Coverage, Capacity, & Resilience Enhancement in Limited Public Safety Network

Project Period: 6/1/2017 – 12/31/2019

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Agenda

Project Overview

- **Task 1: Intelligent, Dynamic Coverage, Capacity, and Resilience Enhancement**
- **Task 2: LTE Multicast for Public Safety Networks**

Task 2: Multicast Quality-of-Service for PSNs

Task 1: Intelligent Mobile Base Station Placement

Project Overview

Objectives: To support communications for First Responders (FRs) through

- **Extending Coverage and Capacity**
- **Real-time Scheduling of Relay Operation (on/off) and Coordination**
- **Enhancing LTE Multicast Capabilities for PSN**
- **QPP-Integrated Resource Allocation in LTE Multicast**

Main Tasks

Investigation of prudent use of relays and mobile eNBs to support FRs through trajectory and placement optimization, and real-time scheduling of relay operation and coordination

Investigation of PSN-specific LTE Multicast incorporating QoS, prioritization, and preemption (QPP) for Mission-Critical Communications (MCC)

Project Overview
Accomplishments – Statement of Work

- **Task 1.1: Optimal Placement of Relays and BSs in Off-Networks**
- **Task 1.2: Mobile Relays and Mobile BSs Trajectory Optimization and Scheduling**
- **Task 1.3: Network Resilience: FRs aided by a Mobile BS or Relay**
- **Offline/online, distributed/centralized, deterministic/stochastic, and hybrid algorithms and techniques to support Task 1.1-1.3.**

- **Task 2.1: Base Station QPP eMBMS**
- **Task 2.2: Base Station to Off-Network UE Multicast**
- **Task 2.3: UE-to-UE Multicast**
- **Offline/online, deterministic/stochastic, distributed/centralized, and hybrid algorithms and performance analysis for**
  - **eMBMS from Macro BS to support Task 2.1;**
  - **BS to off-network multicast to support Task 2.2.**
- **Distributed and semi-distributed, deterministic/stochastic and hybrid algorithms for UE-to-UEs multicast to support Task 2.3.**

Project Overview
Accomplishments

Deliverables	Percentage of Completion
Task 1.1: Optimal Placement of Relays and BSs in Off-Networks	100 % Completed
Task 1.2: Mobile Relays and Mobile BSs Trajectory Optimization and Scheduling	100 % Completed
Task 1.3: Network Resilience: FRs aided by a Mobile BS or Relay	100 % Completed
Task 2.1: Base Station QPP eMBMS	100 % Completed; Further Investigation in Year 2, in collaboration with NIST/CTL
Task 2.2: Base Station to Off-Network UE Multicast	80 % Completed; In Progress, TBC by Year 2, Q10
Task 2.3: UE-to-UE Multicast	100 % Completed; Extended Results with Task 2.2

Project Overview
Accomplishments - Productions

[‡]: In Collaboration with NIST/CTL Researchers

Ph.D. Dissertations Completed

- Mahir Ayhan, "Efficient Resource Allocation Algorithms for 4G-LTE Networks," May 2018.
- Chen Shen, "Enhancing Wireless Network Performance and Security through Physical Layer Properties," May 2019.
- Siyuan Feng, "On Enhancing Communications among End-Users with Limited Network Accessibility," in progress.

Papers Published

- M. Ayhan, & H.-A. Choi, "A Priority and QoS-Aware Scheduler for LTE Based Public Safety Networks," in Future of Information and Communication Conference (FICC) 2019, San Francisco, CA, March 2019.
- C. Shen, M. Yun, A. Arora, & H.-A. Choi, "Efficient Mobile Base Station Placement for First Responders in Public Safety Networks," in FICC 2019, San Francisco, CA, March 2019.
- C. Shen, M. Yun, A. Arora, & H.-A. Choi, "Dynamic Placement Algorithm for Multiple Classes of Mobile Base Stations in Public Safety Networks," in 2019 EAI International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM), Poznan, Poland, June 2019.
- [‡] C. Liu, C. Shen, J. Chuang, R. A. Rouil, & H.-A. Choi, "Throughput Analysis between Unicast and MBSFN from Link Level to System Level," in 2019 IEEE Vehicular Technology Conference (VTC-Fall), Honolulu, HI, September, 2019.

Project Overview
Accomplishments - Productions

[‡]: In Collaboration with NIST/CTL Researchers

Paper Under Review

- [‡] **S. Feng, H.-A. Choi, D. W. Griffith, & R. A. Rouil, "On Selecting Channel Parameters for Public Safety Network Applications in LTE Direct," under review.**

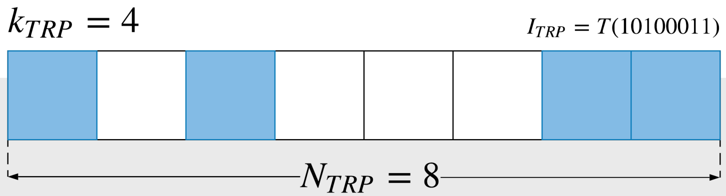
Papers In Progress

- [‡] **S. Feng, C. Shen, C. Liu, R. A. Rouil, & H.-A. Choi, "Optimal Resource Allocation for LTE eMBMS in Priority-Enabled Public Safety Networks," in progress.**
- **S. Feng, & H.-A. Choi, "Multi-hop Direct Communications: from Base Station to Out-of-Coverage UEs through D2D-enabled UE Relay," in progress.**
- [‡] **C. Liu, C. Shen, J. Chuang, R. A. Rouil, & H.-A. Choi, "Evaluating Unicast and MBSFN in Public Safety Networks," in progress.**
- [‡] **S. Feng, H.-A. Choi, C. Liu, & R. A. Rouil, "Performance Analyses of V2X Direct Communications in Public Safety under 4G LTE and Future 5G NR," in progress.**

Task 2: LTE Multicast for Public Safety Networks

- **Task 2.1: Base Station QPP eMBMS**
  - Optimal Resource Allocation for eMBMS
  - Performance Analysis of Unicast/Multicast (in collaboration with NIST/CTL)
- **Task 2.2: Base Station to Off-Network UE Multicast**
  - Multi-hop D2D Communications; (continuation from results of Task 2.3)
- **Task 2.3: UE-to-UE Multicast**
  - On Selecting Channel Parameters to provide QoS for Public Safety Network Applications in LTE Direct

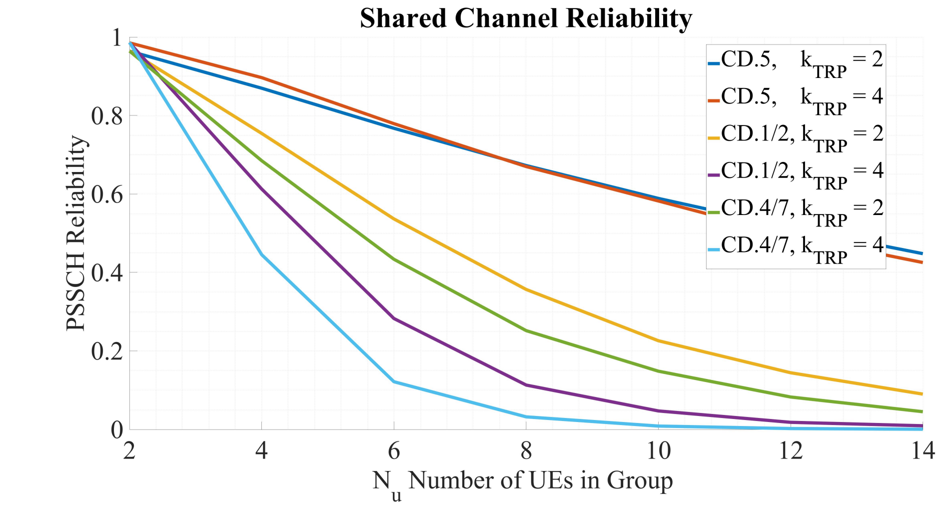
Task 2.3 UE-to-UE Multicast: Channel Parameters of D2D Communication



- Mode 2 Communication of the ProSe (Proximity Services) under LTE Direct
  - D2D communications in Out-of-Coverage areas through Sidelink (SL) channels
    - SL Parameters related to Time-Domain, as well as to Frequency-Domain and Channel Quality
  - User Equipment (UEs) allocate resources autonomously without backhauling
    - Fixed Uniform Parameter Settings base on 3GPP Specification [TS 36.101]

Table A.6.5-1/2 for 10 MHz BW			
Ref. Ch.	Allocated RBs	MCS Index	TB Size
CD.1	10	5	872
CD.2	10	14	2 536
CD.4	50	14	12 960
CD.5	2	10	328
CD.7	50	23	25 456

