > 1 - \delta$ for some $\delta > 0$.
  - Willie's test needs to be close to a blind test.
  - This criterion does not tell anything about Willie's actual decision!
  - It tells us that Willie's decision is not **credibly** better than a blind one.

Covert Communications Literature

[Bash et al., JSAC '13], [Bloch, Trans. IT '16], . . .

- Willie has all the channel state information (CSI) and the channel statistics.
    - Discrete, AWGN, block fading, MIMO etc.
- The only uncertainty is the *realization* of the noise.
- **Main Result:** Tom can only send $\mathcal{O}(\sqrt{n})$ bits reliably and covertly in n channel uses.
    - Known as the **square-root law**.
    - Zero covert rate.

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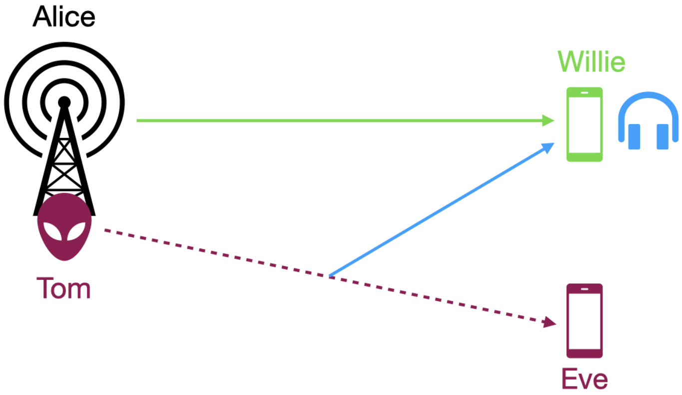
  - Known as the **square-root law**.
  - Zero covert rate.
- Additional sources of uncertainty may improve covert rate.
  - Channel gain, noise variance, crossover probability, channel state, timing of the communication etc.

Covert Communications of Hardware Trojans



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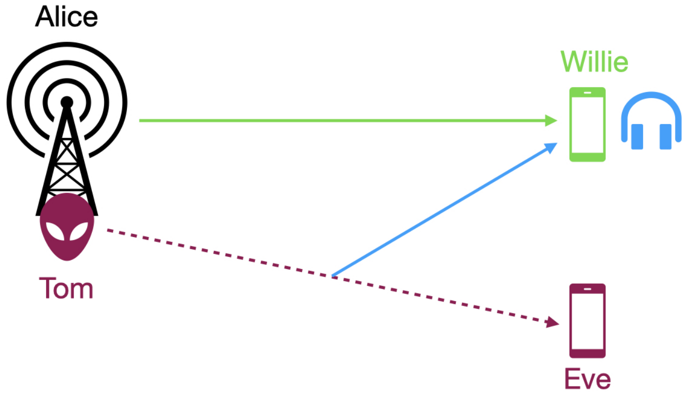
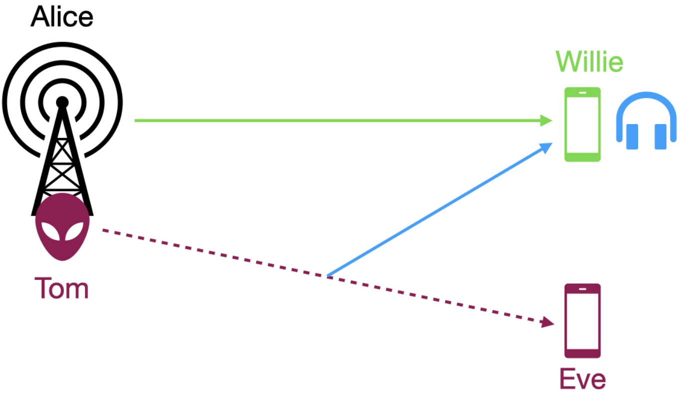


- Can Tom inject extra uncertainty by controlling the channel estimation phase?

