

Energy-Harvesting Enabled Unmanned Aerial Vehicles for Reliable Ground User Localization under Lognormal-Nakagami- m Fading Channels

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- Analytical results
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- Conclusions

□ DIN Pilot Project:

❖ 2019-DIN Pilot Project “*A novel non-GPS based positioning, navigation and timing solution for reconnaissance missions*”

❖ Team:

- UOW (Le Chung Tran (Lead CI), Christian Ritz, Son Lam Phung and Salim Bouzerdoun).
- UTS (Xiaojing Huang, Eryk Dutkiewicz and Daniel Franklin)

❖ Funding: 130 K

□ Aim: propose novel non-GPS localization techniques for reconnaissance missions.

□ **Why non-GPS?**

- Global positioning systems (GPS) work well in open areas.
- GPS performance is worse in many scenarios such as indoors, urban areas, deep forests, underwater or even denied in military operations.
- Radio frequency localization using wireless sensor networks (WSN) is therefore crucial for emergency responders and military personnel.

1. “Energy-harvesting enabled unmanned aerial vehicles for reliable ground user localization under lognormal-Nakagami-m fading channels”, *to be submitted to IEEE Transaction on Vehicular Technology (TVT)*, 2020.
2. “Unbalanced hybrid AOA/RSSI localization for simplified wireless sensor networks”, *Sensors*, Vol. 20, No. 14, July 2020.
3. “Performance evaluation of non-GPS based localization techniques under shadowing effects”, *Sensors*, vol. 19, no. 11, pp. 2633-1-2633-21, June. 2019.

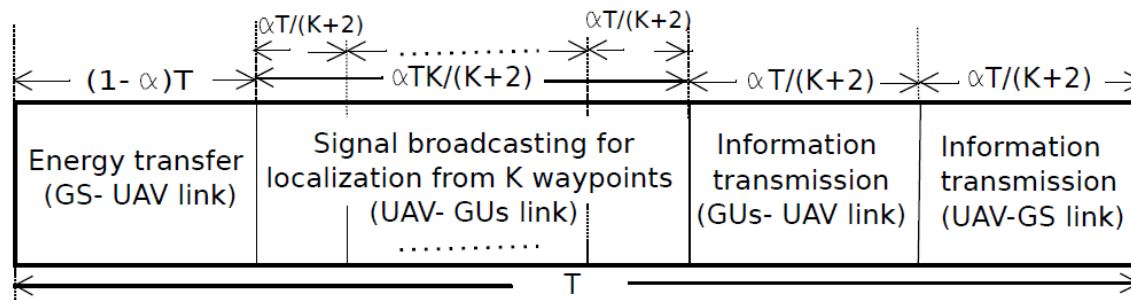
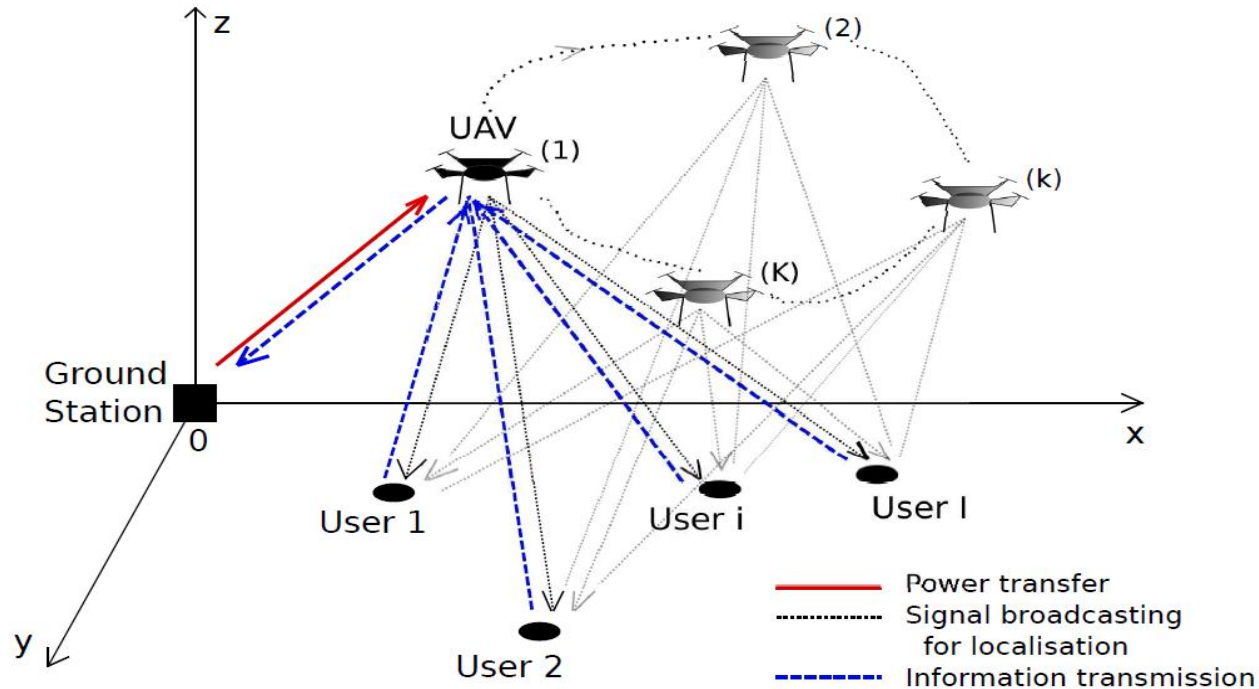
□ Motivation:

- ❖ **UAVs**: potential for future wireless communications and localization applications
 - *Problem: limited energy to sustain UAVs' operations*
 - *Possible solution: Energy-harvesting techniques*
- ❖ **Received Signal Strength (RSS) based localization**: attractive due to its simplicity
- ❖ **Realistic channel environments**: spatial correlated shadowing
- ❖ **Practical localization scenarios**: information on estimated position is needed not only by ground objects but also by UAVs and/or Central station.

□ **Research problem**: investigating a joint localization and communication in an energy-harvesting UAV based ground user localization system over correlated shadowing channels.

System Model (1)

□ System model and proposed protocol



System Model (2)

❖ **Energy-harvesting phase:** *The averaged harvested energy*

$$E_u = \eta P_b(1 - \alpha) T G_{bu} S_{bu} \quad (P_b: \text{transmit power}, \eta: \text{energy conversion efficiency})$$

❖ **Localization phase:** *The time-averaged received signal power*

$$P_i^k = P_u G_{uo,i}^k S_{uo,i}^k = \frac{(K + 2)(1 - \alpha) \eta P_b G_{bu} G_{uo,i}^k S_{bu} S_{uo,i}^k}{(K + 1) \alpha} \quad k = 1, 2, \dots, K$$

➤ GUs estimate their location using ML or LS method based on $P_i^k, k = 1, 2, \dots, K$

❖ **Information transmission phase:** *The received SNR values*

$$\gamma_{ou,i} = \frac{P_{o,i} G_{ou,i}^1 S_{ou,i}^1 H_{ou,i}^1}{N_0} \quad \text{and} \quad \gamma_{ub,i} = \frac{(P_u/I) G_{ub} S_{ub} H_{ub}}{N_0} = \frac{(K + 2)(1 - \alpha) \eta P_b G_{bu} G_{ub} S_{bu} S_{ub} H_{ub}}{(K + 1) \alpha I N_0}$$

Notation:

Channel links	Label ⁽¹⁾	Distance-based path gain	Large-scale fading	Small-scale fading
$GS \rightarrow UAV$	bu	$G_{bu} = g_{0,b}/d_{ub}^\beta$	$S_{bu} \sim \text{lognormal}(\mu_{ub}, \sigma_{ub}^2)$	$H_{bu} \sim \text{Nakagami-}m$
$UAV \rightarrow GS$	ub	$G_{ub} = g_{0,u}/d_{ub}^\beta$	$S_{ub} \sim \text{lognormal}(\mu_{ub}, \sigma_{ub}^2)$	$H_{ub} \sim \text{Nakagami-}m$
$GU(i^{th}) \rightarrow UAV(k^{th})$	ou	$G_{ou} = g_{0,o}/d_{i,k}^\beta$	$S_{ou,i}^k \sim \text{lognormal}(\mu_{ou}, \sigma_{ou}^2)$	$H_{ou,i}^k \sim \text{Nakagami-}m$
$UAV(k^{th}) \rightarrow GU(i^{th})$	uo	$G_{uo} = g_{0,u}/d_{i,k}^\beta$	$S_{uo,i}^k \sim \text{lognormal}(\mu_{ou}, \sigma_{ou}^2)$	$H_{uo,i}^k \sim \text{Nakagami-}m$

⁽¹⁾Note : b : base station; u : uav; o : object

Analytical Results: *Analysis of CRLB*

□ Crame-Rao Lower Bound (CRLB) under correlated shadowing:

$$\text{var}_{\mathcal{L}_i}(\hat{\mathcal{L}}_i) \geq \frac{-(K-1)\rho^2 + (K-2)\rho + 1}{(K-2)\rho + 1} \left(\frac{\sigma_{buo} \ln 10}{10\beta} \right)^2 \times \frac{\sum_{k=1}^K (X_{i,k}^2 + Y_{i,k}^2)}{\sum_{k_1=1}^K \sum_{k_2=1}^K (X_{i,k_1}^2 Y_{i,k_2}^2 - X_{i,k_1} X_{i,k_2} Y_{i,k_1} Y_{i,k_2})},$$

K : number of waypoints

ρ : correlated shadowing coefficient

β : the path-loss exponent

σ : lognormal shadowing standard deviation

$X_{i,k} \triangleq (x_i - x_k)/d_{i,k}^2, Y_{i,k} \triangleq (y_i - y_k)/d_{i,k}^2,$

Remark: *The deployment of an additional waypoint leads to the decrease of the CRLB bound.*

Approximations of Channel Distribution

❑ Two probability density function (PDF) approximations used for information transmission analysis

❖ Lognormal PDF shadowing $\sim$ Gamma PDF⁽¹⁾

$$f_{L,\phi}(x) = \frac{1}{\sqrt{2\pi\sigma_{L,\phi}^2}x} e^{-\frac{(\ln(x)-\mu_{L,\phi})^2}{2\sigma_{L,\phi}^2}}$$

$\sim$

$$f_{G,\phi}(x) = \frac{1}{\theta_{\phi}^{\varphi_{\phi}} \Gamma(\varphi_{\phi})} x^{\varphi_{\phi}-1} e^{-x/\theta_{\phi}}$$

❖ Nakagami-lognormal fading $\sim$ Mixture gamma (MG) distribution approximation⁽²⁾

$$f_{NL,\phi}(x) = \int_0^{\infty} \frac{x^{m_{\phi}-1} e^{-m_{\phi}x/\varrho_{\phi}y}}{\Gamma(m_{\phi})} \left(\frac{m_{\phi}}{\varrho_{\phi}y}\right)^{m_{\phi}} \frac{e^{-\frac{(\ln(y)-\mu_{L,\phi})^2}{2\sigma_{L,\phi}^2}}}{\sqrt{2\pi}\sigma_{L,\phi}y} dy,$$

$\sim$

$$f_{MG,\phi}(x) = \sum_{n=1}^{N_{\phi}} a_{\phi,n} x^{b_{\phi,n}-1} e^{-c_{\phi,n}x}, x \geq 0,$$

⁽¹⁾ P. M. Shankar, "Outage analysis in wireless channels with multiple interferers subject to shadowing and fading using a compound pdf model, *AEU International Journal of Electronics and Communications*, vol. 61, no. 4, pp. 255-261, Apr. 2007.

⁽²⁾ S. Atapattu, C. Tellambura and H. Jiang, "A mixture Gamma distribution to model the SNR of wireless channels," *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 4193-4203, Dec. 2011.