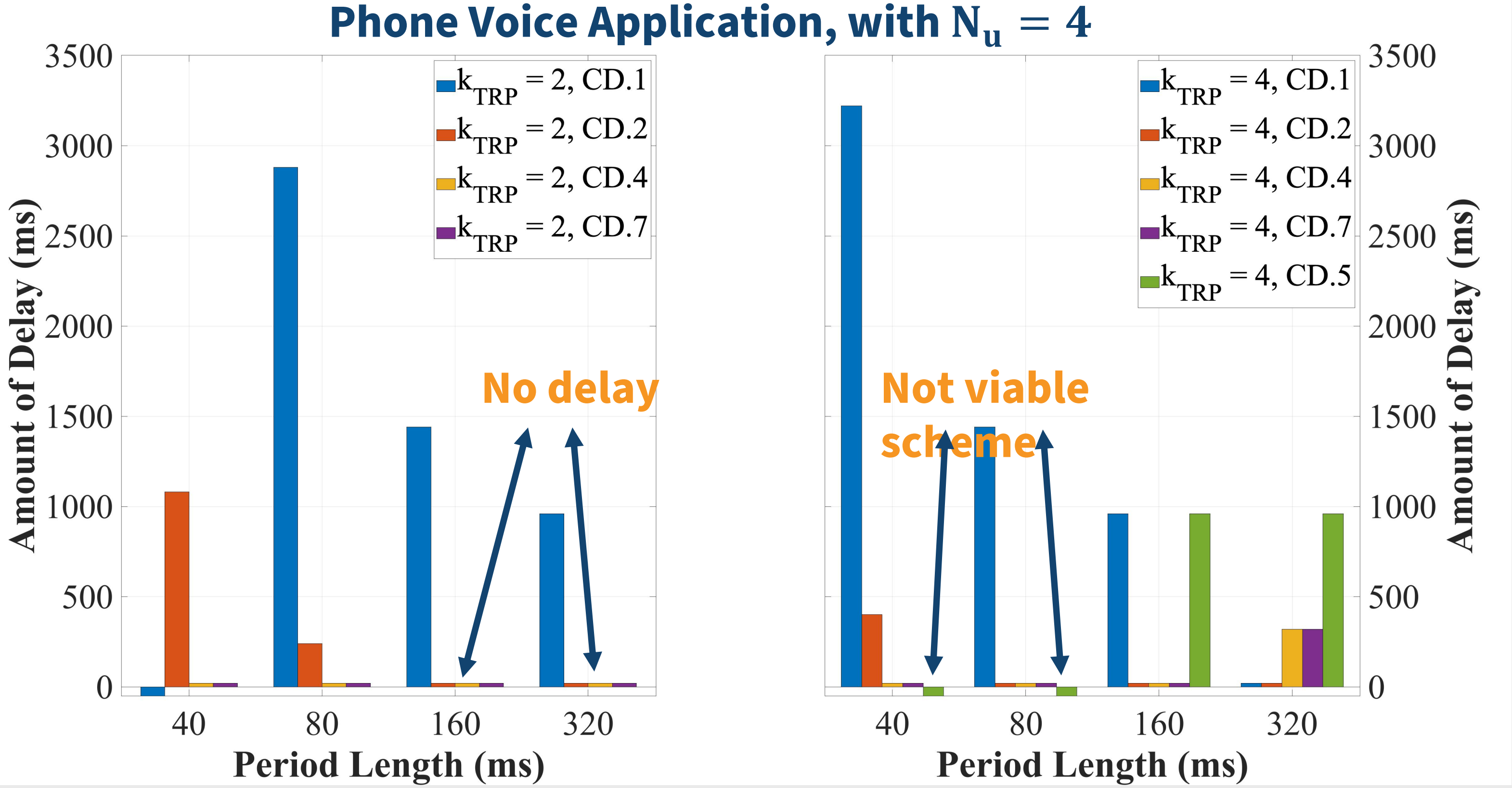
- However, when the number of simultaneous transmissions (broadcasting) increases, the Transmission Reliability, i.e. the likelihood of successful receptions, degrades rapidly.
  - Since there's no centralized coordination, nor 'effective' mechanism to mitigate packet loss, due to competing for resources.



[‡]: D. W. Griffith, E. J. Cintron, and R. A. Rouil, "Physical sidelink control channel (pscch) in mode 2: Performance analysis," in 2017 IEEE International Conference on Communications (ICC), May 2017, pp.

Task 2.3 UE-to-UE Multicast: Channel Parameters of D2D Communication

- **Given: System Parameters and corresponding Transmission Reliability**
- **Consider PSN Application* QoS: to meet Data Rate Requirement, how much Delay should be expected?**



Application Name	DL Demand (b/s)	UL Demand (b/s)
Helmet video	13 576	42 094
Tactical Telemetry	71	775
Biometrics	11,754	11,754
Deployed Camera HQ	20,276	1,142,171
... ...	... ...	... ...
Phone Voice	30,440	30,440
... ...	... ...	... ...
NG911 Video MQ	274,562	18,187
Helicopter Video HQ	1,142,171	20,276
EMS Video	18,023	284,980
Patient Biometrics	13,518	13,518
Satellite Imaginery	288,413	1,127
Building and Utility Plans	1,543,861	4,117
CAD and Telemetry	144,180	45,057

[*]: Televate, LLC & Minnesota Department of Public Safety & NIST CTL, "Public Safety Wireless Data Network Requirements Project Needs Assessment Report Phase 1-Task 4/Deliverable 2."

Channel Parameters of D2D Communication Statement of Problem

- For OOC half-duplex UEs, all within others' proximities, and all transmitting their own data simultaneously
- We focus on a UE of interest (UE-1), who currently has an MCC message with a minimum throughput requirement to disseminate within the group of FRs.
- What is the most efficient approach to fulfill this transmission requirement for UE-1, such that as many other UEs as possible (Coverage) can successfully receive the message within the range of some acceptable amount of delay (Capacity)?
  - Our problem is different from those in related work to better fit PSN scenarios:
    - We focus on a specific MCC UE of interest, instead on a random UE and aggregate throughput.
    - We focus on the Guaranteed Bit Rate to ensure MCC delivery, instead of aggregated throughput of the Best Effort.

Channel Parameters of D2D Communication Results and Impact

- We conduct Monte Carlo simulations, and produced trustworthy results of the Channel Reliabilities of the PSCCH and PSSCH under various system parameter settings and group sizes.

- With the Data Channel Reliability results and different throughput requirement values, we derive the corresponding amount of delays under various system parameter settings and group sizes.

- For the amount of delay results, we generated sets of tables with completeness; hence network operators can setup the channel/RP and UEs accordingly based on delay budget, as well as drafting new delay policies based on our results.

- The parameters can be pre-configured, or be dynamically adopted on the fly.

Task 2.2 Base Station to Off-Network UE Multicast

- **Multi-hop Direct Communications**
  - **Base Station ⟹ On-Network D2D-enabled UE ⟹ Off-Network D2D-enabled UEs**
    - **Downlink Unicast through *Uu* link**
    - **Sidelink Broadcast (through PC5 link) in Direct Mode 4 (or 3)**

- **Utilizes Sidelink methodologies and results from Task 2.3, along with Sidelink Relay specifications from the 3GPP Proximity Services (ProSe) Protocols**
  - **S. Feng, & H.-A. Choi, "Multi-hop Direct Communications: from Base Station to Out-of-Coverage UEs through D2D-enabled UE Relay," in progress.**

Further Discussions

- **V2X as an Extension/Upgrade to D2D**
  - **Stalling of D2D in industrial development; lacking of chipset manufacturers**
  - **Rapid development and active promotion of V2X; more clear and concrete use cases with more vital impacts: ambulance emits signals to vehicles not in Line-of-Sight, and communications via local infrastructures, for instance light poles, and etc.**
  - **Potentially higher Reliability and less Delay ⇒ higher Coverage and Capacity**

- **V2X in 5G NR**
  - **Much more Flexible Frame Structure allowing shorter scheduling period ⇒ faster channel measurement and adaptation, less delay, which is primary for V2X.**
  - **Allowing higher moving speed FR devices and mobile infrastructures to maintain communication reliability.**

Task 1: Intelligent, Dynamic Coverage, Capacity, and Resilience Enhancement

- **Task 1.1: Optimal Placement of Relays and BSs in Off-Networks**
- **Task 1.2: Mobile Relays and Mobile BSs Trajectory Optimization and Scheduling**
- **Task 1.3: Network Resilience: FRs aided by a Mobile BS or Relay**

Intelligent Mobile Base Station Placement Introduction

- **What is Mobile Base Station (mBS)?**

- **Mobile BS is not frequently being used in our normal life. Exceptions can be the big events like live music shows or popular sports games which are predictable and prepared, or the disasters which usually can not be predicted.**