Covert Communications of Hardware Trojans

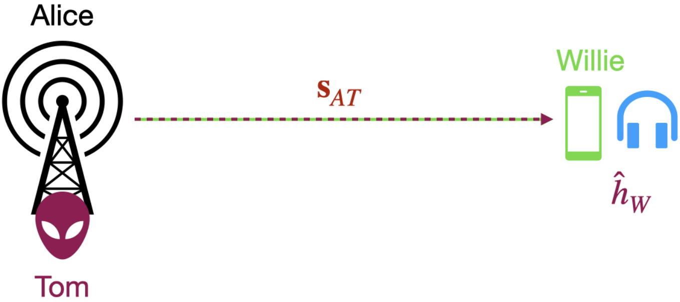


- Can Tom inject extra uncertainty by controlling the channel estimation phase?
- Tom needs to communicate covertly in the presence of Alice-Willie communication.

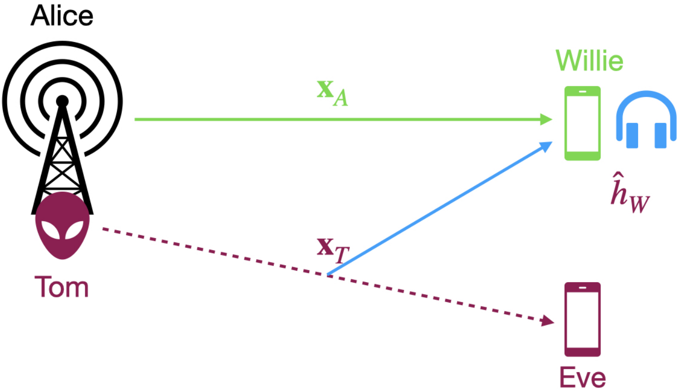
Tom's Strategy

1. Tamper with Alice's pilot sequence $\mathbf{s}_A$ **covertly** to corrupt Willie's channel estimate $\widehat{h}_W$.
   - Scaling pilot corruption: $\mathbf{s}_{AT} = (1+\epsilon)\mathbf{s}_A$.
2. Prey on Willie's estimation error to communicate **covertly** with Eve.

Channel Estimation Phase



Communication Phase



Willie's Strategy

1. In the channel estimation phase, try to detect whether there is pilot scaling or not.
    - If the test is credibly better than a blind test, use its output as the decision.

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   - If the test is comparable to a blind test, assume H_0.
   - Estimate the channel $\widehat{h}_W$ and proceed with the communication phase.
2. In the communication phase,
   - First decode Alice's signal and remove from the received signal.
   - **Effective interference at Alice:** $(h_W - \widehat{h}_W)x_A + h_W x_T$.
   - Then try to detect whether Tom is communicating with Eve or not.

Covertness Criteria

- We say Tom remains *covert* if
    1. Willie fails to credibly detect Tom's pilot scaling attack in the channel estimation phase.
    2. Willie also fails to credibly detect Tom's communication with Eve in the communication phase.
    3. Tom's actions do not disrupt the legitimate Alice-Willie link.
       Note: Tom exploits the link margin.

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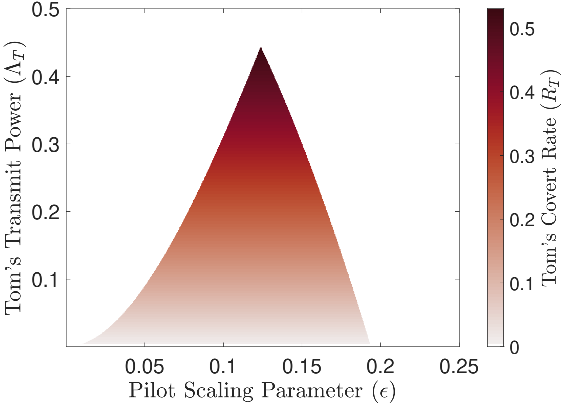
  3. Tom's actions do not disrupt the legitimate Alice-Willie link. **Note:** Tom exploits the link margin.
- Tom can control:
  - Pilot scaling ϵ.
  - His transmit power Λ_T.

Main Result

Positive covert rates are possible by pilot scaling.



- Effective interference power at Willie: $\epsilon^2|h_W|^2\Lambda_A + |h_W|^2\Lambda_T$.
- High ϵ helps covertness by increasing channel estimation error, but also increases effective interference at Willie.

Conclusion

Information and communication theory incorporating hardware constraints.

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(2) Hardware Trojans.

- Pilot scaling attacks and impact on Trojan covertness.

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