РЕПУБЛИКА БЪЛГАРИЯ
МИНИСТЕРСТВО НА ОБРАЗОВАНИЕТО И НАУКАТА
ИЗПЪЛНИТЕЛНА АГЕНЦИЯ
"ПРОГРАМА ЗА ОБРАЗОВАНИЕ"

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Using Drones for Enhanced Communications in Cases of Emergency

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Presentation Outline

- Introduction
- Comparison of Drone-based Communication to Traditional Communication
- Drone Deployment in Cases of Emergency
- Technologies for Drone-based Messaging
- Smart Algorithms for Drone Operation
- Drone Integration with Satellite Communication Systems
- A2G Communication Models and Technical Foundations
- Country Case Studies
- Urban vs Rural Adaptations
- Future Trends in Drone-based Communication in Cases of Emergency
- Conclusion

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INTRODUCTION

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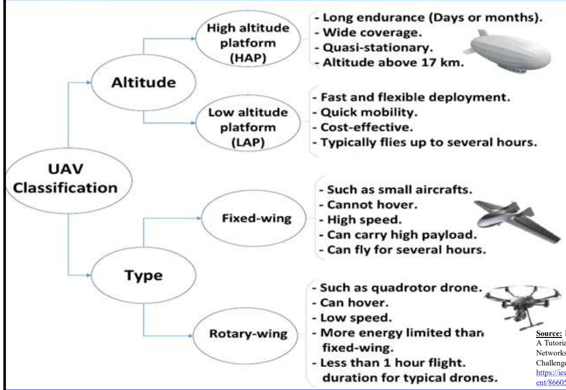
Introduction: UAV Classification



Source: MOZAFFARI et al.: A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems. https://ieeexplore.ieee.org/document/8660516

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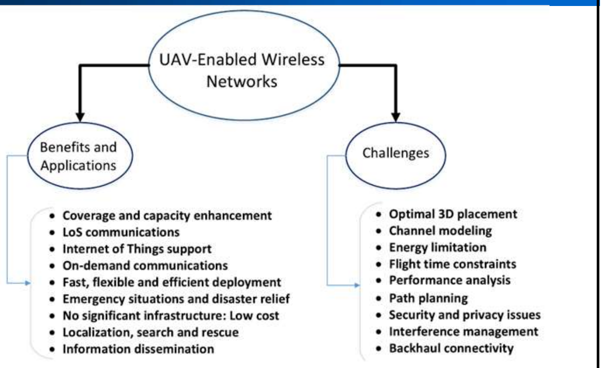
Introduction: UAV-enabled Networks



Source: MOZAFFARI et al.: A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems. https://ieeexplore.ieee.org/document/8660516

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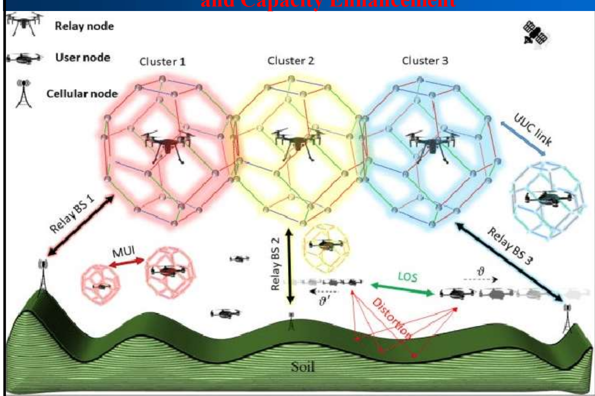
Introduction: Using Drones for Communication Coverage and Capacity Enhancement



Source: HOSSEINI et al.: UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems.

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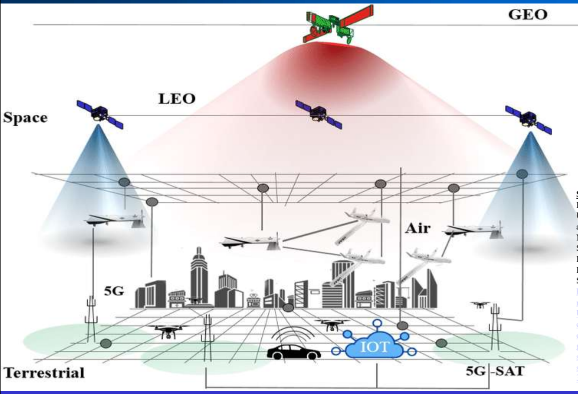
Introduction: Using Drones for IoT support