- **The usage of mobile BS in disastrous situations (i.e. in PSNs) is our interest. The following facts need to be always considered while solving the problem of providing wireless communications for PSN.**

Intelligent Mobile Base Station Placement
Specialties of mBS in PSN

- **mBS should be “strong” enough to survive the disaster, which usually makes it sacrifice some performance and convenience.**

- **Quick deployment, setting up the communication quickly can be significant for First Responders (FR).**

- **Performance as good as possible, like serving more FRs, providing more bandwidth, and always put reliability with high priority.**

- **Good algorithms to initialize/deploy them. There is no such problem for constant BS. Since the mobility of mBS, the optimal way to initialize them or even dynamically running them is a new problem in its field.**

Intelligent Mobile Base Station Placement BS Comparisons - per FirstNet.gov - 2016

Characteristic	VNS (Vehicle Network System)	CoLT (Cells on Light Truck)	CoW (Cells on Wheels)	SoW (System on Wheels)	DACA (Deployable Aerial Communications Architecture)
Capacity	Low	Medium	High	High	Low
Coverage	Low	High	High	High	High
Band 14 Radio	Yes	Yes	Yes	Yes	Yes
Standalone	Yes	No	No	Yes	No
Availability	Immediately	Drive Time	Drive Time	Drive Time	Launch Time
Power	Vehicle Batteries	Generator	Generator	Generator	Airframe

Intelligent Mobile Base Station Placement BS Comparisons - per FirstNet.gov - 2016

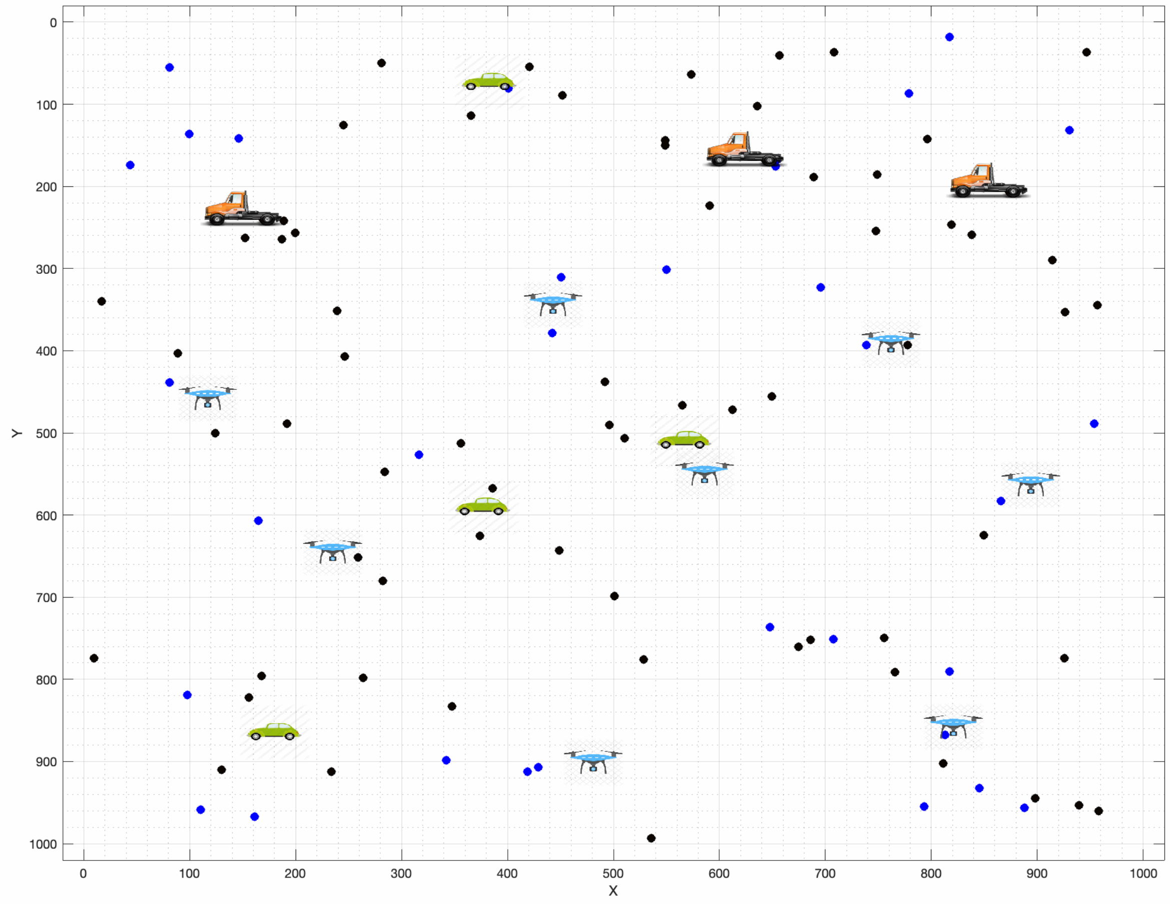
Characteristic	VNS (Vehicle Network System)	CoLT (Cells on Light Truck)	CoW (Cells on Wheels)	SoW (System on Wheels)	DACA (Deployable Aerial Communications Architecture)
Deployment Time	Zero	Medium	Medium	Long	Long
Incident Duration	Low	Medium	Medium	Long	Long
Physical Nature	FR Vehicle	Dedicated Truck	Dedicated Trailer	Dedicated Trailer	Aerial
Typical Number	Thousands	Hundreds	Hundreds	Dozens	Not Yet Used

Intelligent Mobile Base Station Placement UE (FR) Mobility Models

1. **Random Destination Point Oriented**
2. **Random Direction with Bound Oriented**
3. **Leader Direction Oriented, with Leaders using Random Direction with Bound**
4. **(Point of Interest) POI Location Oriented**

- **UE moves very fast in the demo for better visual effect.**
- **Pause behaviors may be introduced later.**

1. Random Destination Point Oriented

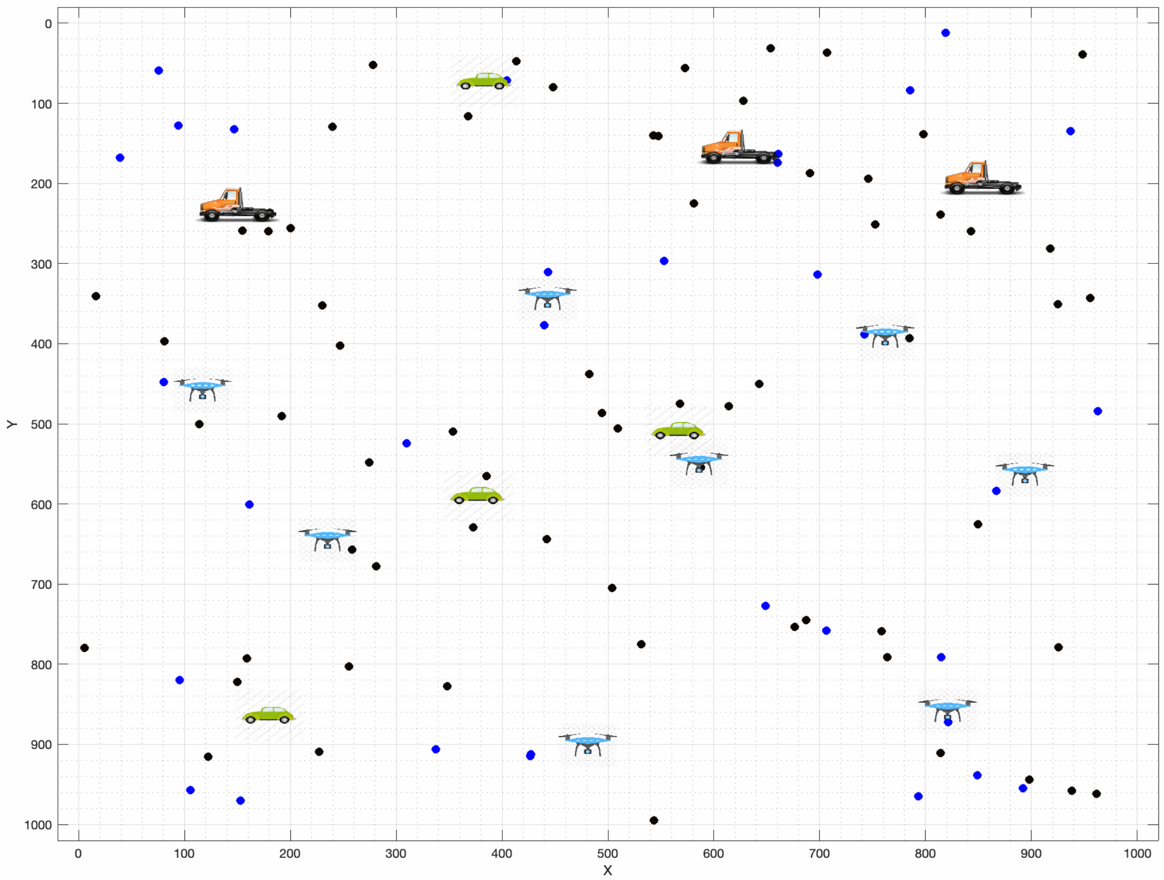


UE randomly selects a destination and then move towards it in a straight line.

