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Massive UAV-to-Ground Communications: A Mean Field Approach

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Introduction

- Cellular connections in our everyday life are about to be ubiquitously reliable in 5G cellular systems. The remaining cellular coverage holes would come from disaster scenarios, which significantly disrupt the search and rescue operations [1].
- To fill these holes quickly and efficiently, it is envisaged to **utilize unmanned aerial vehicles (UAVs)** that support air-to-ground cellular communications
- We focus particularly on an **urban disaster scenario requiring a large number of emergency connections** that are enabled by a massive number of UAVs.
- We tackle this **real-time massive UAV control problem** by proposing a distributed UAV velocity control algorithm.

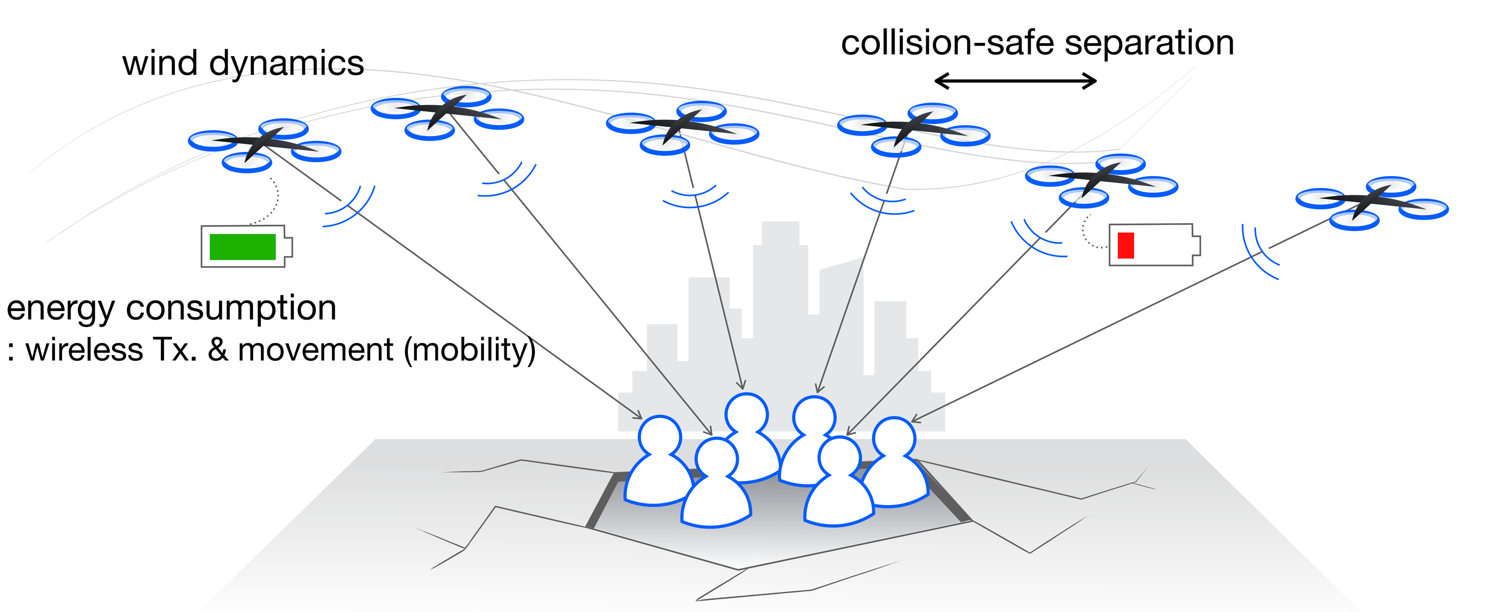


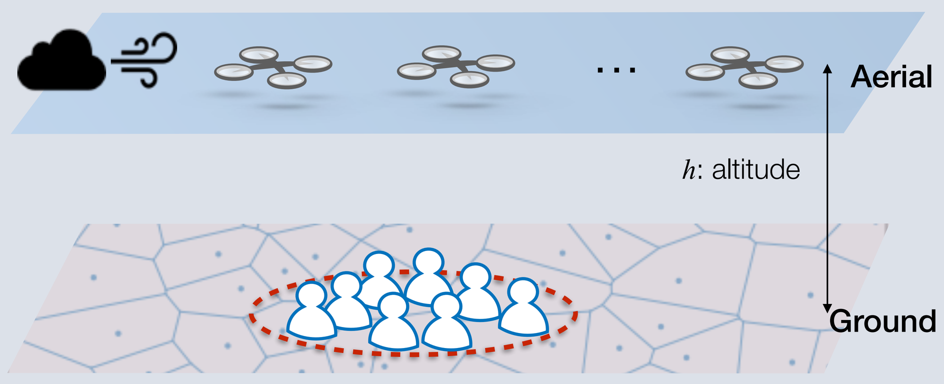
Fig. 1. An illustration of a UAV-to-ground cellular network that supports the ground users crowded around a disaster hotspot.

System Model & Problem formulation (1/2)

System model

- We consider an air-to-ground downlink network comprising N UAVs at an identical altitude of h meters.