Source: HOSSEINI et al.: UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems. https://www.researchgate.net/figure/UAV-communication-entities-including-ground-air-and-space-segments_fig1_333919084

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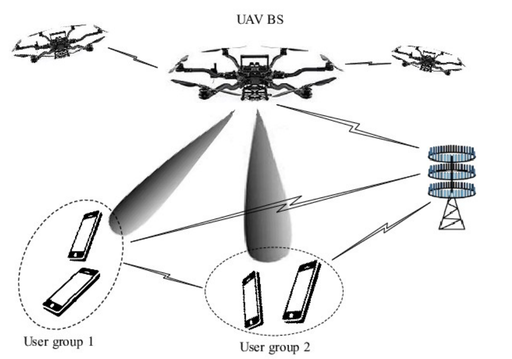
Introduction: Using Drones for On-demand Communications



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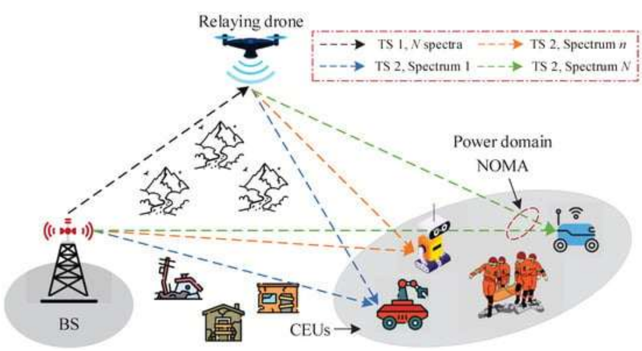
Introduction: Using Drones for Disaster Relief



Source: LI et al.: Post-Disaster Emergency Communications Enhanced by Drones and Non-Orthogonal Multiple Access: Three-Dimensional Deployment Optimization and Spectrum Allocation. https://www.mdpi.com/2504-446X/8/2/63

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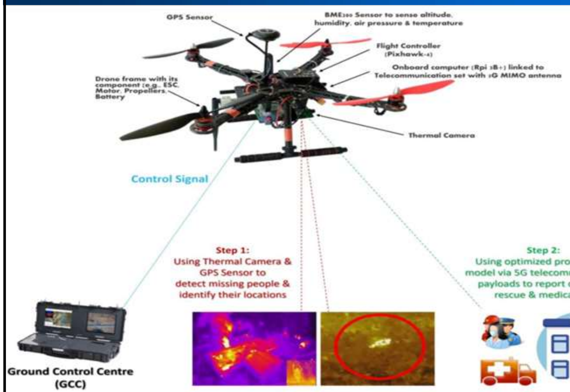
Introduction: Using Drones for Localization, Search and Rescue



Source: ALMALKI et al.: Drones, Smartphones and Modifying Hata-Davidson Propagation Model for Remote Sensing in Complex Environments Using a Multifactional Drone. https://www.researchgate.net/figure/Proposed-structure-of-a-drone-for-use-in-search-and-rescue-operations_fig2_338850033

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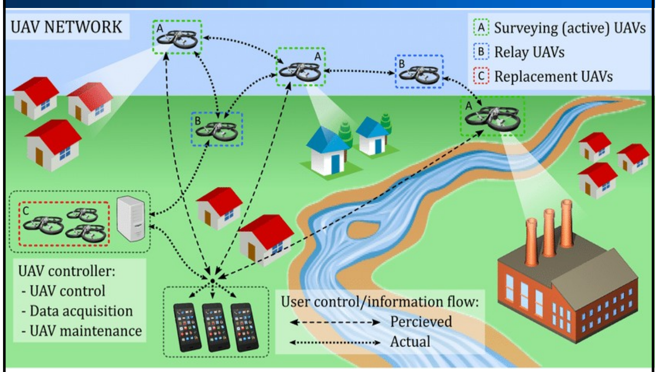
Introduction: Using Drones for Information Dissemination



Source: ERDELJ et al.: Drones, Smartphones and Sensors to Face Natural Disasters. https://www.researchgate.net/figure/UAV-network-used-for-surveillance-and-communication-support_fig1_325335622

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Comparison of Drone-based Communication to Traditional Communication

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Traditional Communication Methods

- E.g., using terrestrial radio, mobile cell towers, emergency broadcast TV.
- Vulnerable to:
  - ➢ Ground infrastructure collapse (damaged towers, downed power lines)
  - ➢ Inflexibility in targeting affected areas
  - ➢ Delayed deployment/repair times
  - ➢ Limited reach into remote, mountainous, or inundated regions.