After reaching the destination, another one is randomly selected.

- **Trucks: System on Wheels (SoW)**
- **Automobiles: Cells on Wheels (CoW)**
- **Drones: Deployable Aerial Communications Architecture (DACA)**

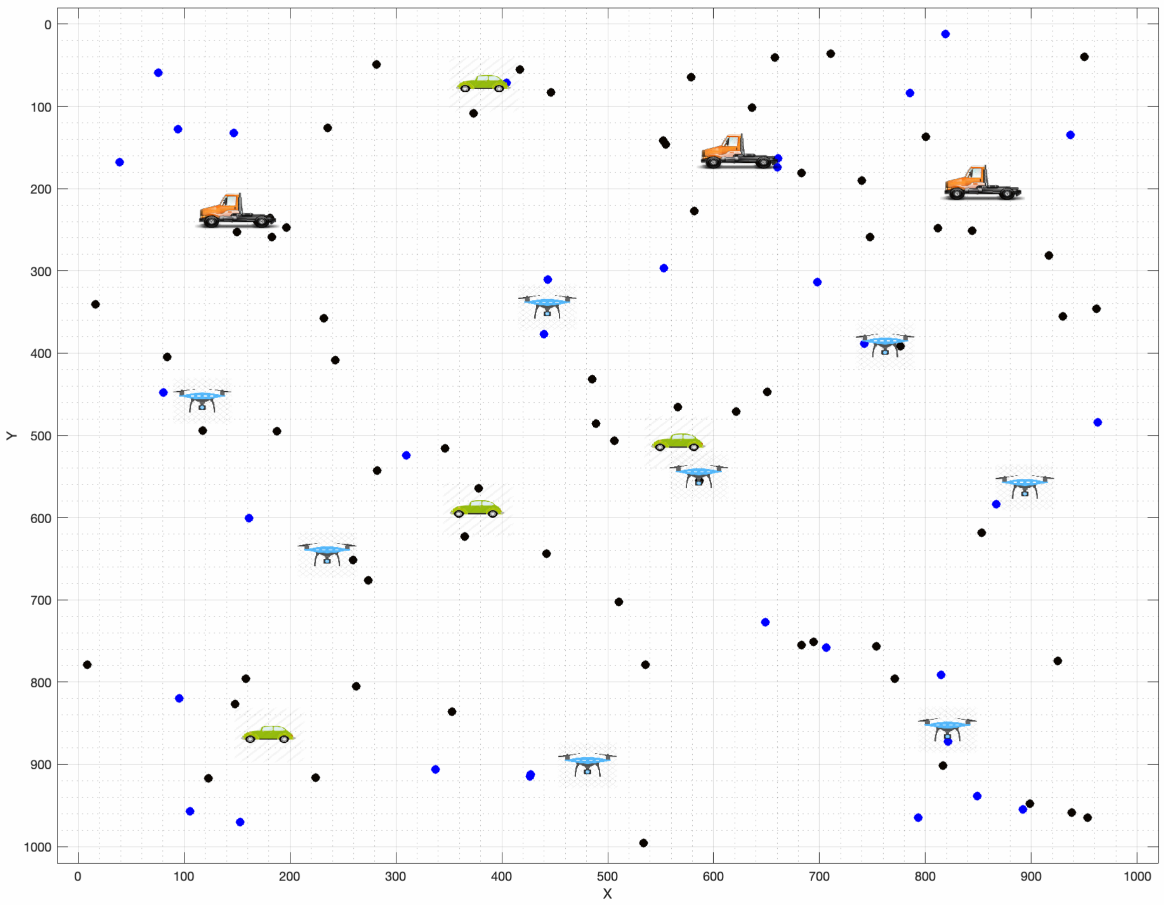
2. Random Direction with Bound Oriented



UE randomly selects a direction within a range based on its current direction, and moves a single step.

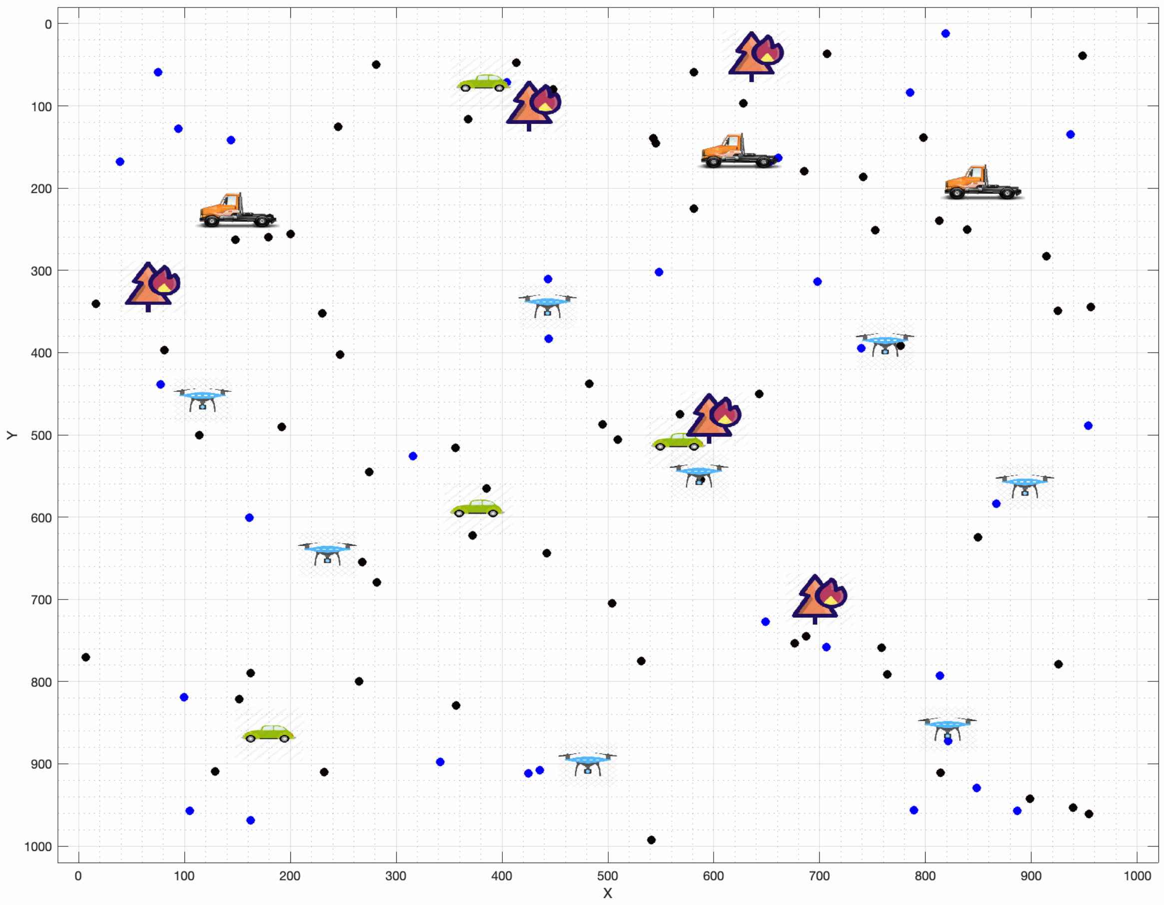
Then, another direction is randomly selected and moves again.

3. Leader Direction Oriented, with Leaders using Random Direction with Bound



The blue dots represent group leaders, who have higher priorities than the black dots, i.e. regular group members.

4. (Point of Interest) POI Location Oriented



- **Fire Disaster Locations: Point of Interest Locations**

Intelligent Mobile Base Station Placement Related Work

- For mobile base station deployment (PSN oriented or not), there are many works in this field. Most of them focus on drone based mBS only.
- The problem modeling is also very diverse. Some assume drone always moves with a constant speed. Some assume drone with MIMO capability and that its configuration can be optimized dynamically, etc.
- Algorithm can be brute force (location problem can be NP-hard) or game theory based (no coordination.)