- The coordinates of the i-th UAV at time t is denoted as $z_i(t) \in \mathbb{R}^3$.
- We assume the wind dynamics follows an Ornstein-Uhlenbeck process [2]:

$$dz_i(t) = (v_i(t) + A)dt + \eta_A \mathrm{d}W_i(t)$$



- The channel link between each UAV and the associated user follows from the UAV channel model provided by the 3GPP specifications [3].

$$R_i(t) = B\log_2\left(1 + \frac{g_i(t)P_u \cdot 10^{-L_i(t)/10}}{N_o B}\right) \quad P_{LOS} = \begin{cases} 1, & \text{if } \sqrt{d_z^2 - h^2} \le d_o, \\ \frac{d_o}{\sqrt{d_z^2-h^2}} + \exp\left\{\left(\frac{-\sqrt{d_z^2-h^2}}{p1}\right)\left(1 - \frac{d_o}{\sqrt{d_z^2-h^2}}\right)\right\}, & \text{if } \sqrt{d_z^2 - h^2} > d_o, \end{cases}$$

$$L_i(t) = \begin{cases} 30.9 + (22.25 - 0.5\log_{10} h)\log_{10} d_z(t) + 20\log_{10} f_c, \text{if LOS link,} \\ \max\{L_i^{LOS}, 32.4 + (43.2 - 7.6\log_{10} h)\log_{10} d_z(t) + 20\log_{10} f_c\}, \text{if NLOS link,} \end{cases}$$

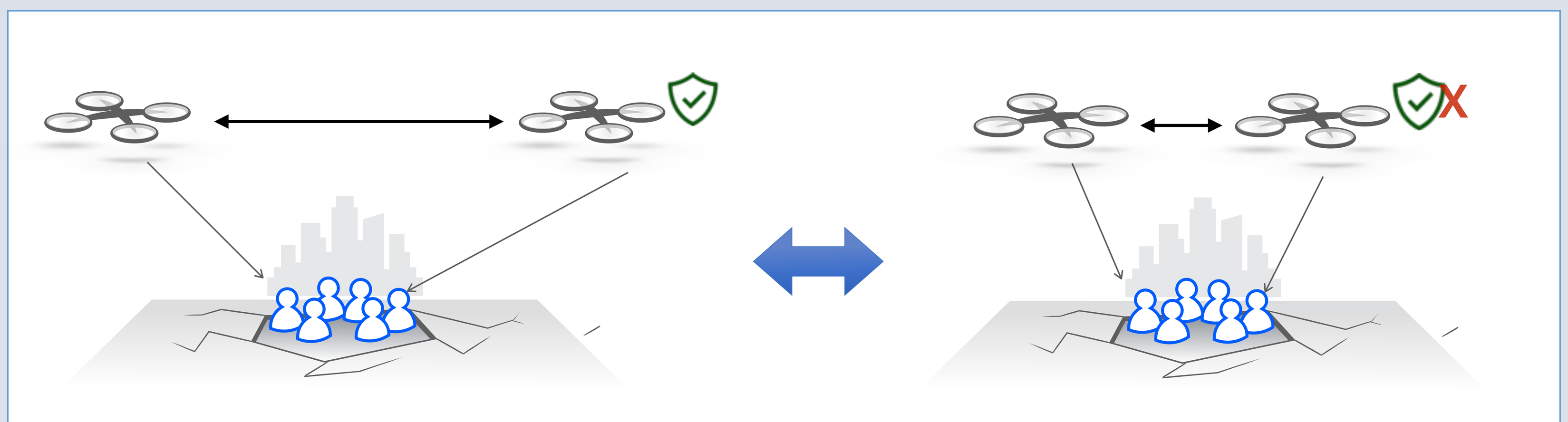
- The **path loss is stochastically determined** by line-of-sight (LOS) and non-line-of-sight (NLOS) link states, depending on the height of UAV, the distance from its ground user, and the carrier frequency.