Advantages of Drone-based Approaches

- Speed of deployment (minutes versus hours or days)
- Spatial flexibility allowing communication in isolated or inaccessible areas
- Redundancy through combined loudspeakers, displays, Bluetooth/Wi-Fi/cellular/satellite communication modules, ensuring at least one channel reaches most recipients
- Direct integration with real-time data collection (for damage assessment, crowd location, rescue coordination)
- Lower operational costs and risk than crewed aircraft or redeploying ground infrastructure

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Limitations of Drone-based Approaches (1)

- Weather sensitivity
  - Severe weather (e.g., strong wind, precipitation, or poor visibility) can ground even rugged drones
  - Constraining reliable window for extended communication
  - Median global "flyability" often below that of weather-resistant ground systems
- Battery life, payload and range constraints
  - The heavier the communication equipment, the shorter the drone's operational range and endurance.
  - Energy solutions (advanced batteries, solar) under investigation to extend flight duration

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Limitations of Drone-based Approaches (2)

- Signal interference and jamming
  - In some emergencies—especially those overlapping with conflict or electronic warfare—drones may suffer from jamming or deliberate interference
  - Robust anti-jamming protocols and frequency agility required
- User comprehension
  - In extremely noisy environments or under panic, even high-decibel announcements may not be understood
  - Visual displays help but are not always sufficient for all population groups
- Personnel training
  - Effective drone operation hinges on skilled operators or the availability of completely autonomous, reliable systems.
  - Persistent organizational challenge

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Drone Deployment in Cases of Emergency

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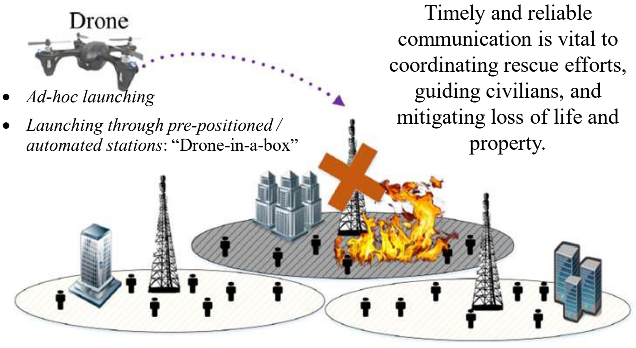
Drone Deployment: Single-drone Approach



- *Ad-hoc launching*
- *Launching through pre-positioned / automated stations*: "Drone-in-a-box"

Timely and reliable communication is vital to coordinating rescue efforts, guiding civilians, and mitigating loss of life and property.

Source: MOZAFFARI et al.: A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems. https://ieeexplore.ieee.org/document/8660516

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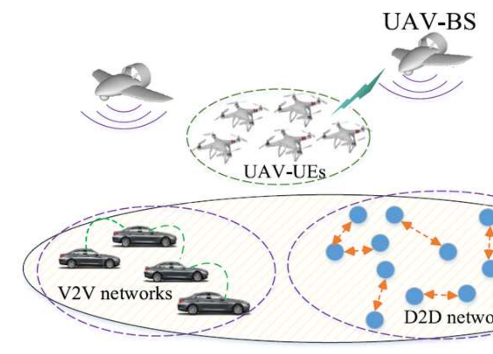
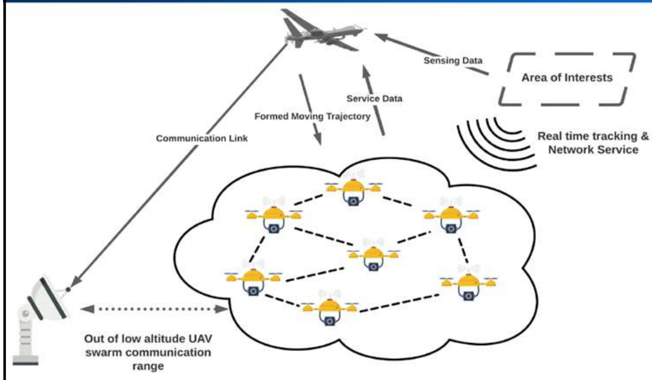
Drone Deployment: Clustered-drone Approach



- *Resilience to failure*
- *Scalability*
- *Low latency*
- *Multiple tiers possible (1 UAV-BS + multiple UAV-relays)*

