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DEER: SIMULTANEOUS MULTI-MODAL DECENTRALIZED ENERGY EFFICIENT COVERT ROUTING

K F Haque[*], ***Justin Kong*** [†], Terrence J. Moore [†], Francesco Restuccia[*], Fikadu T. Dagefu

[*]Institute For the Wireless Internet of Things, Northeastern University, Boston, USA
DEVCOM Army Research Laboratory

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Ensuring Resiliency and Security of Wireless Networks Is of Paramount Importance

Agent **Client**

Covert communication aims to evade detection by adversary

Covert networks need to meet a multitude of conflicting requirements

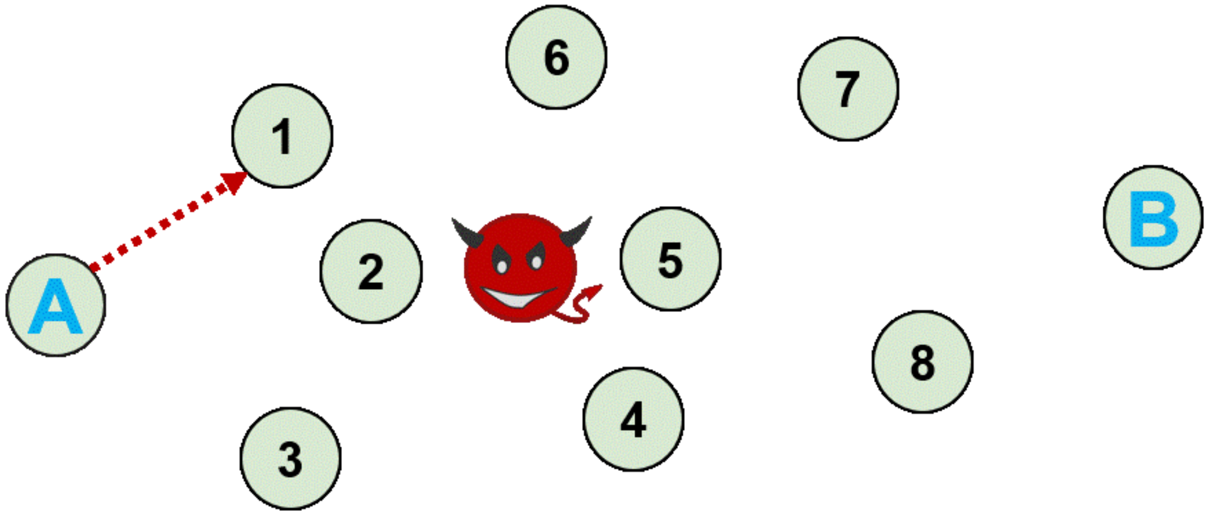
State of the art single-modal covert routing is inefficient

Modality 1

Modality 2

Modality 3

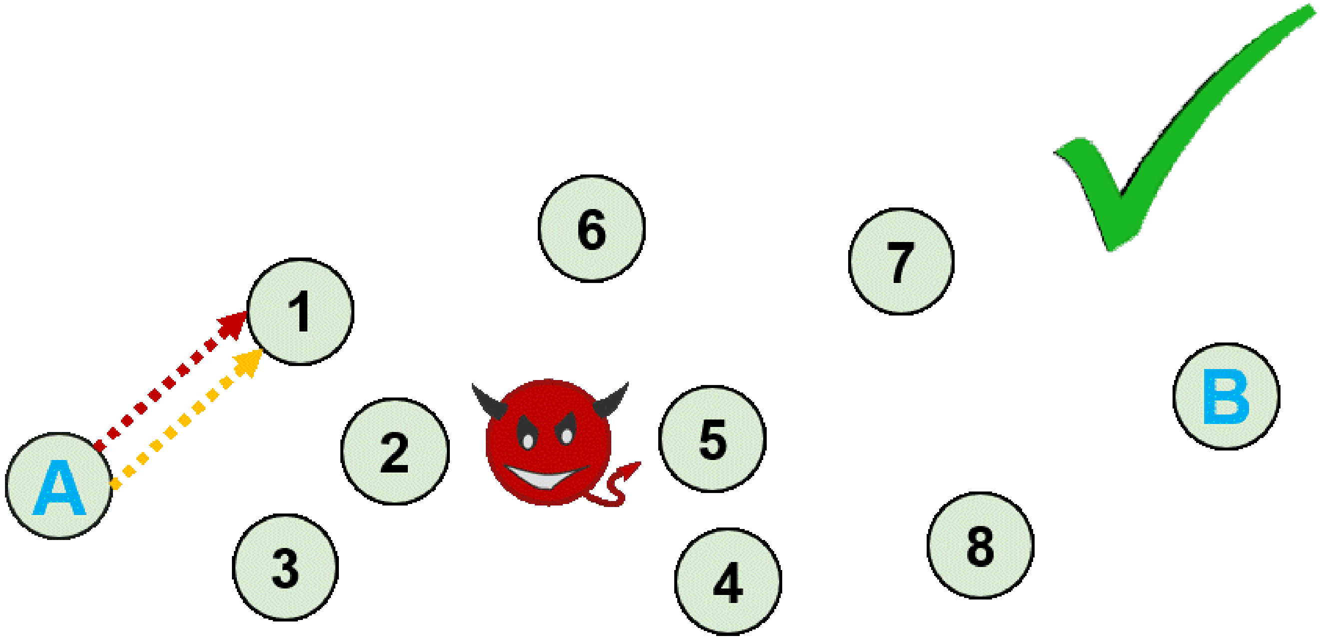
- Most works are based on single modality
- Doesn't fully exploit the diversity of the HetNets