Analytical Results: *Outage Probability*

❑ Closed-form expression of outage probability

$$P_{out}(\gamma_{th}) = Pr(\gamma_{ou} < \gamma_{th}) + Pr(\gamma_{ub} < \gamma_{th}, \gamma_{ou} \geq \gamma_{th}),$$

where γ_{th} is the SNR threshold.

$$P_{out}(\gamma_{th}) = \sum_{n=1}^{N_{ou}} a_{ou,n} c_{ou,n}^{-b_{ou,n}} (b_{ou,n} - 1)! \left(1 - e^{-c_{ou,n} \gamma_{th} / \bar{\gamma}_{ou}} \sum_{m=0}^{b_{ou,n}-1} \frac{(c_{ou,n} \gamma_{th} / \bar{\gamma}_{ou})^m}{m!} \right) \\ + \left[1 - \sum_{n=1}^{N_{ou}} a_{ou,n} c_{ou,n}^{-b_{ou,n}} (b_{ou,n} - 1)! \left(1 - e^{-c_{ou,n} \gamma_{th} / \bar{\gamma}_{ou}} \sum_{m=0}^{b_{ou,n}-1} \frac{(c_{ou,n} \gamma_{th} / \bar{\gamma}_{ou})^m}{m!} \right) \right] \times \\ \sum_{n=1}^{N_{ub}} a_{ub,n} c_{ub,n}^{-b_{ub,n}} (b_{ub,n} - 1)! \left(1 - \sum_{m=0}^{b_{ub,n}-1} \frac{2}{m! \Gamma(\varphi_{ub})} \left(\frac{c_{ub,n} \gamma_{th}}{\theta_{ub} \bar{\gamma}_{ub}} \right)^{(\varphi_{ub}+m)/2} K_{\varphi_{ub}-m} \left(2 \sqrt{\frac{c_{ub,n} \gamma_{th}}{\theta_{ub} \bar{\gamma}_{ub}}} \right) \right),$$

where $\bar{\gamma}_{ou} \triangleq \frac{P_o G_{ou}^1}{N_0}$, $\bar{\gamma}_{ub} \triangleq \frac{(K+2)(1-\alpha)\eta P_b G_{bu} G_{ub}}{(K+1)\alpha I N_0}$, $K_\nu(.)$ denotes the ν -th order modified Bessel function of the second kind.

Analytical Results: *Link Capacities*

- ❑ Closed-form expressions for ergodic capacities of the GU-UAV link and the UAV-GS link

$$C_{ou} = \varepsilon\{\log_2(1 + \gamma_{ou})\},$$

$$C_{ub} = \varepsilon\{\log_2(1 + \gamma_{ub})\}.$$

where $\varepsilon\{.\}$ denotes the expectation and γ is the received SNR.

$$C_{ou} = \frac{1}{\ln 2} \sum_{n=1}^{N_{ou}} a_{ou,n} c_{ou,n}^{-b_{ou,n}} (b_{ou,n} - 1)! \left(\frac{c_{ou,n}}{\bar{\gamma}_{ou}} \right)^{b_{ou,n}} e^{c_{ou,n}/\bar{\gamma}_{ou}} \sum_{v=1}^{b_{ou,n}} \frac{\Gamma(-b_{ou,n} + v, c_{ou,n}/\bar{\gamma}_{ou})}{(c_{ou,n}/\bar{\gamma}_{ou})^v},$$

$$C_{ub} = \frac{1}{\ln 2} \sum_{n=1}^{N_{ub}} a_{ub,n} c_{ub,n}^{-b_{ub,n}} (b_{ub,n} - 1)! \sum_{m=0}^{b_{ub,n}-1} \frac{1}{m! \Gamma(\varphi_{ub})} \times$$

$$\left[-m G_{4,2}^{1,4} \left(\frac{\theta_{ub} \bar{\gamma}_{ub}}{c_{ub,n}} \middle| \begin{matrix} -\varphi_{ub} + 1, -m + 1, 1, 1 \\ 1, 0 \end{matrix} \right) + G_{4,2}^{1,4} \left(\frac{\theta_{ub} \bar{\gamma}_{ub}}{c_{ub,n}} \middle| \begin{matrix} -\varphi_{ub} + 1, -m, 1, 1 \\ 1, 0 \end{matrix} \right) \right],$$

where $\Gamma(.)$, $\Gamma(., .)$, and $G(.)$ are the gamma function, the upper incomplete gamma function, and the Meijer G-function.

