# CIFellows 2020-2021

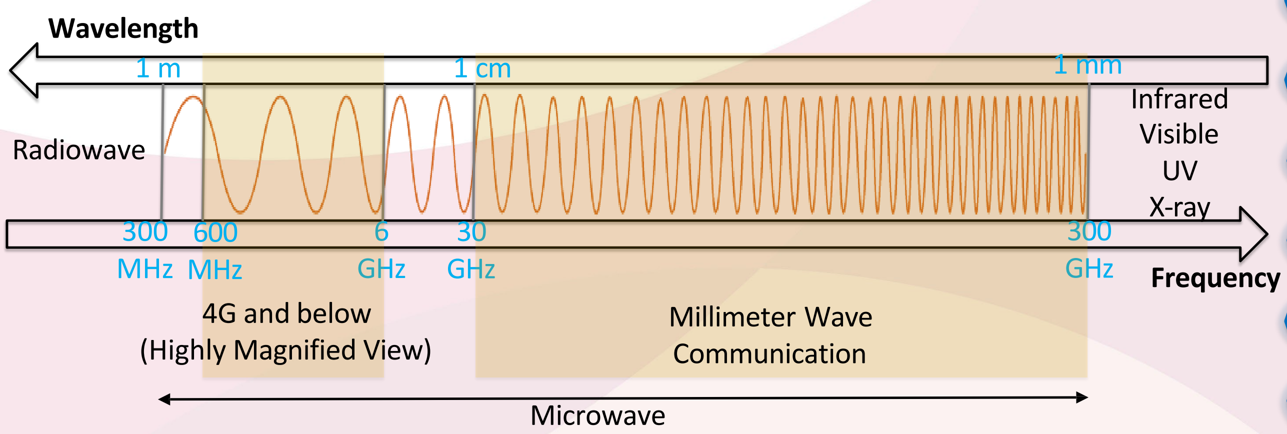
Computing Innovation Fellows

# Scheduling and Learning Algorithms for Millimeter-Wave Communication


## Gourav Saha

Purdue University


## WHAT IT MILLIMETER WAVE COMMUNICATION?



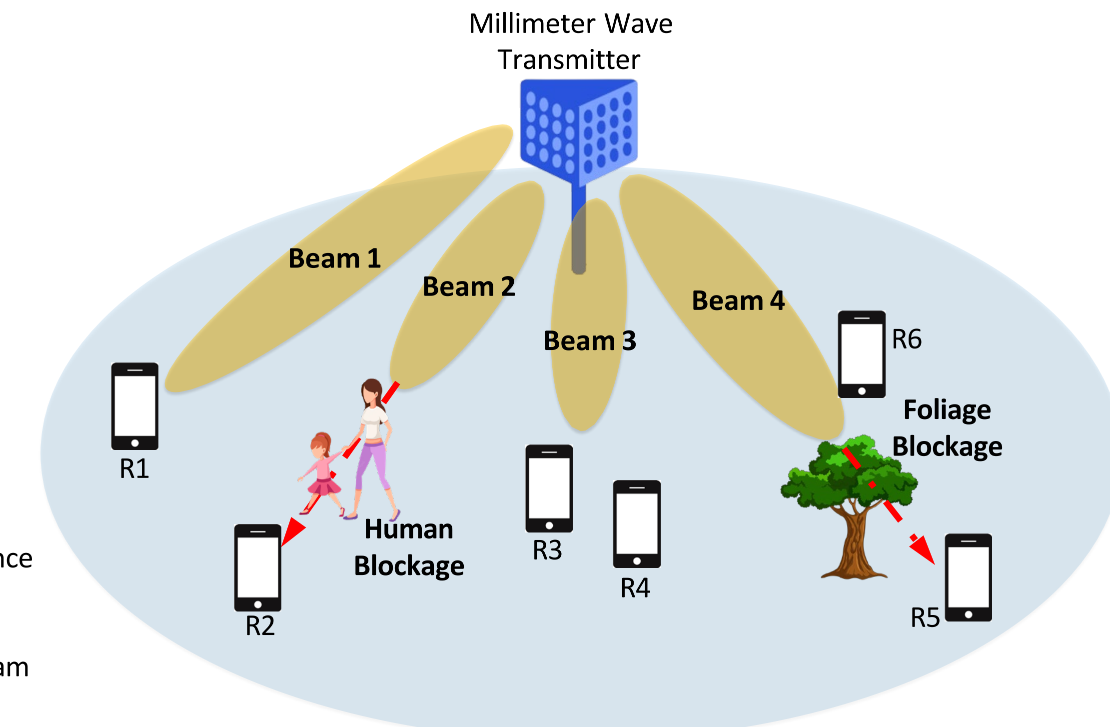

Technologies supporting improve "5G and beyond" communication standard:

- Millimeter wave (mmWave) communication. *Very large bandwidth*; hence it should lead to high throughput and low latency communication.
- Spectrum sharing (3.55 GHz/CBRS band).