High Energy Consumption

Low Throughput

DEER: Simultaneous Multi-modal Decentralized Energy Efficient Routing



High Throughput

Low Energy Consumption

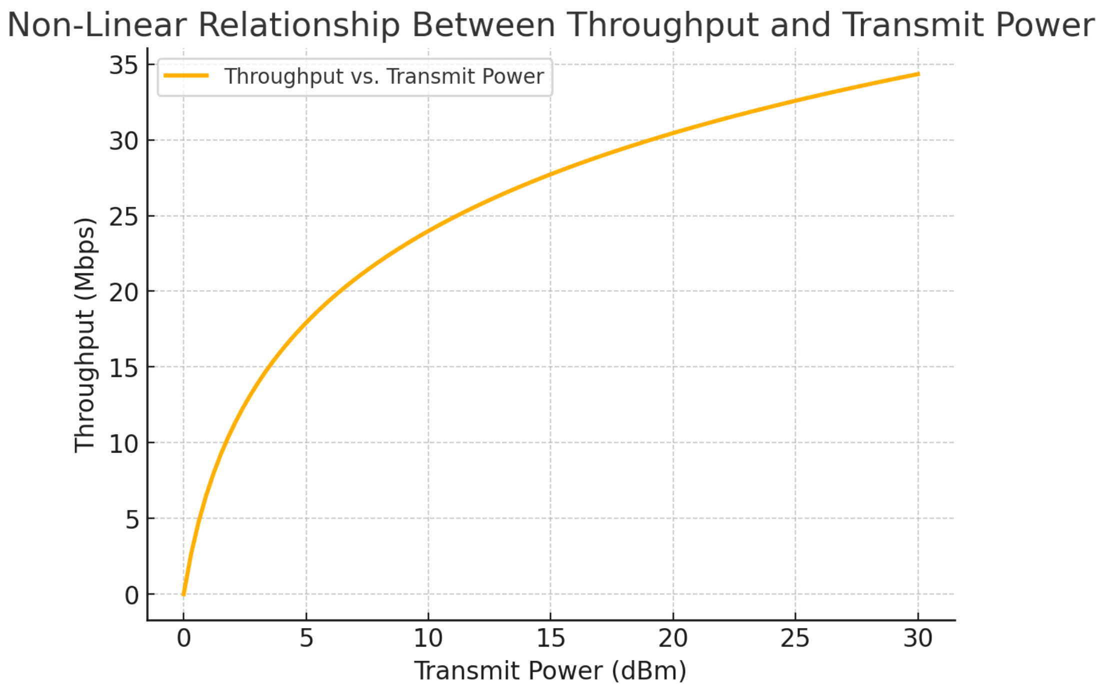
DEER aims to minimize combined transmit power while maintaining throughput and covertness

Novel Contributions of DEER

- DEER Leverages simultaneous multi-modal transmissions
- Minimizes total end-to-end transmit power through node-level and network-level optimization.
- Maintains user-required constraints on throughput and covertness.
- Enables decentralized, energy-efficient routing using local information.

Intuition Behind DEER

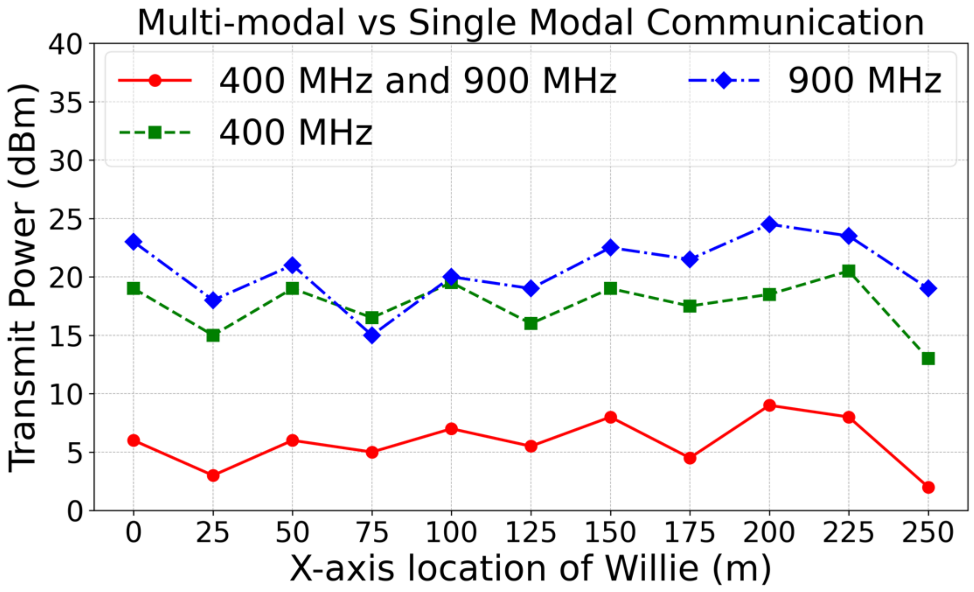
- Throughput depends on channel conditions
- It has a non-linear relationship with transmit power