Analytical Results: *System Throughput*

□ Delay-limited transmission (DL)

$$\tau_{DL} = \frac{\alpha T / (K + 2)}{T} (1 - P_{out}) R_c = \frac{\alpha}{K + 2} (1 - P_{out}) R_c,$$

where P_{out} is the outage probability and $R_c = \log_2(1 + \gamma_{th})$.

□ Delay-tolerant transmission (DT)

$$\tau_{DT} = \frac{\alpha T / (K + 2)}{T} C = \frac{\alpha}{K + 2} \min\{C_{ou}, C_{ub}\},$$

where C is the capacity of the whole link GU-UAV-GS.

Analytical Results: *Optimal Energy-harvesting Time*

- Optimal energy-harvesting time for the maximal throughput (delay-tolerant transmission at a high SNR)

$$\alpha^{opt} = \frac{1}{1 + e^{W(e^{\Phi/\Upsilon} - 1) + 1 - \Phi/\Upsilon}},$$

where $W(.)$ is the Lambert W function, and

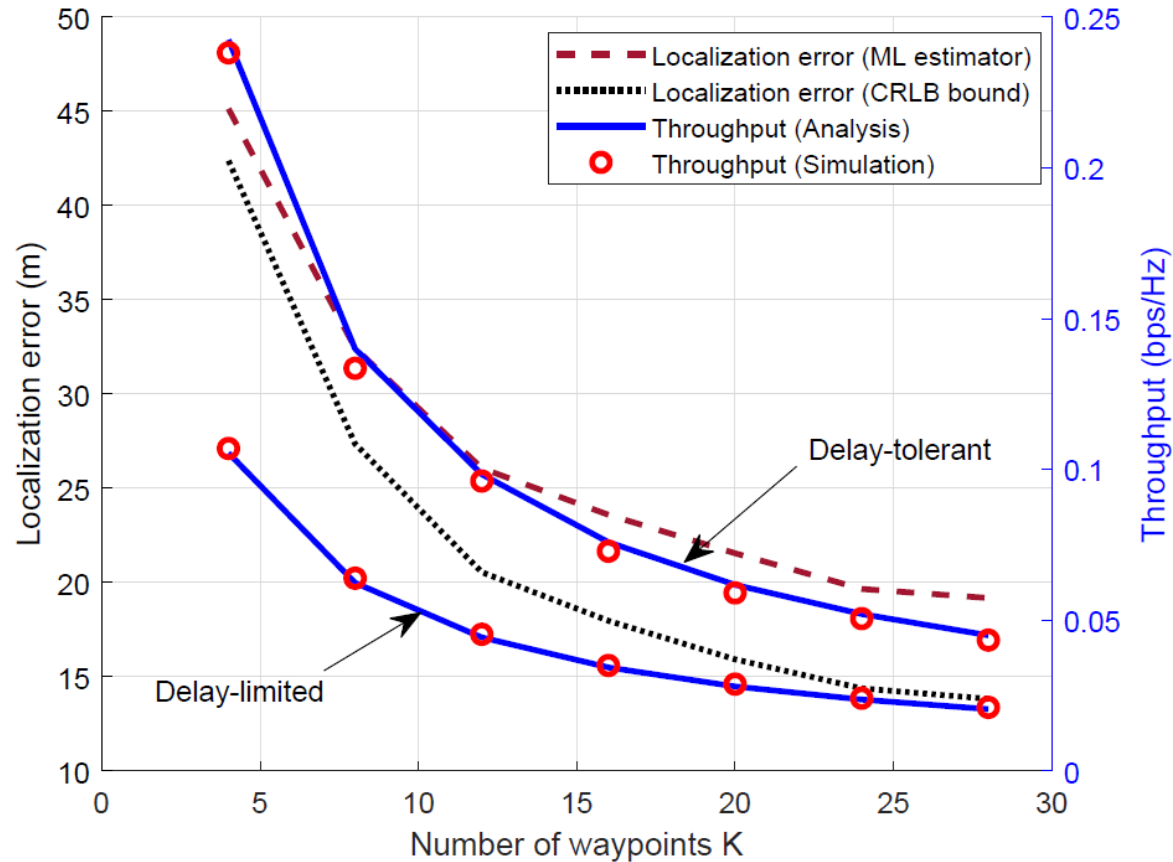
$$\Phi \triangleq \frac{1}{\ln 2} \sum_{n=1}^{N_{ub}} a_{ub,n} c_{ub,n}^{-b_{ub,n}} (b_{ub,n} - 1)! \left[\psi(\varphi_{ub} + 1) + \psi(1) + \ln \left(\frac{\theta_{ub}(K + 2)\eta P_b G_{bu} G_{ub}}{c_{ub,n}(K + 1)IN_0} \right) + \sum_{m=1}^{b_{ub,n}-1} \frac{1}{m} \right]$$