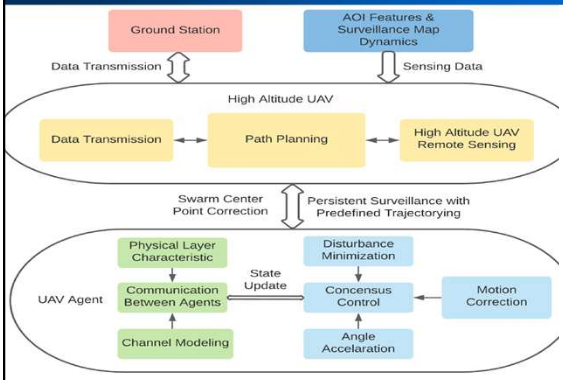
Source: MOZAFFARI et al.: A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems. https://ieeexplore.ieee.org/document/8660516

Drone Deployment: Hierarchical Swarm



Source: XU et al.: Communication Aware UAV Swarm Surveillance Based on Hierarchical Architecture. https://www.mdpi.com/2504-446X/5/2/33

Drone Deployment: Swarm Operation



Game-theory and ML algorithms, e.g., federated (deep) reinforcement learning (D/RL), are used for trajectory, coverage, cooperation, and interference management as to maximize comm. range and reliability.

Source: XU et al.: Communication Aware UAV Swarm Surveillance Based on Hierarchical Architecture. https://www.mdpi.com/2504-446X/5/2/33

Drone Swarm Operation: Scanning and Coverage

- To maximize message reach, scanning strategies are used where drone fleets follow preassigned or dynamically computed paths—either grid-based, sweep-line, or region-dividing methods—to ensure comprehensive and overlapping area coverage
- Advanced region scanning algorithms consider:
  - ➢ The number and positions of drones
  - ➢ Topographical obstacles (mountains, buildings)
  - ➢ Predicted crowd/equipment locations and movement
  - ➢ Real-time connectivity assessment
- Simulation studies and real-life experiments demonstrate that ***collaborative*** drone missions markedly improve the speed and completeness of emergency communication, compared to isolated single-drone missions.

Technologies for UAV-based Information Dissemination

- Bluetooth Broadcasting via Drones
- Wi-Fi Broadcasting via Drones
- Cellular-Enabled Drones
- Digital Display-Equipped Drone Messaging
- Loudspeaker-Based Drone Broadcasting

MEPI

Background: Bluetooth

- ❑ Wireless communication standard used for exchanging data over short distances using radio waves.
- ❑ Enables devices like smartphones, laptops, headphones, and speakers to connect and communicate without the need for cables.
  - ✓ Frequency band: 2.4 GHz ISM
  - ✓ Range:
    - Class 1: Up to 100m (up to **400m** with Bluetooth Low Energy, BLE)
    - Class 2: Up to 10m (most common in mobile devices)
    - Class 3: Up to 1m
  - ✓ Data rates:
    - Bluetooth 1.2: Up to 1 Mbps
    - Bluetooth 2.0 + EDR: Up to 3 Mbps
    - Bluetooth 3.0 + HS: Up to 24 Mbps (using an alternate 802.11 link)
    - Bluetooth 4.0: Up to 1 Mbps (optimized for low energy consumption)
    - Bluetooth 5.0 and later: Up to 2 Mbps, with improved range and speed
  - ✓ Network topology: Piconets, consisting of one master device and up to seven active slave devices. Multiple piconets can form a scatternet.
  - ✓ Security: Pairing, encryption, and authentication to protect data during transmission
- ❑ Commonly used for hands-free calling, wireless audio streaming, and file transfers. Its low power consumption makes it ideal for portable devices.

Bluetooth®

Developed by	Bluetooth Special Interest Group
Introduced	7 May 1998
Industry	Personal area networks