## CHALLENGES

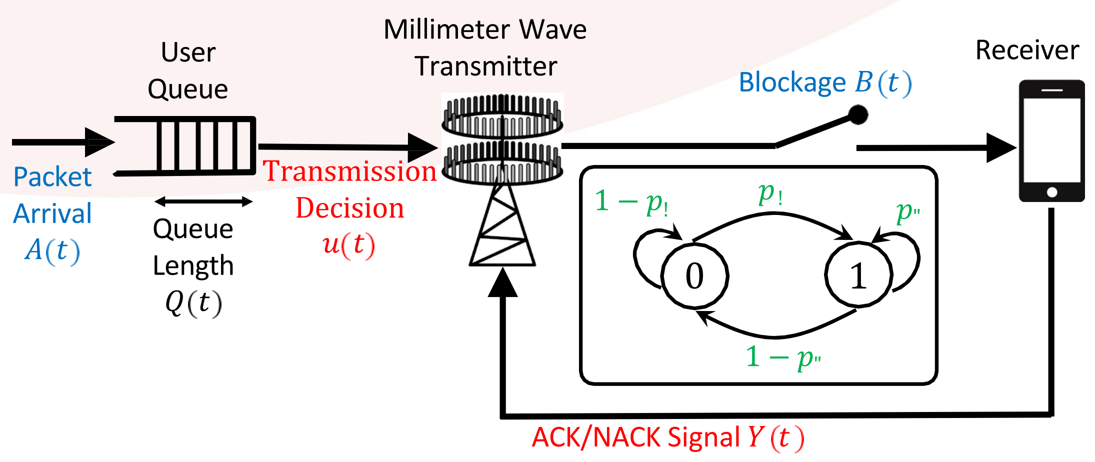
The effective bandwidth of mmWave communication reduces because of:

1. **Blockage**
   - Due to *higher path loss* and *penetration loss* compared to sub-6 GHz communication.
   - Concrete structures, foliage, humans, rainy days severely hamper communication.
2. **Highly directional communication**
   - To combat path and penetration loss.
   - Achieved using *phased-array antennas*. The science is similar to double-slit experiment.
   - A good portion of the time might be used for beam alignment rather than data transmission.




## MINIMIZING LATENCY UNDER BLOCKAGE

### SYSTEM MODEL

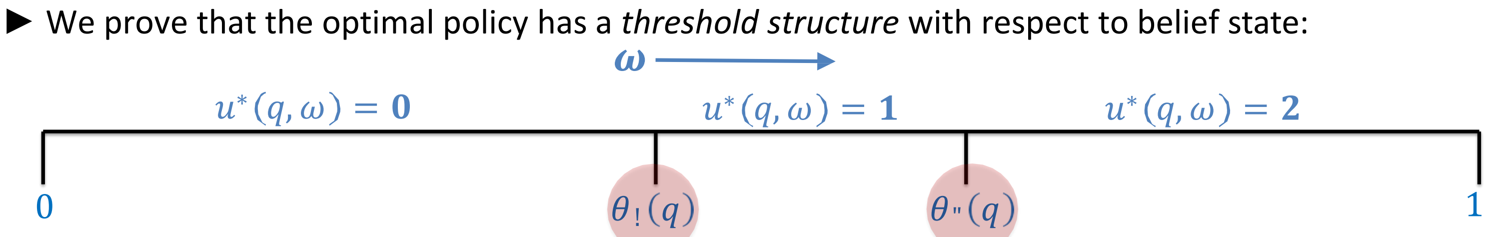



*No channel probing*: The transmitter does not know the instantaneous blockage state, $B(t)$.

- Cost to transmit $u = j$ packets is $\theta_j$.
- *Objective*: Minimize the long-term average transmission delay + transmission cost.

### MAIN RESULT

- If the instantaneous blockage state is known, we can formulate our optimization problem as a Markov Decision Process (MDP) with queue length, $Q(t)$, and blockage state, $B(t)$ as states.
- Since, instantaneous blockage state is not available, we instead formulate a partially-observable MDP (POMDP), with queue length, $Q(t)$, and *belief state*, $\omega(t)$ as states.
  - Belief state is the probability that the mmWave channel is not blocked.
- We prove that the optimal policy has a *threshold structure* with respect to belief state:

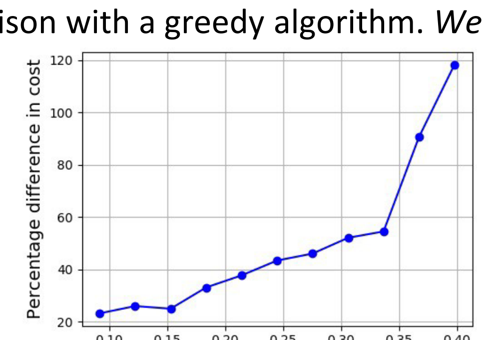


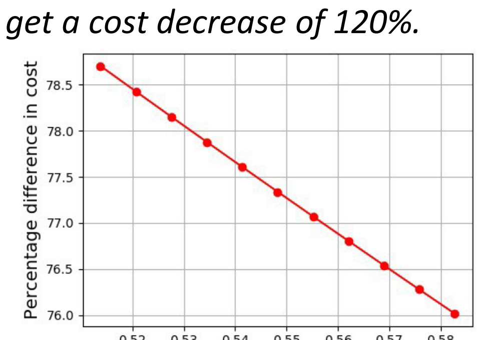

Thresholds are functions of queue length.