$$\Upsilon \triangleq \frac{1}{\ln 2} \sum_{n=1}^{N_{ub}} a_{ub,n} c_{ub,n}^{-b_{ub,n}} (b_{ub,n} - 1)!$$

where $\psi(.)$ is the Psi function.

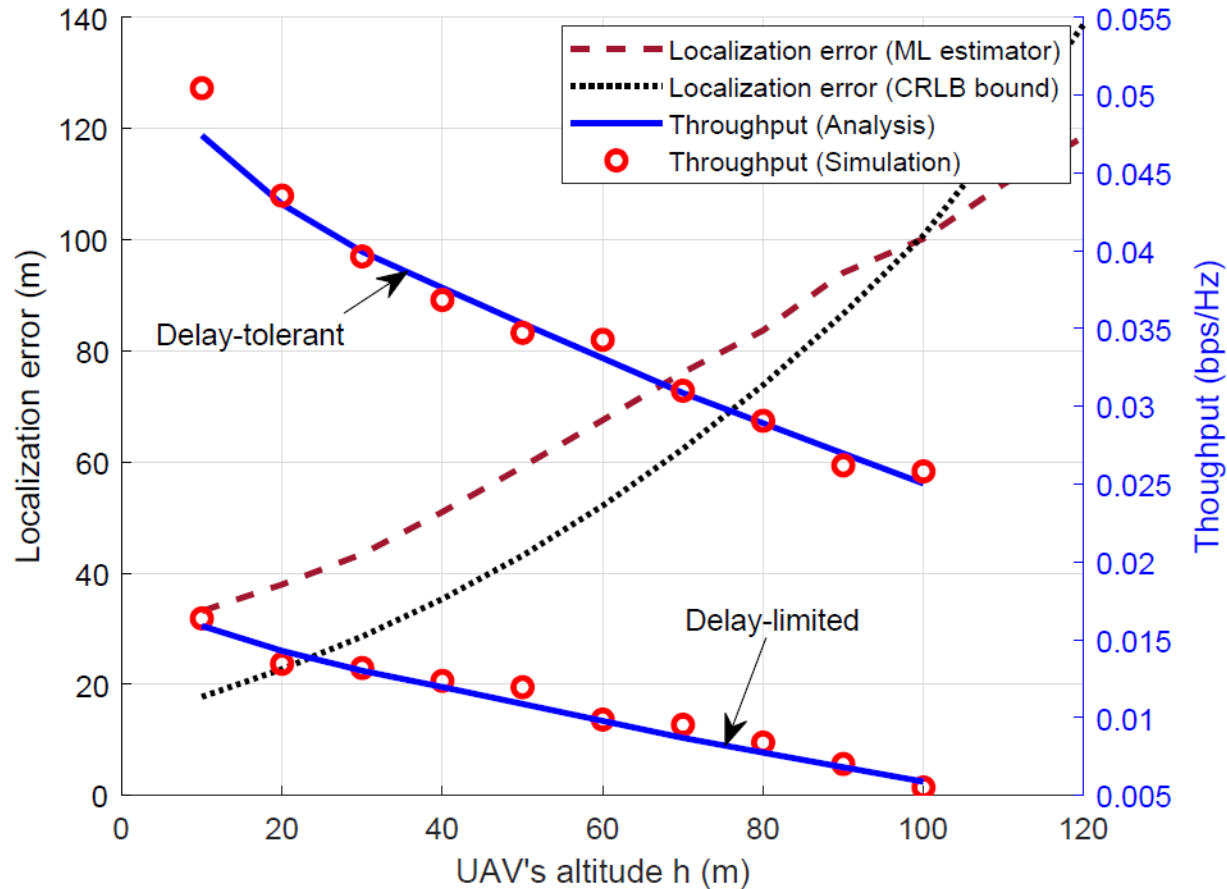
Simulation Results (1)