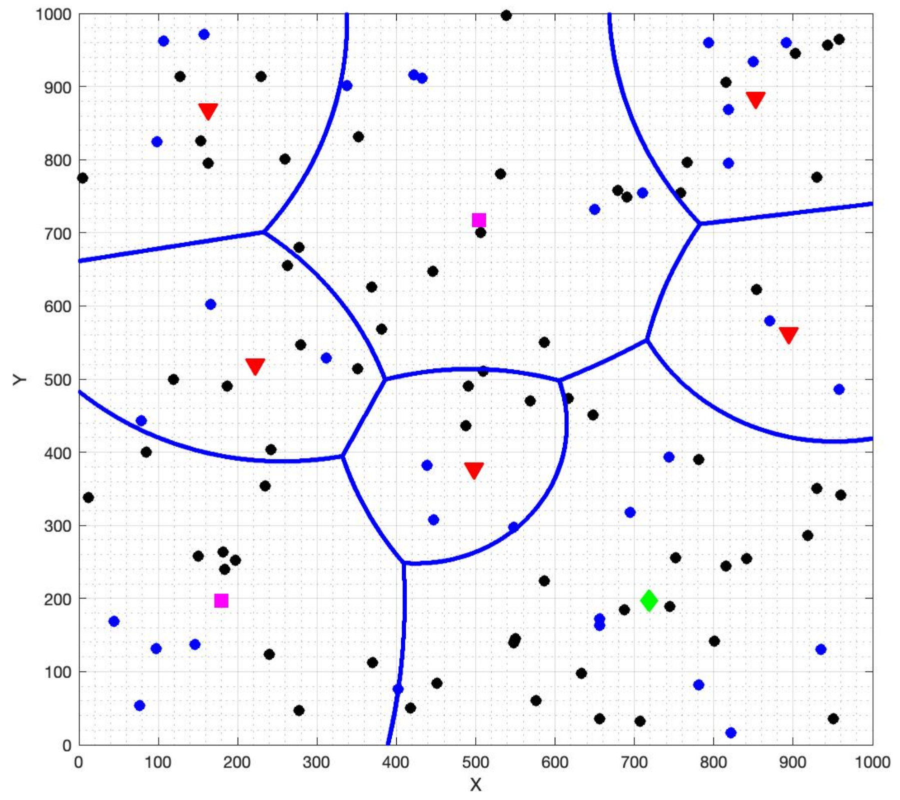
Dynamic Heterogeneous mBS Deployment Algorithm

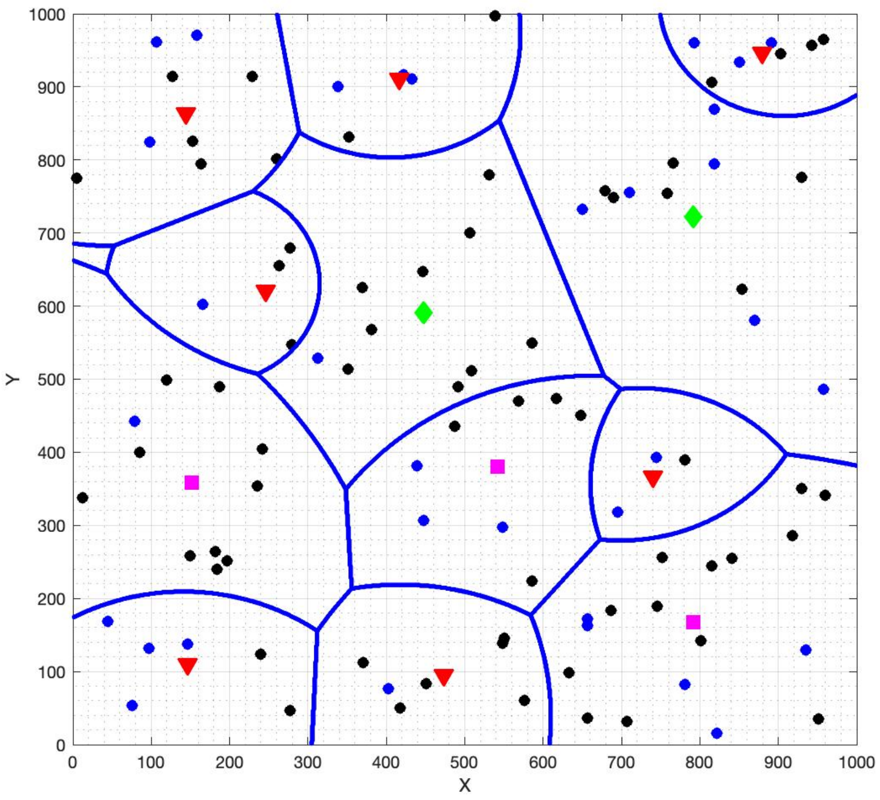
- **The mBS are deployed with centralized control.**
- **Different types of mBS have been researched and 3 are modeled in our simulation.**
- **Multiple UE mobility models have implementation for dynamic deployment performance analysis.**

Intelligent Mobile Base Station Placement System Model and Performance Metric

mBS Class	Drone	CoW	SoW
Capacity Weights	1	1.5	2
Recalculation Period (multiples of 10 seconds)	1	30	90
Relocation Threshold (meters)	1	30	50
Height (meters)	30	10	10
Transmit Power (watts)	20	30	40

Intelligent Mobile Base Station Placement
Results of Placement Algorithms





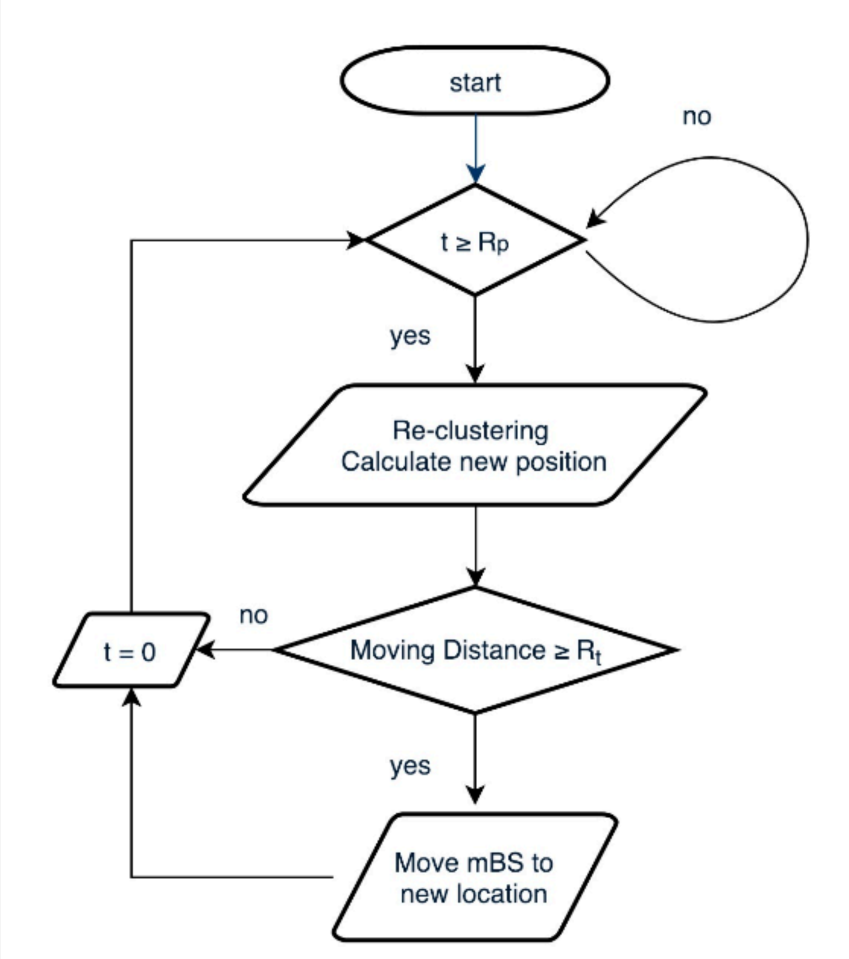
Blue and black dots represent UEs, where blue ones are leaders in leading UE mobility model. Drones, CoW and SoW are presented as Red Triangles, Magenta Squares, and Green diamonds, respectively.