- We also designed a *policy gradient* method using *Simultaneous Perturbation Stochastic Approximation (SPSA)* technique to learn the threshold parameters when the system parameters (packet arrival rate, Markovian blockage parameters etc) are not known.

### SIMULATION RESULTS

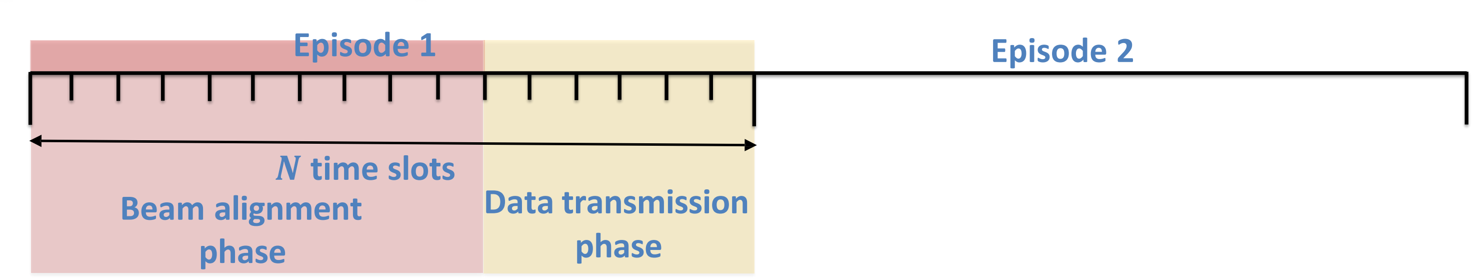
- Comparison with a greedy algorithm. *We can get a cost decrease of 120%.*




## EFFICIENT BEAM ALIGNMENT TO MAXIMIZE THROUGHPUT

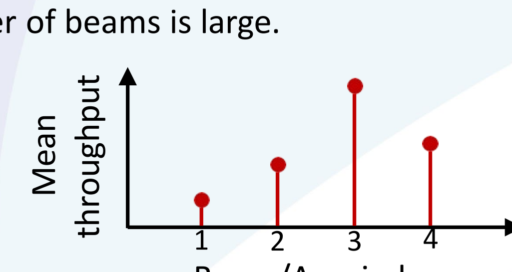
### PROBLEM STATEMENT

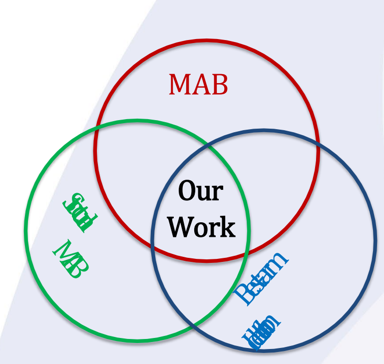



- Episodic setup used to account for multiple users, mobility of users, and non-stationarity of mmWave channels.
- In a given episode, the mmWave channel parameters and the user/receiver are stationary.
  - Mean throughput for the chosen user when using the $k^{th}$ beam, $\mu_k$. Throughput per time slot is still varying during to varying channel conditions.
- Pilot signals are sent during beam alignment phase. Data packets are sent during data transmission phase.
- *Objective*: Maximize the mean throughput per episode when channel parameters, $\{\mu_k\}_{k}$, are not known apriori; only data packets are considered.

### NOVELTY OF THE PROBLEM AND RELATION TO MULTI-ARMED BANDITS (MAB)

- *Exploration-exploitation tradeoffs:* If the beam alignment phase *(exploration)* is too short, then the beam with maximum throughput may not be discovered. If the beam alignment phase is too long, there may not be enough time left for the data transmission phase *(exploitation)*.
- *Zero reward in exploration phase. Also, exploration phase has to end before data transmission phase.*
- *Unimodal reward/throughput structure*: Can be used to reduce the pre-factor of the regret. Specially, important when the number of beams is large.





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2. Y. Jedra, A. Proutiere, *"Optimal Best-arm Identification in Linear Bandits"*, NeurIPS-2020.
3. R. Combes, A. Proutiere , *"Unimodal Bandits: Regret Lower Bounds and Optimal Algorithms"*, ICML-2014.
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