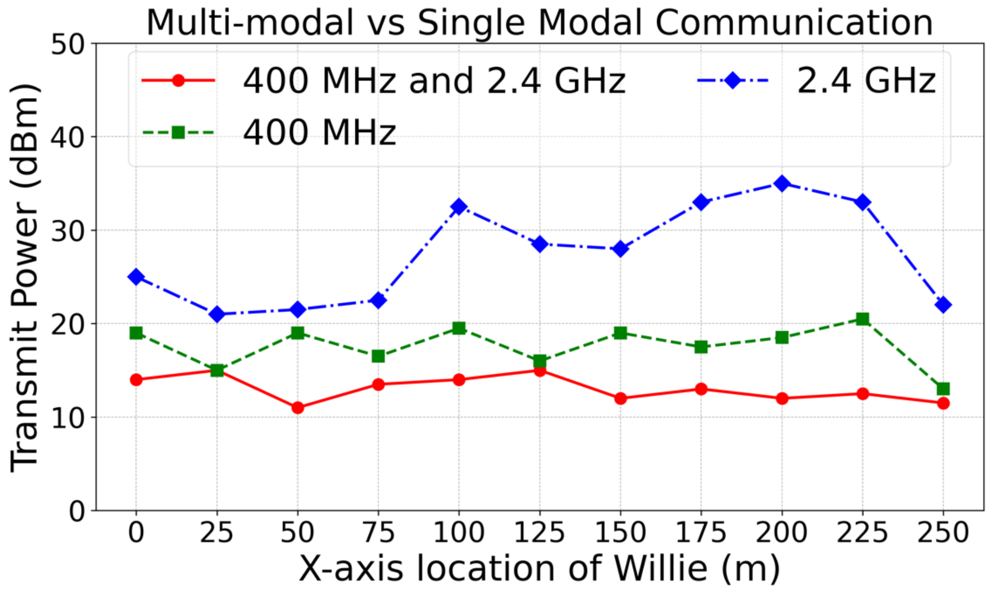


DEER Optimally leverages multiple modalities simultaneously to achieve higher throughput with lower energy consumption

Proof of simultaneous multi-modal transmission being more energy efficient

Simultaneous multi-modal approaches take least transmission power while achieving same throughput and DEP (single hop test)





Covertness threshold = 0.5 and Throughput threshold = 40 Mbps

DEER Overview

- DEER aims to minimize the end-to-end total transmit power of the whole route in a decentralized fashion
- It also maintains the constraints on end-to-end throughput and per-hop detection error probability (DEP)

End-to-end transmit power

$$\min_{\psi\in\Psi,h\in\psi} \boxed{P(\psi)}$$

Per-hop DEP

$$\text{s.t.} \quad \boxed{\mathrm{P}_{\mathrm{DEP},h}} \geq \mathrm{P}_{\mathrm{req\ DEP},h}$$

End-to-end throughput

$$\boxed{U(\psi)} \geq U_{req},$$

Signal Model

Signal is transmitted from Transmitter T_h to Receiver R_h for the hop h of the whole route ψ where Willie W is the adversary. Here m^k = { m^1, m^2}

$$\boxed{y^{(m)}_{T_h,R_h}[l]} = \sqrt{\boxed{P^{(m)}_h}}\,\boxed{g^{(m)}_{T_h,R_h}}\,\boxed{x_h[l]} + \boxed{n^{(m)}_{T_h,R_h}[l]},$$

$$\boxed{y^{(m)}_{T_h,W}[l]} = \sqrt{\boxed{P^{(m)}_h}}\,\boxed{g^{(m)}_{T_h,W}}\,\boxed{x_h[l]} + \boxed{n^{(m)}_{T_h,W}[l]}.$$

Rcv signal   Tx Power   Channel   Tx data   AWGN noise

Network Metrics

Overall E2E throughput

$$U(\psi) = U^{(m^{(a)})}(\psi) + U^{(m^{(b)})}(\psi)$$

E2E throughput for

$$U^{(m)}(\psi) = \min_{h \in \psi} U_h^{(m)}$$

Throughput for modality *m* and hop *h*

$$U_h^{(m)} = \Omega^{(m)} \log_2 \left(1 + \frac{P_h^{(m)} \left| g_{T_h,R_h}^{(m)} \right|^2}{\Omega^{(m)} N_{0,R_h}} \right)$$