Background: Wi-Fi

- Wireless communication technology that allows devices like computers, smartphones, and tablets to connect to the Internet and communicate with each other without the need for physical cables. Uses radio waves to transmit data over short to medium distances.
  - ✓ Standards: IEEE 802.11 family, e.g.,:
    - 802.11n: Operates on both 2.4 GHz and 5 GHz bands, with speeds up to 600 Mbps.
    - 802.11ac (Wi-Fi 5): Operates on the 5 GHz band, with speeds up to 3.5 Gbps.
    - 802.11ax (Wi-Fi 6): Operates on 2.4 GHz, 5 GHz, and 6 GHz bands, with speeds up to 9.6 Gbps.
    - 802.11 (Wi-Fi 7): Operates on 2.4 GHz, 5 GHz, and 6 GHz bands, with speeds up to 46 Gbps.
  - ✓ Range:
    - Indoors: Typically, up to 30 meters.
    - Outdoors: Can extend up to 150+ meters (and up to **3 km** with Wi-Fi HaLow/IEEE 802.11ah operating in the sub-1GHz unlicensed band).
  - ✓ Security:
    - WEP (Wired Equivalent Privacy): An older, less secure protocol.
    - WPA (Wi-Fi Protected Access) and WPA2: More secure protocols that use stronger encryption methods.
    - WPA3: The latest security protocol, offering enhanced protection against brute-force attacks and improved encryption.
  - ✓ Network Topology: star/mesh (*physical*) / bus (*logical*)

Introduced 21 September 1997

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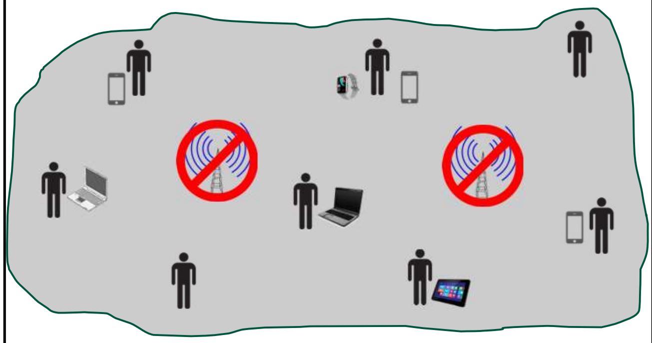
MEPI: Operational Model (1)



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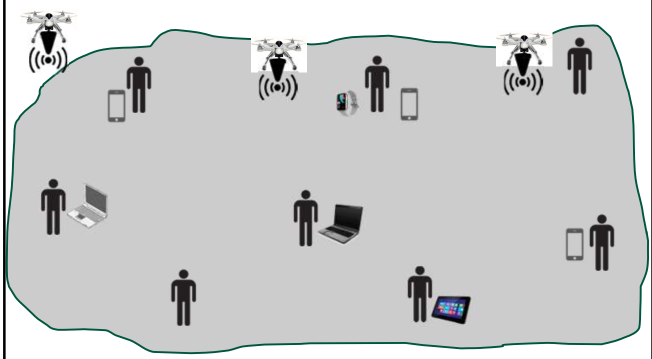
MEPI: Operational Model (2)



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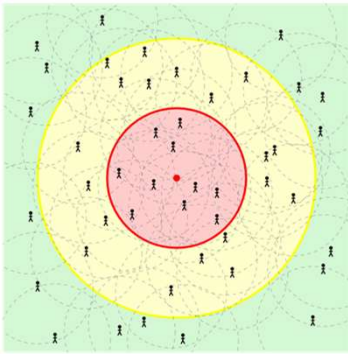
MEPI: Message Spreading by App (1)



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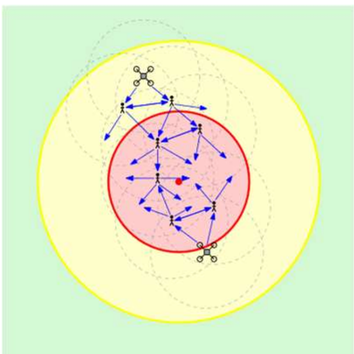
MEPI: Message Spreading by App (2)



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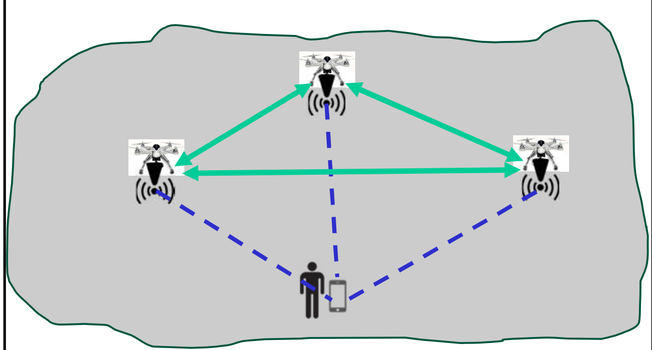
MEPI: User Location Determination (1)