- ❖ Localization error and system throughput versus the number of waypoints



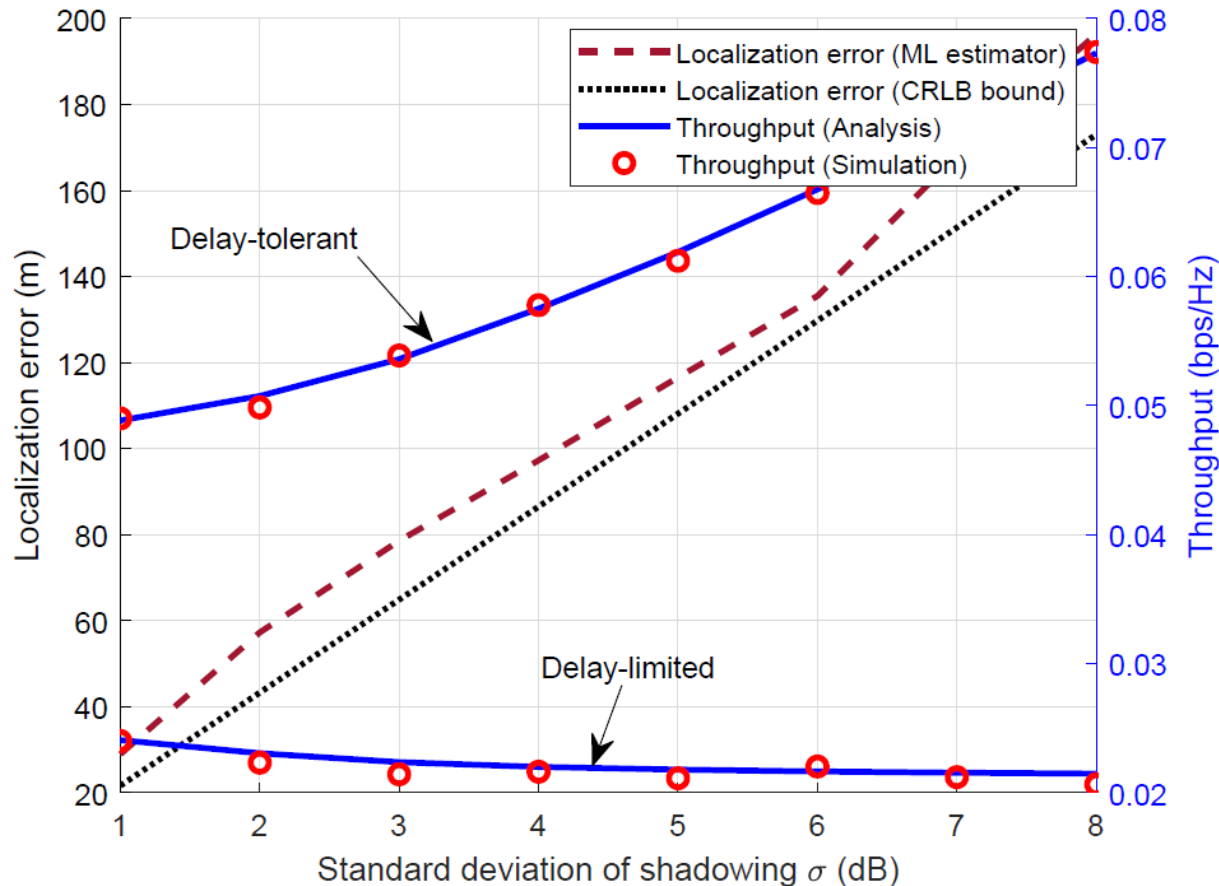
Simulation Results (2)