E2E Tx Power

$$P(\psi) = \sum_{h \in \psi} P_h$$

Combined Tx Power of hop h

$$P_h = P^{(m^{(a)})} + P^{(m^{(b)})}$$

Detection at Willie

- Willie perform separate hypothesis for each modality. For each modality, Willie has null hypothesis, H_0 (no transmission) and and alternative hypothesis, H_1 (transmission exists)

$$\mathcal{H}_0^{(m)} : y_{T_h,W}^{(m)}[l] = n_{T_h,W}^{(m)}[l]$$

$$\mathcal{H}_1^{(m)} : y_{T_h,W}^{(m)}[l] = \sqrt{P_h^{(m)}}\, g_{T_h,W}^{(m)} x_h[l] + n_{T_h,W}^{(m)}[l]$$

- Willie calculate the average RSS for L channel uses and perform threshold check

$$\bar{y}_{T_h,W}^{(m)} = \frac{1}{L}\sum_{l=1}^{L} \left| y_{T_h,W}^{(m)}[l] \right|^2$$

$$\bar{y}_{T_h,W}^{(m)} \underset{\mathcal{D}_0^{(m)}}{\overset{\mathcal{D}_1^{(m)}}{\gtrless}} \delta$$

- $\delta \in \{\delta_h^{(a)}, \delta_h^{(b)}\}$ denotes the detection threshold for modality {a, b}, and D_0 and D_1 denote decisions in favor of H_0 and H_1 for modality {a, b } and hop **h**

Detection at Willie

- The associated detection error probabilities (DEPs) for each threshold test are defir

$$\mathrm{P}_{\mathrm{MD},h}^{(m)} \triangleq \mathbb{P}\left(\mathcal{D}_0^{(m)} \mid \mathcal{H}_1^{(m)}\right), \quad \mathrm{P}_{\mathrm{FA},h}^{(m)} \triangleq \mathbb{P}\left(\mathcal{D}_1^{(m)} \mid \mathcal{H}_0^{(m)}\right)$$

- Willie then combines the decision obtained for each modality

$$\mathcal{D}_0 = \{\mathcal{D}_0^{m^{(a)}} \cap \mathcal{D}_0^{m^{(b)}}\}, \quad \mathcal{D}_1 = \{\mathcal{D}_1^{m^{(a)}} \cup \mathcal{D}_1^{m^{(b)}}\}$$

- Probability of missed detection and the probability of false alarm for the overall decisi

$$\mathrm{P}_{\mathrm{MD},h} = \mathbb{P}(\mathcal{D}_0^{(m^{(a)})}|\mathcal{H}_1)\mathbb{P}(\mathcal{D}_0^{(m^{(b)})}|\mathcal{H}_1) = \mathrm{P}_{\mathrm{MD},h}^{(m^{(a)})}\mathrm{P}_{\mathrm{MD},h}^{(m^{(b)})}$$

$$\begin{aligned}\mathrm{P}_{\mathrm{FA},h} &= \mathbb{P}(\mathcal{D}_1^{(m^{(a)})} \cup \mathcal{D}_1^{(m^{(b)})} \mid \mathcal{H}_0) \\ &= \mathrm{P}_{\mathrm{FA},h}^{(m^{(a)})} + \mathrm{P}_{\mathrm{FA},h}^{(m^{(b)})} - \mathrm{P}_{\mathrm{FA},h}^{(m^{(a)})}\mathrm{P}_{\mathrm{FA},h}^{(m^{(b)})}\end{aligned}$$

Per hop Covertness in terms of Detection Error Probability

- Alice tosses an unbiased coin to decide whether to transmit or not
- Therefore Alice transmits with equal a priori probabilities of 1/2

$$\begin{aligned}\mathrm{P}_{\mathrm{DEP},h} &= \frac{1}{2}\mathrm{P}_{\mathrm{MD},h} + \frac{1}{2}\mathrm{P}_{\mathrm{FA},h} \\ &= \frac{1}{2}\left(\mathrm{P}_{\mathrm{MD},h}^{(m^{(a)})}\mathrm{P}_{\mathrm{MD},h}^{(m^{(b)})}\right) \\ &\quad + \frac{1}{2}\left(\mathrm{P}_{\mathrm{FA},h}^{(m^{(a)})} + \mathrm{P}_{\mathrm{FA},h}^{(m^{(b)})} - \mathrm{P}_{\mathrm{FA},h}^{(m^{(a)})}\mathrm{P}_{\mathrm{FA},h}^{(m^{(b)})}\right)\end{aligned}$$

P_{DEP} of the hop h

Let's Recap the Problem Formulation

DEER solves the formulated optimization problem with **node-level** and **network-level** optimization strategies

End-to-end transmit power

Per-hop DEP

End-to-end throughput

$$\begin{aligned} \min_{\psi\in\Psi, h\in\psi} \quad & \boxed{P(\psi)} \\ \text{s.t.} \quad & \boxed{\mathrm{P}_{\mathrm{DEP},h}} \geq \mathrm{P}_{\mathrm{req\ DEP},h} \\ & \boxed{U(\psi)} \geq U_{req}, \end{aligned}$$

DEER Optimization Problem

DEER Algorithm : Node Level Optimization

- Minimizes total transmit power (P_h) while ensuring throughput and covertness constraints

- Chooses the best modality combination for each neighbor

Algorithm 1: Node-level optimization

1) Find the optimum $P^{(m^{(a)})}$ and $P^{(m^{(b)})}$ to minimize $P_h = P^{(m^{(a)})} + P^{(m^{(b)})}$ while maintaining $U_h \geq U_{req}$ and $\mathrm{P}_{\mathrm{DEP},h} \geq \mathrm{P}_{\mathrm{req\ DEP},h}$ for each neighboring node across all modality combinations.
2) Find the best modality combination ($m^{(a)}$ & $m^{(b)}$) for all neighboring nodes based on minimum P_h.