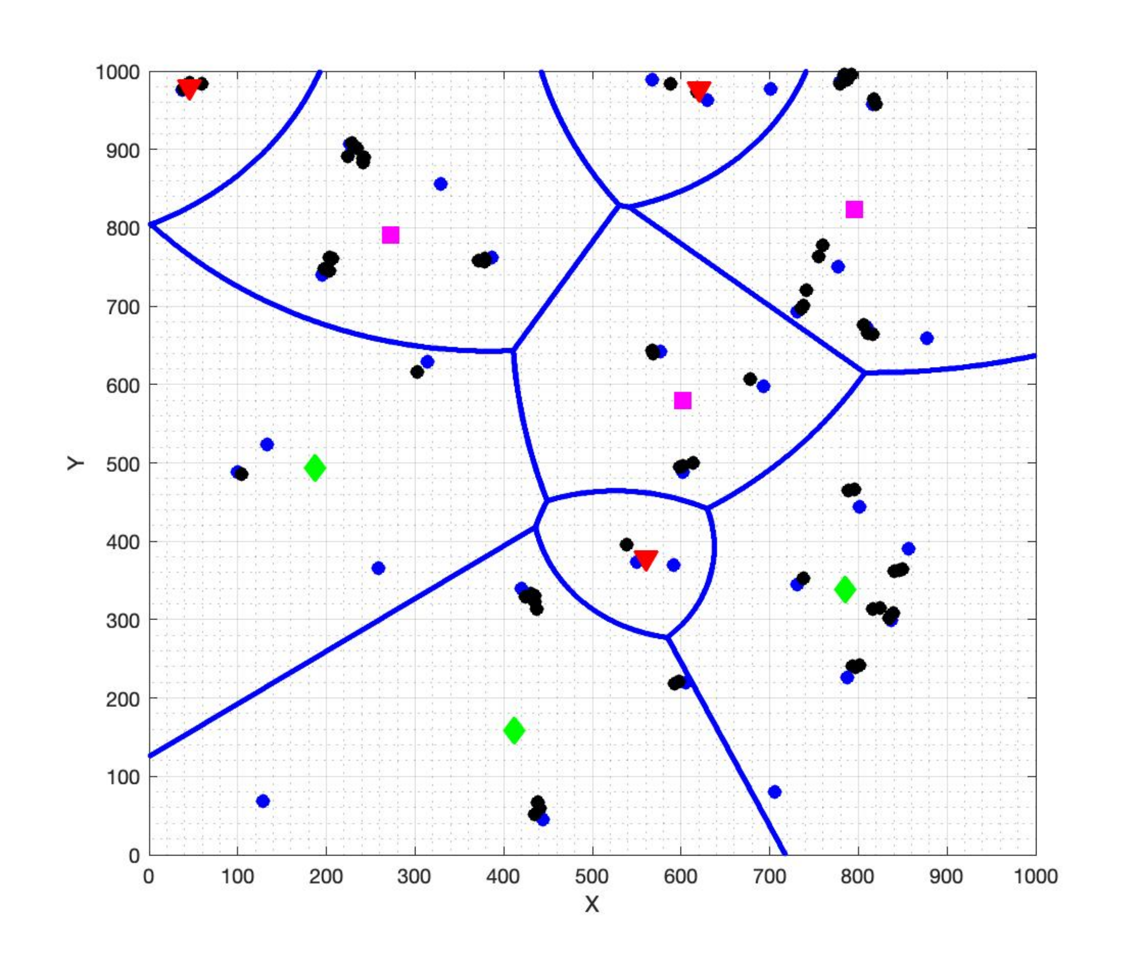
Intelligent Mobile Base Station Placement Algorithm 1

Algorithm 1: Static UE Clustering with Different Mobile Base Station Capacities

Initial mBSs placement;
iter = 1;
while *iter* $<$ *MAX_ITER* **do**
  for $i = 0; i < N_B; i = i + 1$ **do**
    num_UE = 0;
    X = 0;
    Y = 0;
    for $j = 0; j < N_U; j = j + 1$ **do**
      if $U_j \in B_i$ **then**
        $num\_UE = num\_UE + 1$;
        $X = X + U_j.x$;
        $Y = Y + U_j.y$;
      end
    end
    $B_i.x = X \div num\_UE$;
    $B_i.y = Y \div num\_UE$;
  end
  Affiliate UE to mBS in the following loops;
  for $j = 0; j < N_U; j = j + 1$ **do**
    $min_{dist} = Inf$;
    for $i = 0; i < N_B; i = i + 1$ **do**
      $dist = \sqrt{(U_j.x - B_i.x)^2 + (U_j.y - B_i.y)^2}$;
      $dist_w = dist \div B_i.C_w$;
      if $dist_w < min_{dist}$ **then**
        $min_{dist} = dist_w$;
        $U_j.B_{id} = i$;
      end
    end
  end
  iter = iter + 1 ;
end

Intelligent Mobile Base Station Placement Flowchart of Periodical Recalculation of mBS



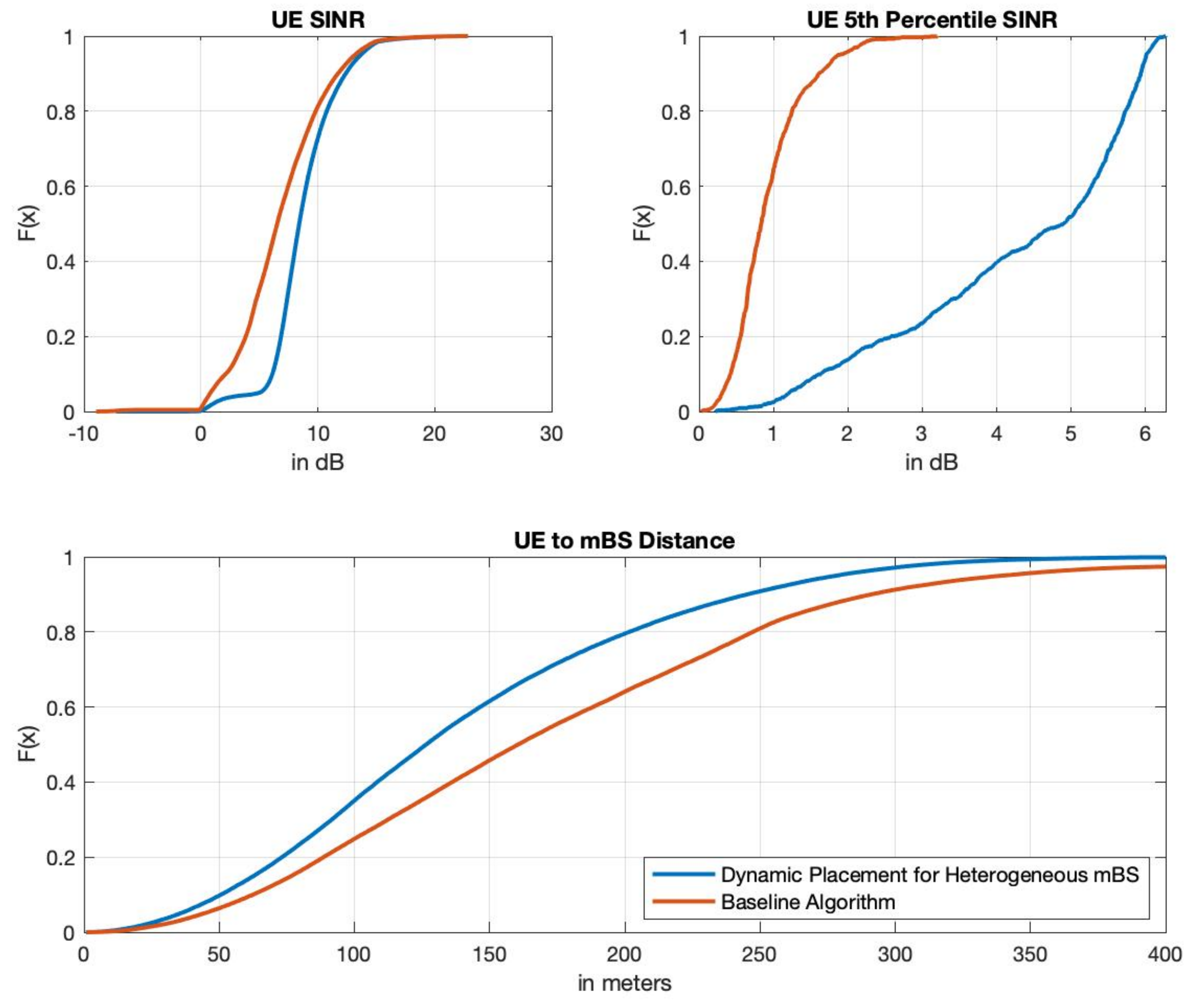


Intelligent Mobile Base Station Placement Empirical Result

- **The results are analyzed with four mobility models and four deployments**
  - **Deployment 1 – 5 Drones, 2 CoWs, 1 SoW (Heterogeneous)**
  - **Deployment 2 – 10 Drones Only**
  - **Deployment 3 – 5 Cells on Wheels Only**
  - **Deployment 4 – 3 System on Wheels Only**