Energy-efficiency massive UAV flocking

Objective

Minimize energy consumption per data rate w.r.t. (1) collision safety constraint, (2) temporal dynamics of wind, and (3) limited information exchange

Trade off between safety and communication efficiency



- Collision avoidance constraint & cost functions

$$\frac{1}{TN}\int_{t=0}^{T}\sum_{j=1}^{N}\mathbb{1}\left(\|z_i(t) - z_j(t)\| < d_s\right)dt \le \epsilon.$$

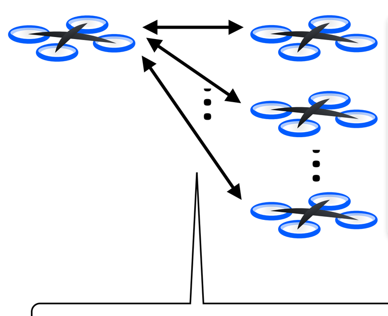
$$F_i(\boldsymbol{v}(t), \boldsymbol{z}(t)) = \frac{1}{N}\sum_{j=1}^{N}\frac{\|v_j(t) - v_i(t)\|^2}{(1/\gamma + \|z_j(t) - z_i(t)\|^2)^\beta} \qquad E_i(v_i(t), z_i(t)) = \frac{e_{m,i}(t) + e_{w,i}(t)}{R_i(t)}$$

collision aversion factor — distance between UAV

System Model & Problem formulation (2/2)

Mean-field game theoretic flocking design

$$\textbf{(P1)} \qquad \psi_i(t) = \inf_{v_i(t)} \mathcal{J}_i(t),$$
$$\text{subject to} \quad dz_i(t) = (v_i(t) + A)dt + \eta_A \mathrm{d}W_i(t)$$



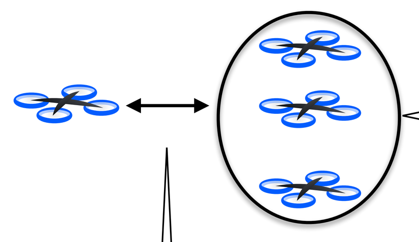
Stochastic Differential Game
- High complexity
- Too many info. exchange

Hamilton-Jacobi-Bellman (HJB) equation
- Each UAV movement
- **Optimal velocity** decision

$$\mathcal{J}_i(t) = \frac{1}{T}\int_t^T w_e E_i(v_i(t), z_i(t)) + w_f F_i(\boldsymbol{v}(t), \boldsymbol{z}(t))$$

$$0 = \partial_t \psi_i(t) + \inf_{v_i(t)}\Bigg[\underbrace{w_e E_i(v_i(t), z_i(t)) + w_f F_i(\boldsymbol{v}(t), \boldsymbol{z}(t))}_{(A)} + \frac{\eta_A^2}{2}\nabla_z^2\psi_i(t) + \underbrace{(v_i(t) + A)}_{(B)}\nabla_{z_i}\psi_i(t)\Bigg]. \quad (9)$$

SDG → Mean-Field Game (MFG)
- Large no. of UAVs
- Exchangeability of decision
- Finite interaction



Fokker-Planck-Kolmogorov (FPK) equation
- Entire distribution of UAVs
- **Estimate other UAVs' decision**

HJB equation
- Each UAV movement
- **Optimal velocity** decision

$$0 = \partial_t m(z(t)) + (v(t) + A)\nabla_z m(z(t)) - \frac{\eta_A^2}{2}\nabla_z^2 m(z(t)), \quad (11)$$