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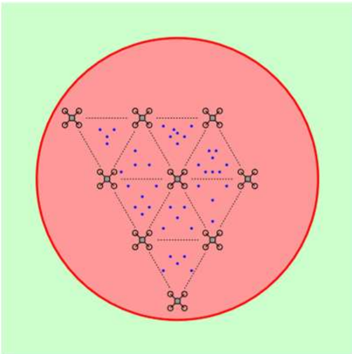
MEPI: User Location Determination (2)



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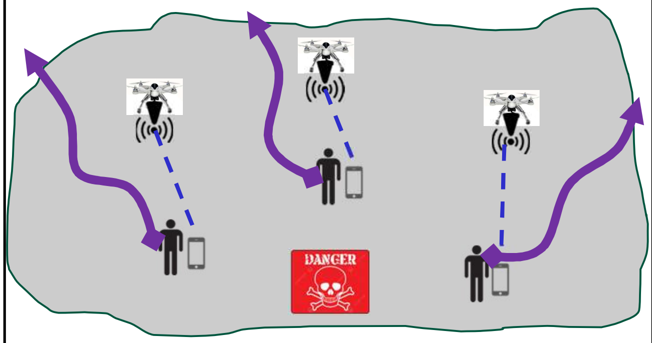
MEPI: Personalized Evacuation Routes Recommendation



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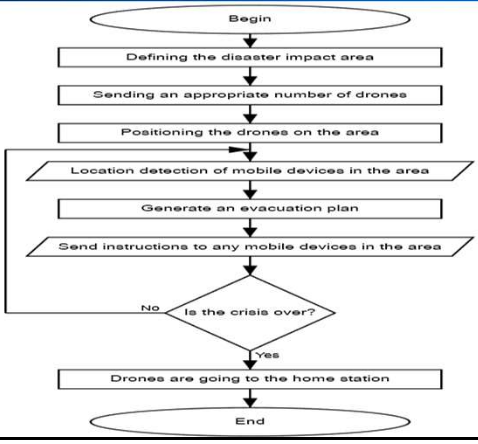
MEPI: Operational Diagram



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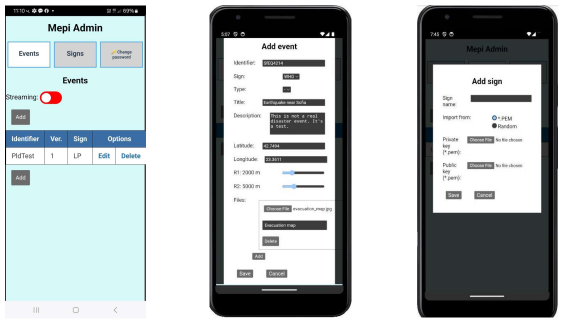
ICT System: MEPI App



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Cellular-Enabled Drones

3GPP:

- Release 15: LTE support for UAVs/drones, e.g., enhanced measurement reporting of UAV height, location, and speed, signaling support for subscription-based aerial user equipment (UE) identification, and flight path reporting.
- Release 17: added UAV identification, authentication, authorization, and tracking, and requirements for security and public safety.
- Release 18: improved UAV coexistence with terrestrial UEs, expanded the use of UAVs in new use cases and application scenarios, enabled UAVs to use beamforming and radio measurement reports, and provided mobility and interference mitigation enhancements allowing UAV smooth integration into the existing 5G New Radio (NR) networks.
- Release 19: introduced "NR sidelink multi-hop relay" targeting the support of up to 2 additional relay hops beyond the single-hop scenario (i.e., remote UE → relay UE (UAV1) → intermediate relay UE (UAV2) → cellular network) in out-of-coverage or weak-coverage scenarios. In addition, in D2D short-range mode of operation (based on NR sidelink), UAVs can facilitate rapid information dissemination. This way UAV-assisted D2D networks may enable rapid spread of warning messages and/or evacuation maps among ground devices and vehicles in cases of emergency.
- Release 20: Candidate topics include sidelink enhancements, such L2 U2U multi-hop relaying, and integrated sensing and communication (ISAC) for UAV use cases.

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Smart Algorithms
for Drone Operation

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Smart Algorithms for Drone Operation

- Smart coordination algorithms for determination of optimal flight paths, dynamic task allocation, and resource management amidst evolving conditions.
  - ➢ Iterative Scheduling Algorithm of Trajectory and Resource (ISATR)
  - ➢ Particle swarm optimization (PSO) algorithm as a trajectory solution, and a block coordinate descent-based method for task offloading and resource allocation.
- DRL algorithms to enable drones to learn from experience and adjust their decision-making in real-time to navigate complex environments and optimize connectivity for tasks.
  - ✓ AD3QN, combined with an attention mechanism, simulates and adapts to realistic ground user distributions, A2G communication models, and electromagnetic interferences.
- ML models and LLM to help interpret vast amounts of data, quickly identify potential targets, and associate relevant knowledge to support the decision-making process.