DEER Algorithm : Network Level Optimization

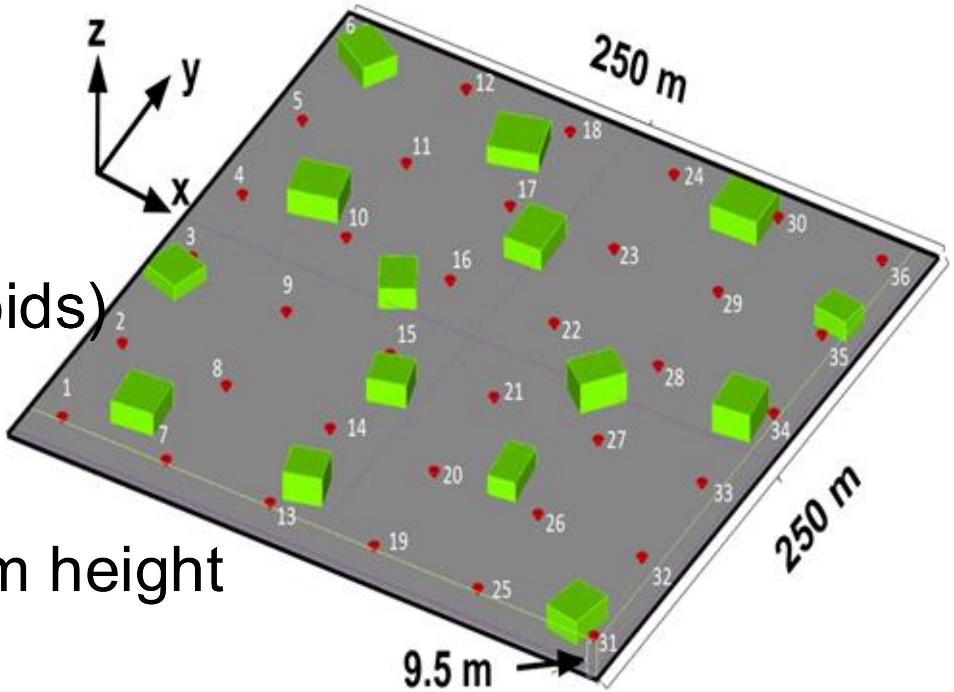
- Initializes D-LSRP by broadcasting LSAs with outgoing links and transmission powers
- Builds LSDB by collecting LSAs to construct the network topology
- Finds the minimum power route using Dijkstra's algorithm
- Updates transmission costs iteratively to minimize end-to-end power consumption

Step 2: Initialize D-LSRP
for each node $n \in N$ **do**
    Broadcast Link State Advertisement LSA(n) with outgoing links and transmission powers.
end for
Step 3: Construct Link State Database (LSDB)
for each node $n \in N$ **do**
    Collect LSAs from all nodes to build the LSDB and network topology.
end for
Step 4: Optimize Transmit Power using Dijkstra's Algorithm
Initialize $p(A) = 0$, $p(n) = \infty$ for $n \neq A$, and an empty set S for visited nodes.
Use a priority queue Q to process nodes based on $p(n)$.
while Q is not empty **do**
    Extract node u with smallest $p(u)$ from Q and & to S.
    for each neighbor v of u **do**
        if $v \notin S$ and $(u, v) \in L$ **then**
            Update $p(v)$ if $p(u) + \text{tx\_power}(u, v) < p(v)$ and adjust Q.
        end if
    end for
end while
Store the minimum power route from A to B.
Return route with minimized transmit power from A to B.

Simulation Scenario of DEER

3D Simulation Setup:

- **Dimensions:** 250 × 250 × 9.5 m³
- **Obstacles:** Multiple concrete buildings (green cuboids)
- **Nodes:** 36 transceiver nodes (red cones) equipped
- with vertically polarized short dipole antennas at 3 m height



Communication Modalities:

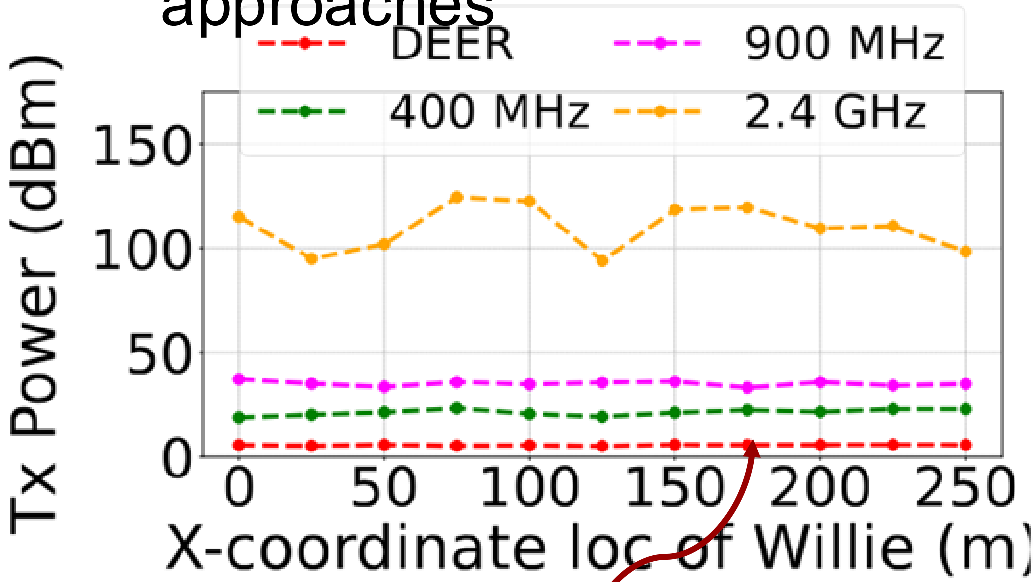
- **Frequencies:** 400 MHz, 900 MHz, and 2.4 GHz
- **Channel Estimation:** Conducted using EM.CUBE ray tracing

DEER as a Function of Willie's Location (1)

End-to-end total transmit power as a function of Willie's X coordinates with

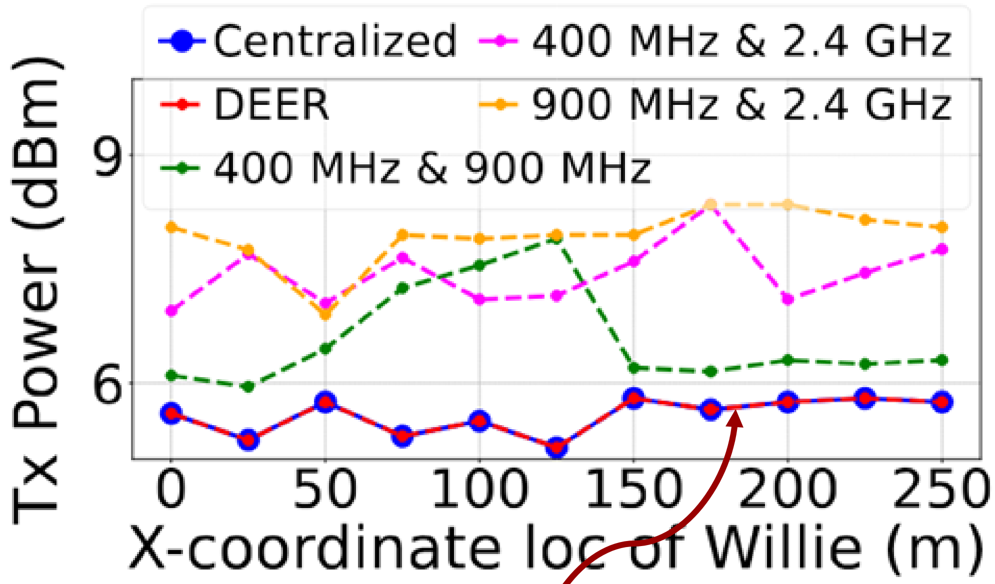
$P_{req\ DEP,h} = 0.5$; $U_{req} = 30$ Mbps; Modality BW: 3 MHz