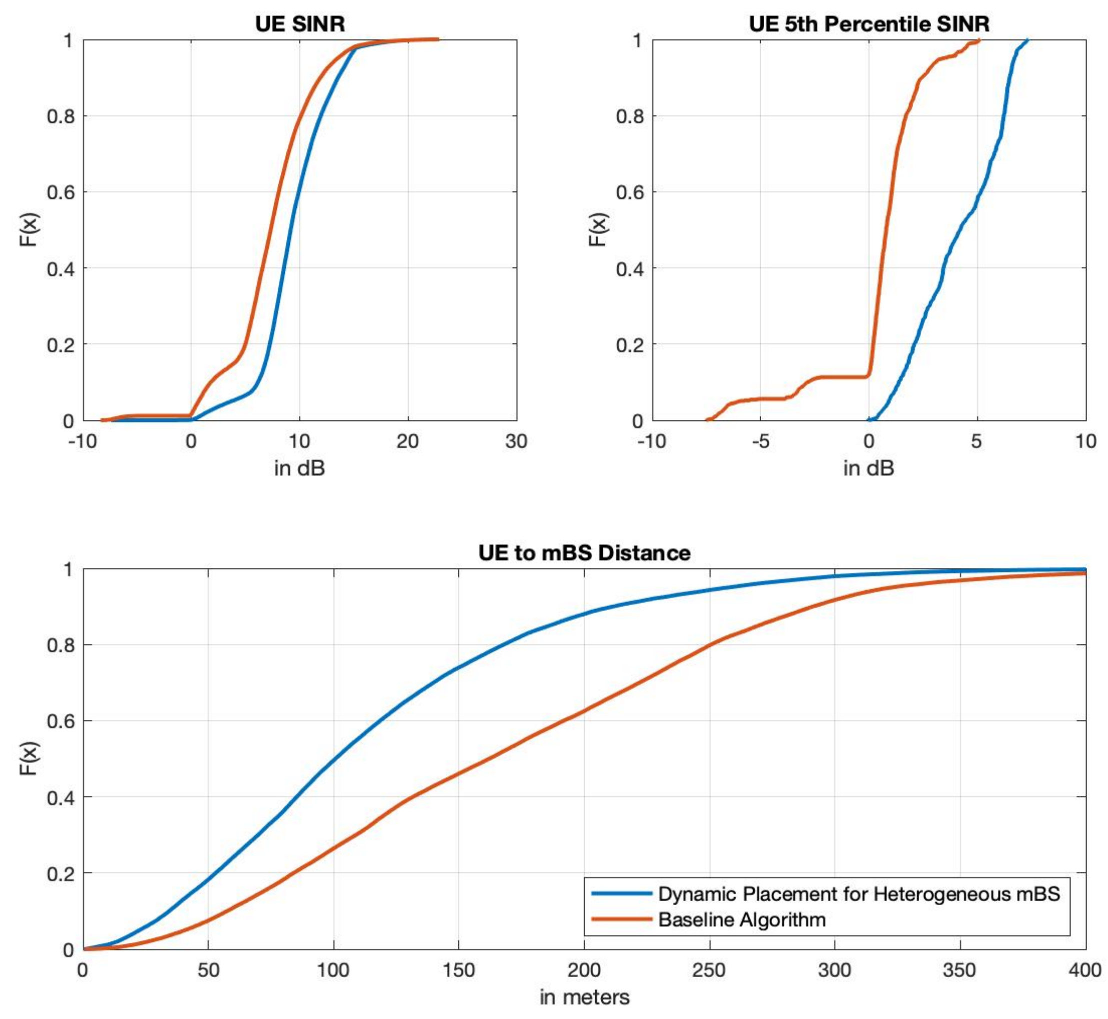
- **The baseline algorithm used as comparison uses the same set of mBS with stationary and regular placement.**

Intelligent Mobile Base Station Placement Comparisons with Baseline Method



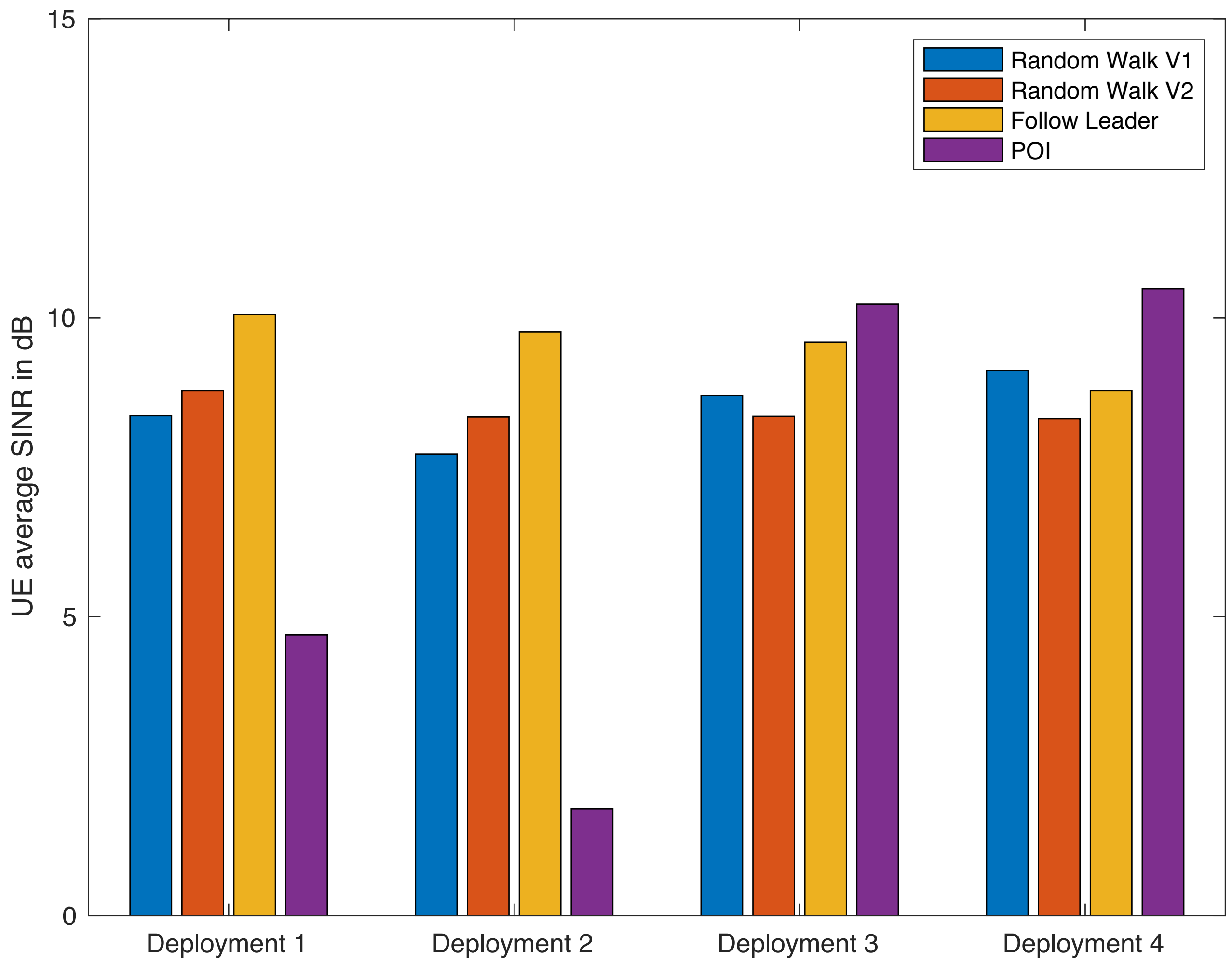
- **Random Walk V2**
- **Deployment 1:**
  - **5 Drones, 2 CoWs, 1 SoW**