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Drone Integration with Satellite Communication Systems

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Satellite-Drone Synergy and Hybrid Links

- Miniaturized direct-to-LEO modules, transmitting telemetry, audio, or imagery at data rates sufficient for emergency communications and maintaining continuous connection even during dynamic flight maneuvers.
- Spot-beam and omni-beam architectures, allowing seamless coverage over hundreds of kilometers, switching between satellites rapidly to avoid signal dropout.
- Hybrid architectures, combining terrestrial cellular, Wi-Fi, and satellite links, allowing drones to select the lowest-latency, highest-available channel based on real-time link quality.

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Satellite-Assisted Peer Coordination

- Satellite links are pivotal in *coordinating drone swarms* beyond the reach of terrestrial control, *uploading new alert messages*, *tasking drones dynamically*, and *keeping base commanders informed* with live sensor/video streams.
- Cognitive satellite-drone networks further enable *on-the-fly protocol/software updates*, or *dissemination of the most up-to-date, situationally relevant information* during drone flights, enhancing adaptability to evolving emergencies.

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A2G Communication Models and Technical Foundations

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Channel Modelling and Analysis

- Drone-based communication performance in emergency contexts crucially depends on precise modelling of A2G propagation channels.
- These models drive the selection of optimal drone altitude, power output, and platform type, considering (N)LoS conditions, fading, delay, and channel dynamics.
  - ✓ LoS conditions deliver higher reliability and capacity, but are swiftly compromised by obstacles—buildings, hills, dense forests;
  - ✓ NLoS conditions, more common in urban or mountainous regions, experience higher path loss, multipath fading, and greater delay.
- In addition, A2G channel models need to consider the effect of the drone's antenna movements and vibrations.

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Fading, delay, and channel dynamics

- Ray-tracing methods and real-world measurements
  - Map the power delay profile, Rician *K*-factor, and root mean square (RMS) delay spread for various scenarios, providing parameters for robust algorithm design.
- Environmental influences
  - Rain, wind, electromagnetic interferences must be considered, particularly at higher frequency (e.g., mmWave), which is more susceptible to weather attenuation.
- Dynamic channel modeling
  - Enables drones to adapt power, bandwidth, and path selection in real time, ensuring QoS targets like latency and throughput are maintained across shifting ground-aerial topologies.

Country Case Studies

Country	Drone Technologies	Operational Context	Distinctive Features/ Programs	Key Outcomes
China	VTOL/ multirotor, LTE, Wi-Fi, AI, loud-speakers	Mountainous/ remote, large cities	Cache-enabled fleets, multi-algorithm swarms, Non-Orthogonal Multiple Access (NOMA) drones	100 km+ coverage, real-time command comms
Japan	Drones with thermal/ visual sensors, digital displays, 5G LTE	Earthquake/ tsunami, medical logistics	1000+ auto-stationed drones, instant survivor location, map-messaging	<10 min deploy-ment, rapid message reach
Australia	Long-range, all-weather drones, loud-speakers, mesh Wi-Fi	Bushfires, rural/remote floods	Drone-in-a-box, government-integrated networks, all-weather drones	Supplement crewed aircraft, even coverage
US	Drones for video streaming, damage assessment, situational monitoring, emergency messaging	Hurricanes, wildfires, road traffic management	Real time, multi-agency streaming	Coordinated response

Urban vs Rural Adaptations

Urban Regions

- Overcome building-induced signal attenuation and NLoS issues
- Maximize message reach through vertical and horizontal drone maneuvering
- Optimize for multiple languages and urban noise levels (favoring displays and mobile data over speakers alone)
- Observe strict flight regulations regarding airspace and crowd safety
- Solutions include multi-tiered drone networks, intelligent altitude switching (provided by AI and real-time urban topology data), network coding to maintain throughput, and the use of digital visual displays to supplement (audio) broadcasts.
- Regulatory and public safety aspects mandate close collaboration with state agencies and local governments

Rural and Remote Regions

- Lower population density
  - Necessitating longer-range, higher-altitude, and longer-endurance drones
- Terrain and vegetation obstacles
  - Increasing value of relay chains and satellite links
- Scarcer user devices (for Bluetooth, Wi-Fi, cellular pickup), favoring broad, redundant broadcasts.
- Cache-enabled drone relays, relay-based 3D deployments, and hybrid terrestrial/satellite integration
  - Dominate, aiming for cost-effective area coverage, minimal human intervention, and power/communication efficiency.