DEER Vs single-modal approaches



Improves energy consumption

DEER Vs naive multi-modal

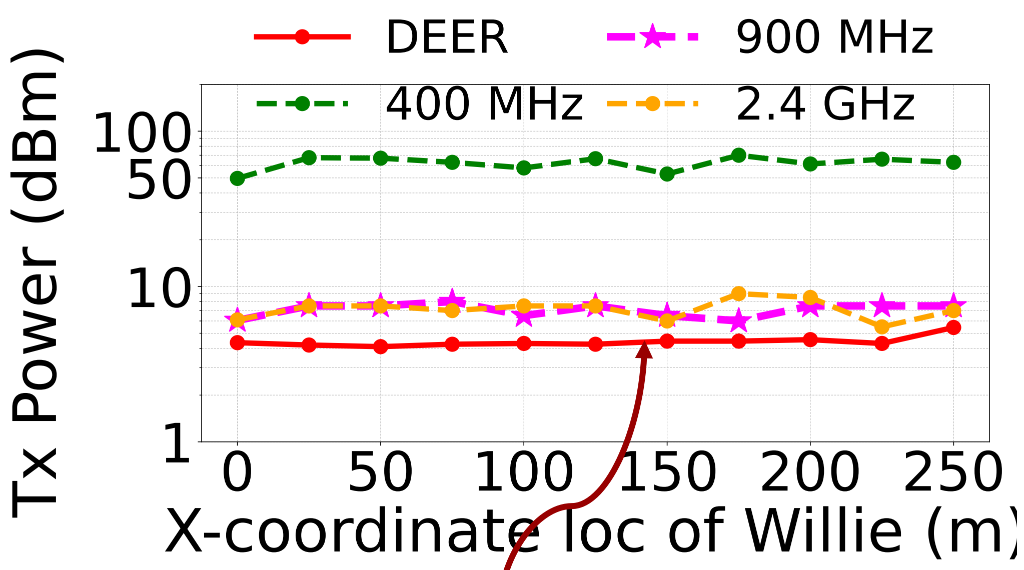


Improves energy consumption by up to 1.5x

DEER as a Function of Willie's Location (2)

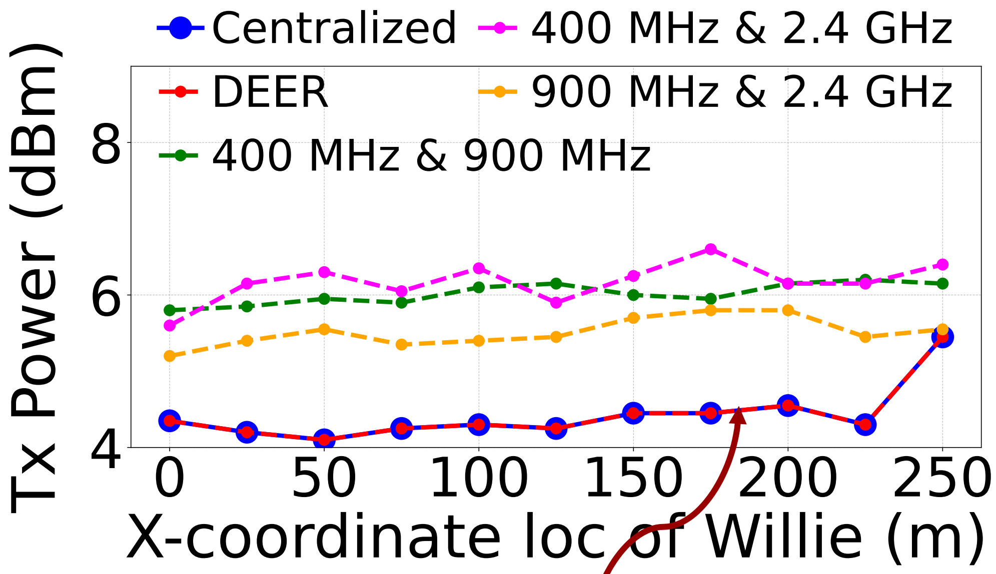
End-to-end total transmit power as a function of Willie's X coordinates with
$P_{req\ DEP,h} = 0.5$; $U_{req} = 30$ Mbps; Modality BW: 1% of center freq.