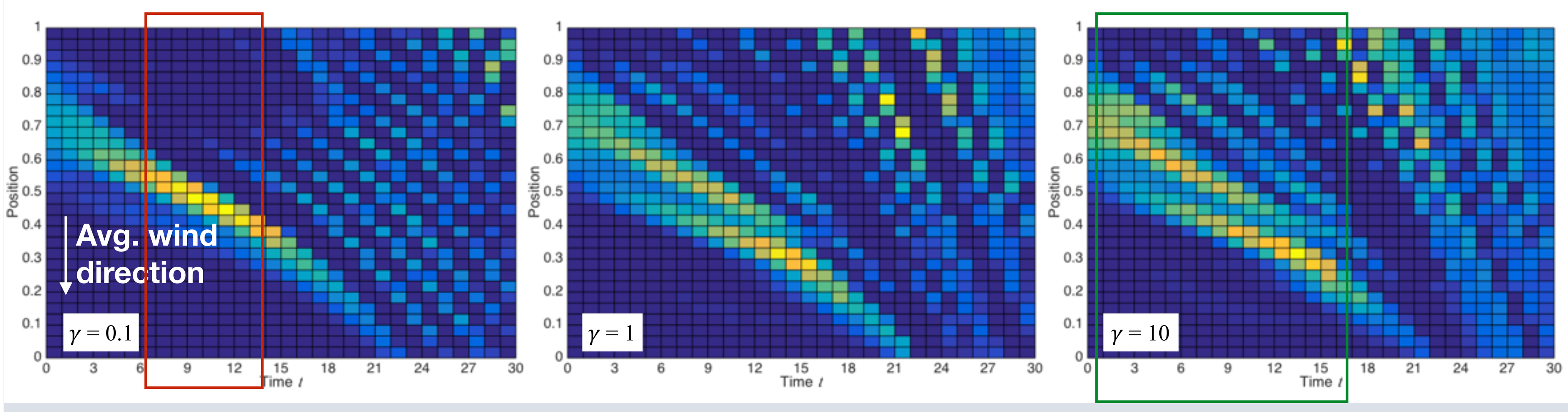
Proposition 1. *The optimal velocity is given by:*

$$v_i^* = \frac{w_f \int_z \frac{2m^*(z(t))v(z(t))}{(1/\gamma + \|z_i(t) - z(t)\|^2)^\beta}dz - \nabla_{z_i}\psi_i(t)}{\frac{a_m w_e}{R_i(z(t))} + w_f \int_z \frac{2m^*(z(t))}{(1/\gamma + \|z_i(t) - z(t)\|^2)^\beta}}, \quad (3.12)$$

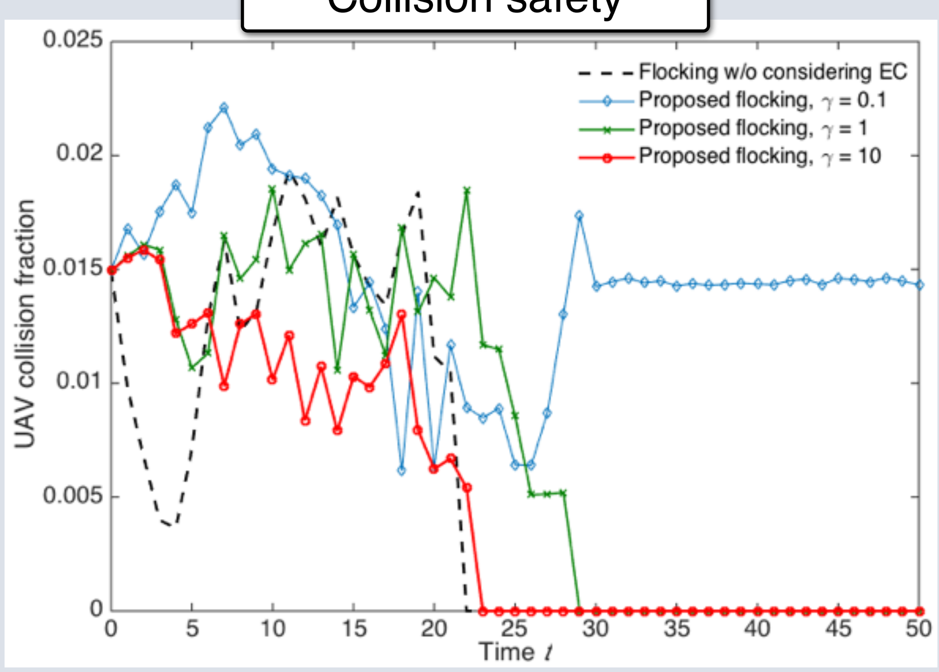
where $m^*(z(t))$ and $\psi^*(t)$ are the unique solutions of the FPK (3.11) and the following modified HJB equation (3.13), respectively.