Intelligent Mobile Base Station Placement Comparisons with Baseline Method



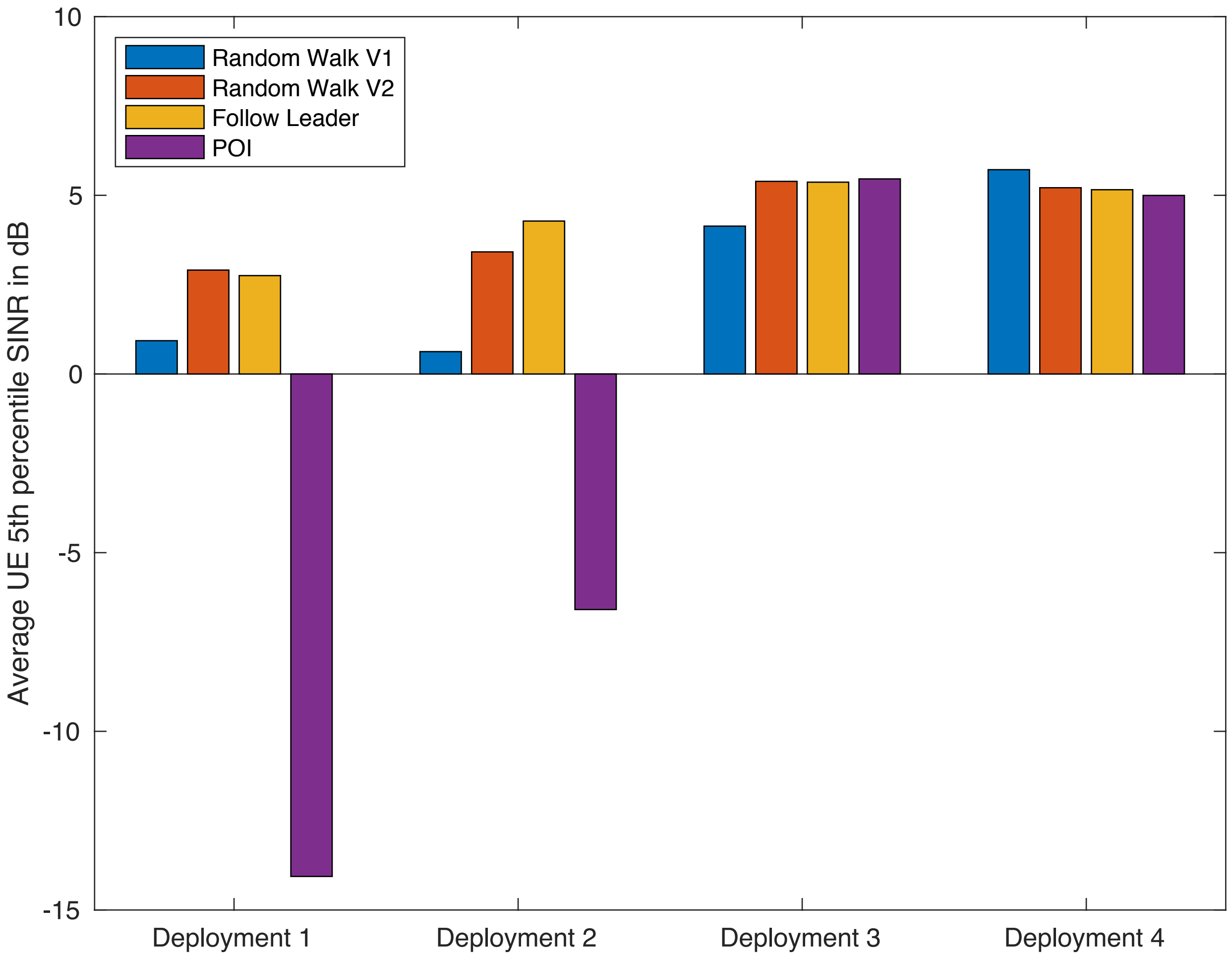
- **Follow Leader**
- **Deployment 1:**
  - **5 Drones, 2 CoWs, 1 SoW**

Intelligent Mobile Base Station Placement UE SINR



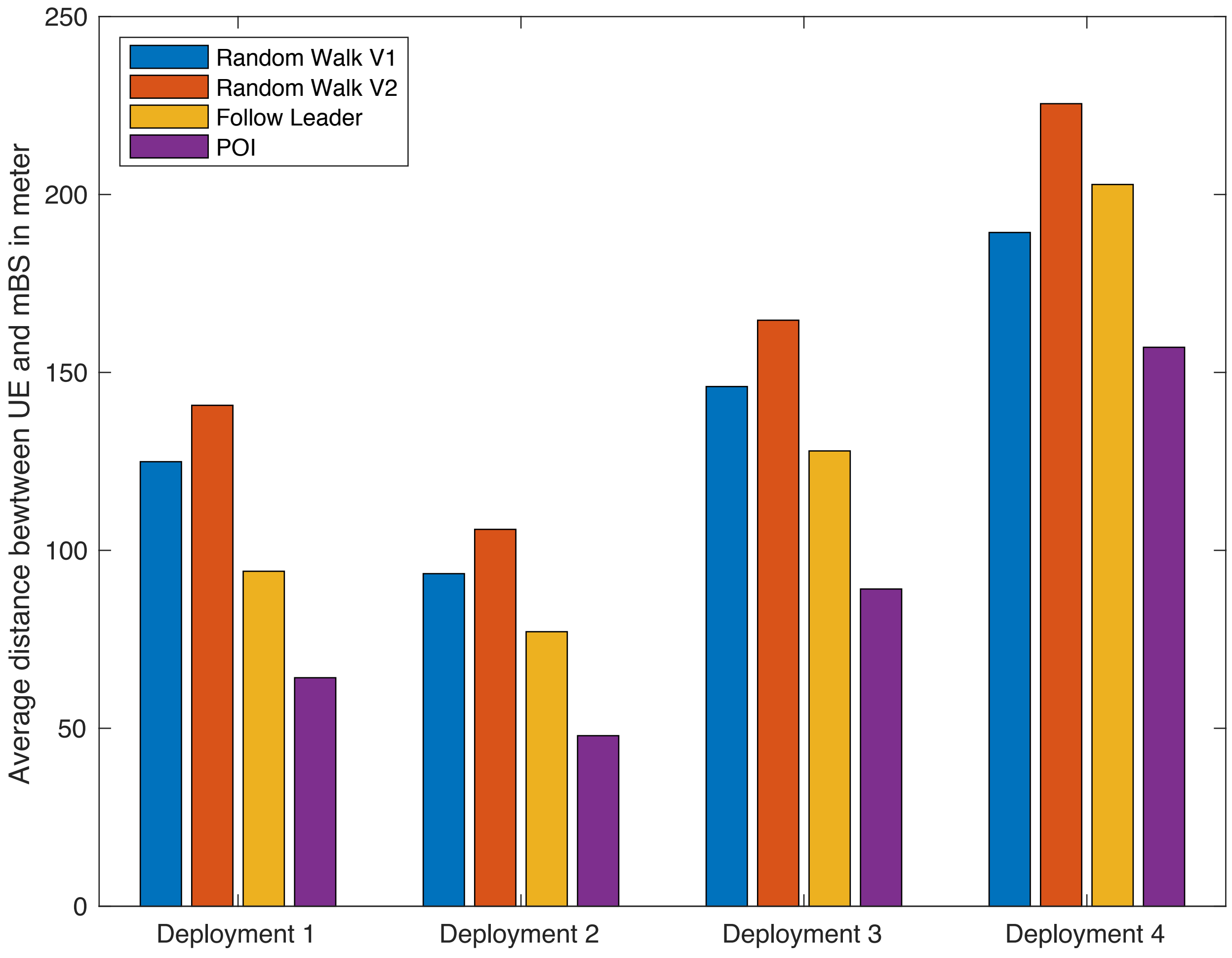
High capacity mBS classes, such as CoW and SoW, with POI model dominate the SINR performance.

Intelligent Mobile Base Station Placement
UE 5th Percentile SINR - at Cell Edge



Similar conclusion can be drawn for the POI model. But due to the high flexibility of drones, Deployment 2 with drones only outperforms the mixed scenarios of Deployment 1.

Intelligent Mobile Base Station Placement
UE to mBS Distance



The drone mBS with better moving flexibility outperformances others in the distance metrics.

Further Discussions

- **In the reality, each kind of mBS should be associated with corresponding cost in operation, which is not considered in our current work.**

- **In that case, the optimal deployment should depend on the "budget" or the mBS' availability in each kind, and the disaster's property.**

- **The disaster scenario and the communication requirements from FRs can vary drastically over time, which is not considered in our current work.**

- **For example, in the POI model, the point of interest can move due to the disaster's changing or other factors.**

- **The simulation result could provide a sight of basic understanding on various deployments and disaster situation.**

Further Discussions

- **Utilizing V2X Communications in mBS Placement**
  - **Vehicular systems (V) as the mBS, and the FR UEs as the Device (X)**
  - **Autonomous mBS Placement through both V2D and V2V direct communications**
  - **Off-Load Network, as well as enabling Off-Network Deployment, by coordinating surrounding UEs' communications**

Conclusion

Project Summary

During the past two years, we have achieved the following goals of this project:

- Delivered several related technical reports, and publications completed (some in collaboration with NIST/CTL researchers);
- Achieved most of the proposed tasks with their corresponding milestones and deliverables. Overall, we have completed about 97% of the proposed research of this project.

In Progress

During the remaining project period, we will be focusing on finishing the following items:

- Completion of Task 2.2: “Multi-hop Direct Communications: from Base Station to Out-of-Coverage UEs through D2D-enabled UE Relay” (based on results of Task 2.3);
- Completion of more publications;
- Completion of the final report.

Q & A

THANK YOU

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Come back for the

Next Session

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