DEER Vs single-modal approaches



Improves energy consumption by up to 10x

DEER Vs naive multi-modal

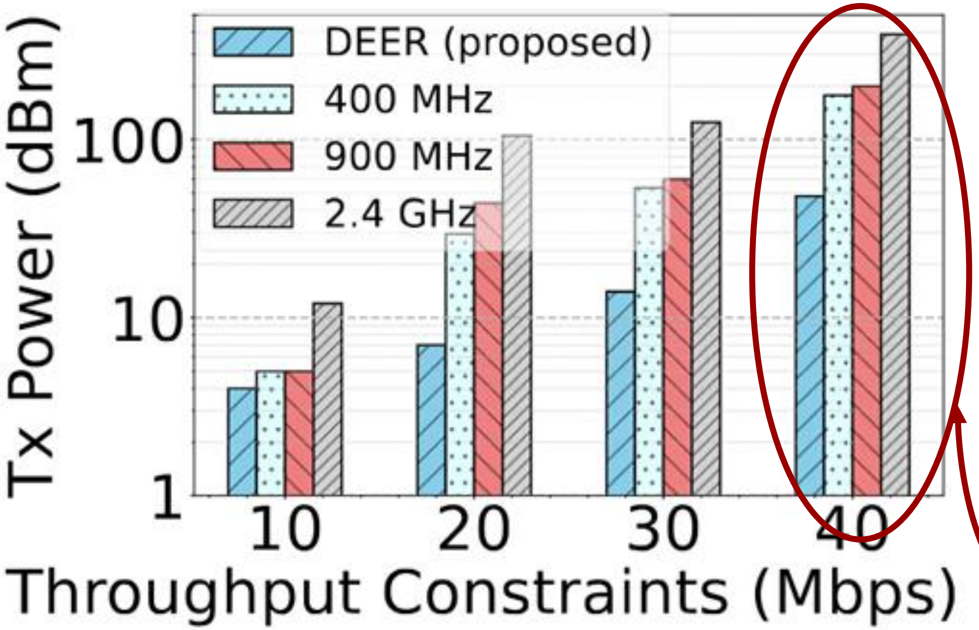


Improves energy consumption by up to 1.5x

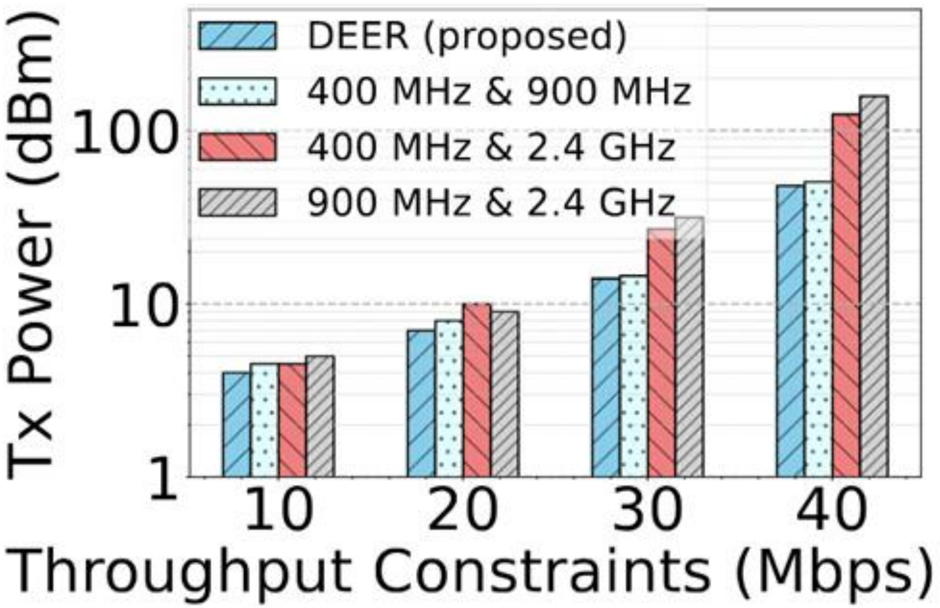
DEER as a Function of Required Throughput

User defined per hop covertness: P_{req} DEP,h = 0.5

DEER Vs single-modal approaches



DEER Vs naive multi-modal approaches

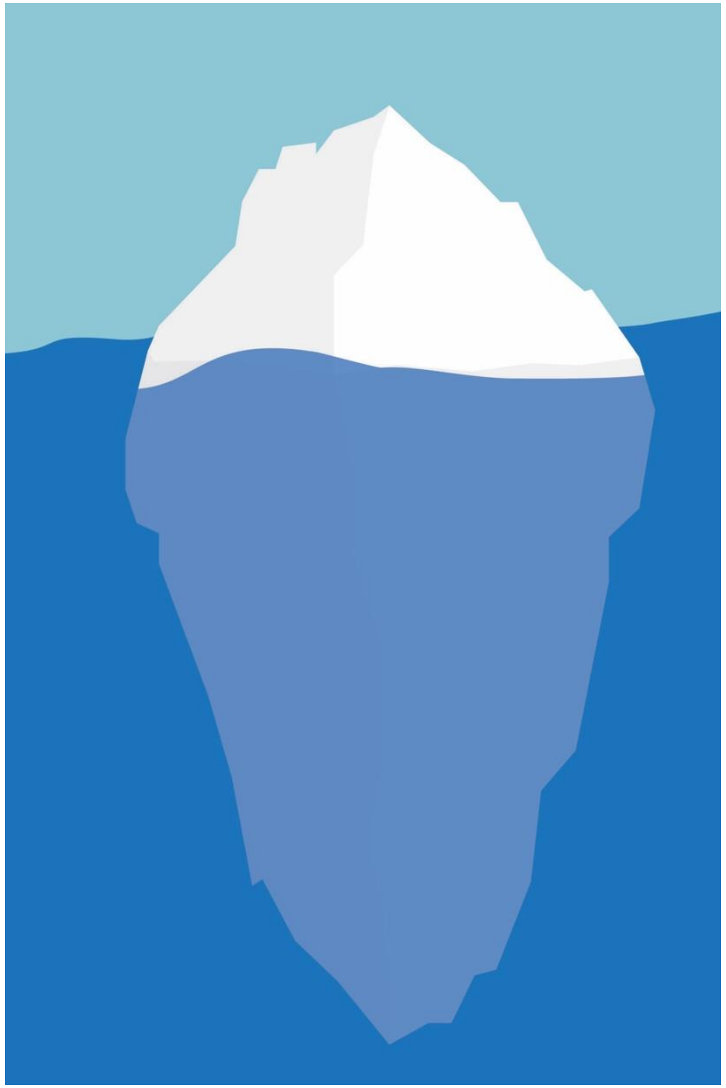


improves energy consumption by up to

Summary of Key Contributions

- ✓ We introduce DEER, a decentralized energy-efficient covert routing strategy
- ✓ It is the first covert routing approach to leverage multiple wireless modalities simultaneously
- ✓ It improves the energy efficiency by up to 23.5%

Possible Next Steps?



This work 💪

Things to do 😅

⚠️ Reduce Routing Data Overhead

⚠️ Scale the System to N number of simultaneous modalities