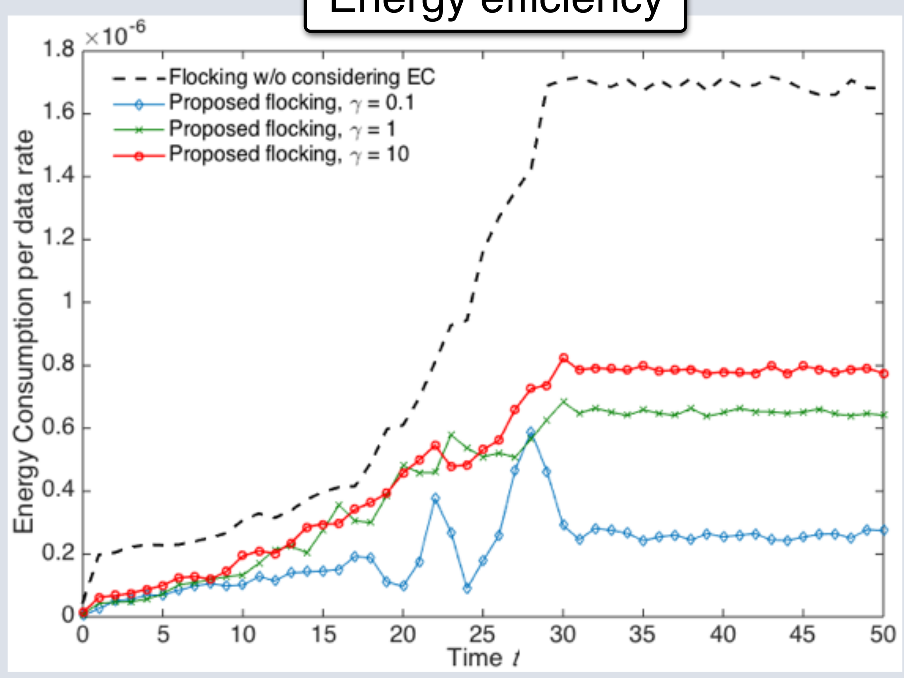
Numerical Results & Concluding Remarks

A heat map illustration of the UAV spatial density over time



Instantaneous performance evaluation w.r.t. different risk aversion factor γ





Concluding remarks

- We proposed an instantaneous movement control algorithm for massive unmanned aerial vehicles (UAVs) providing emergency connections in an urban disaster situation.
- Our algorithm minimizes the energy consumption per downlink rate, while avoiding inter-UAV collision under a temporal wind dynamics.
- Leveraging a mean-field game theoretic flocking approach, the control of each UAV only requires its own location and channel states, enabling a fully-distributed control operations.

References

- [1] M. Erdelj, E. Natalizio, K. R.Chowdhury, and I.F.Akyildiz,"Helpfrom the Sky: Leveraging UAVs for Disaster Management," *IEEE Pervasive Computing*, vol. 16, pp. 24–32, Jan. 2017.
- [2] R. Zárate-Miñano and F. M. Mele and F. Milano, "SDE-based Wind Speed Models with Weibull Distribution and Exponential Autocorrelation," *Proc. IEEE Power and Energy Society General Meeting (PESGM)*, 2016.
- [3] 3GPP TR 36.777 V1.0.0 (2017-12), "Study on Enhanced LTE Support for Aerial Vehicles" (Release 15)