Future Trends in Drone-based Communication in Cases of Emergency

Future Trends in Drone-based Emergency Communication (1)

- Towards Multi-Layered, Intelligent Networks
  - Development of fully integrated *Space-Air-Ground Integrated Networks (SAGINs)*, where drones operate as essential links within dynamic, distributed communication architectures for seamless disaster response.
  - Incorporation of *6G technologies*, enabling higher data rates, lower latency, and *advanced AI/ML-driven autonomy* for deployment, path planning, and adaptive resource allocation.
- Autonomous and AI-Driven Drone Swarms
  - *Proliferation of AI-powered, collaborative drone swarms* capable of self-organizing, negotiating dynamic coverage, and optimizing both communication and data collection roles.
  - *Advanced (multi-agent) DRL* for on-the-fly drone adaptation to evolving disaster parameters.
- Advanced User Interfaces and Personalization
  - Utilization of *context-aware communication*, capable of targeting user clusters with personalized instructions, e.g., for evacuation, potentially integrating with wearable or medical devices.

Future Trends in Drone-based Emergency Communication (2)

- Enhanced Security, Resilience, and Regulatory Integration
  - Continued *evolution of anti-jamming, encryption, and spectrum-management* technologies to protect both the command and message channels from malicious interference or overload.
  - *Standardization and regulatory harmonization* across national and international jurisdictions to ensure safe, controlled, and effective emergency drone operations. Future frameworks will likely include rapid national/international SWAT approval mechanisms, cross-border disaster cooperation protocols, and open interfaces for first-responder networks.
- Deep Multi-Modal Integration
  - *Tightly woven into smart infrastructures*: detecting disaster conditions via onboard sensors, autonomously launching, selecting the best media (text/image/audio/video), and feeding live data back to AI-powered situation rooms for comprehensive, closed-loop emergency management.
  - Broader adoption of cooperative drone–ground vehicle (GV) communication systems for synergistic, multi-modal disaster response — integrating ground sensors, human responders, and aerial fleets for holistic resource optimization.

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CONCLUSION

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Conclusion (1)

- Drones have emerged as a *critical, adaptive, and scalable communication solution in cases of emergency*, enabling authorities and rescue operations to rapidly fill the communications void left by natural disasters, industrial accidents, terrorist attacks, ground infrastructure failures, or hostile interferences.
- Modern deployments *combine loudspeakers, digital displays, Bluetooth/Wi-Fi/cellular/satellite communication* technologies, coordinated by ever-smarter algorithms optimized for coverage, resource efficiency, and adaptability.
- *Real-world applications* in China, Japan, Australia, and the United States demonstrate both the versatility and effectiveness of drones in bridging communication gaps in a wide range of environments, from highly urbanized megacities to rugged, mountainous, and deeply rural regions.

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Conclusion (2)

- The *ongoing integration of AI, hybrid communication networking, and automated swarm coordination* heralds a future where drone networks may play an increasingly central role in disaster management, public safety, and humanitarian response.
- As regulatory environments evolve and technologies mature, the ongoing challenge will be to *ensure universal accessibility, security, reliability, and cost-effectiveness, while fostering interoperability* with traditional and upcoming emergency systems.
- The trajectory for *drone-based emergency communication* is one of continual enhancement—towards greater coverage, higher intelligence, and more inclusive, resilient safety communications for all.

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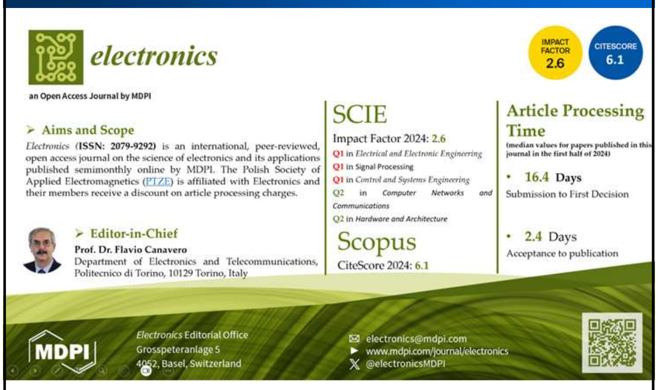

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