❖ Localization error and system throughput versus UAV's altitude



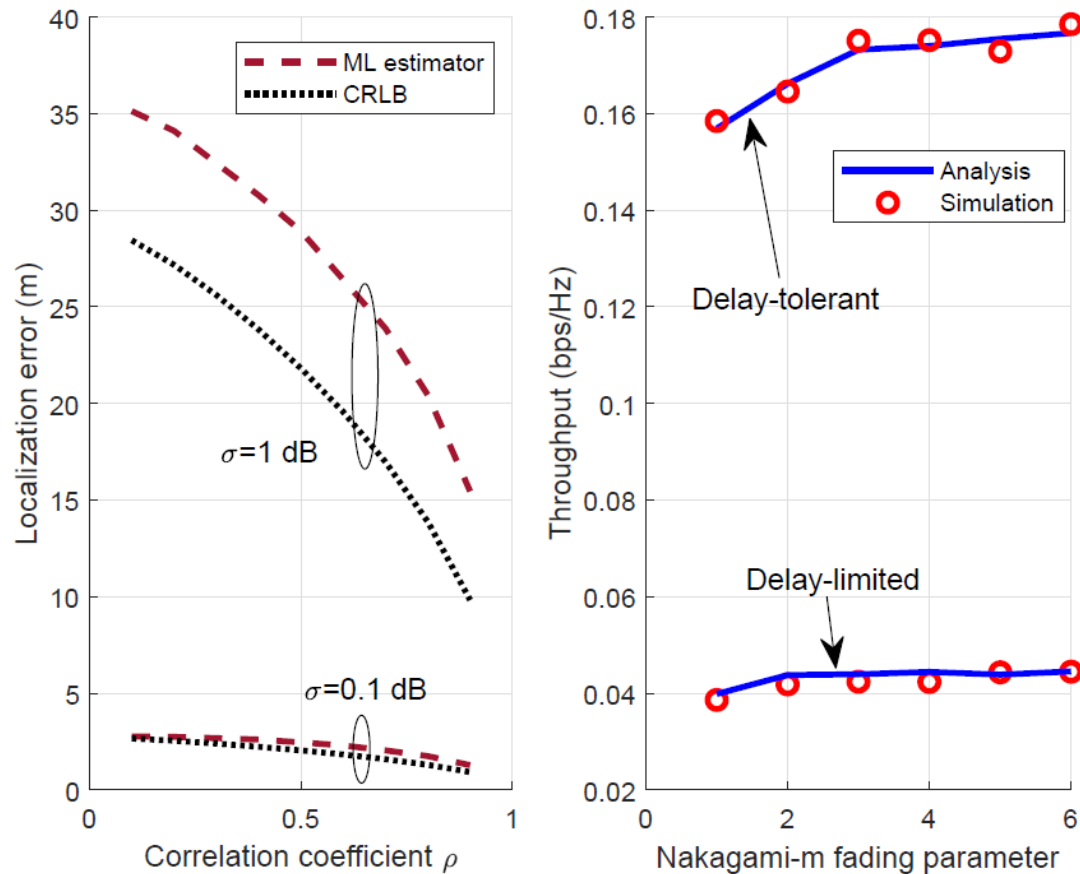
Simulation Results (3)

- Localization error and system throughput versus the standard deviation of the shadowing



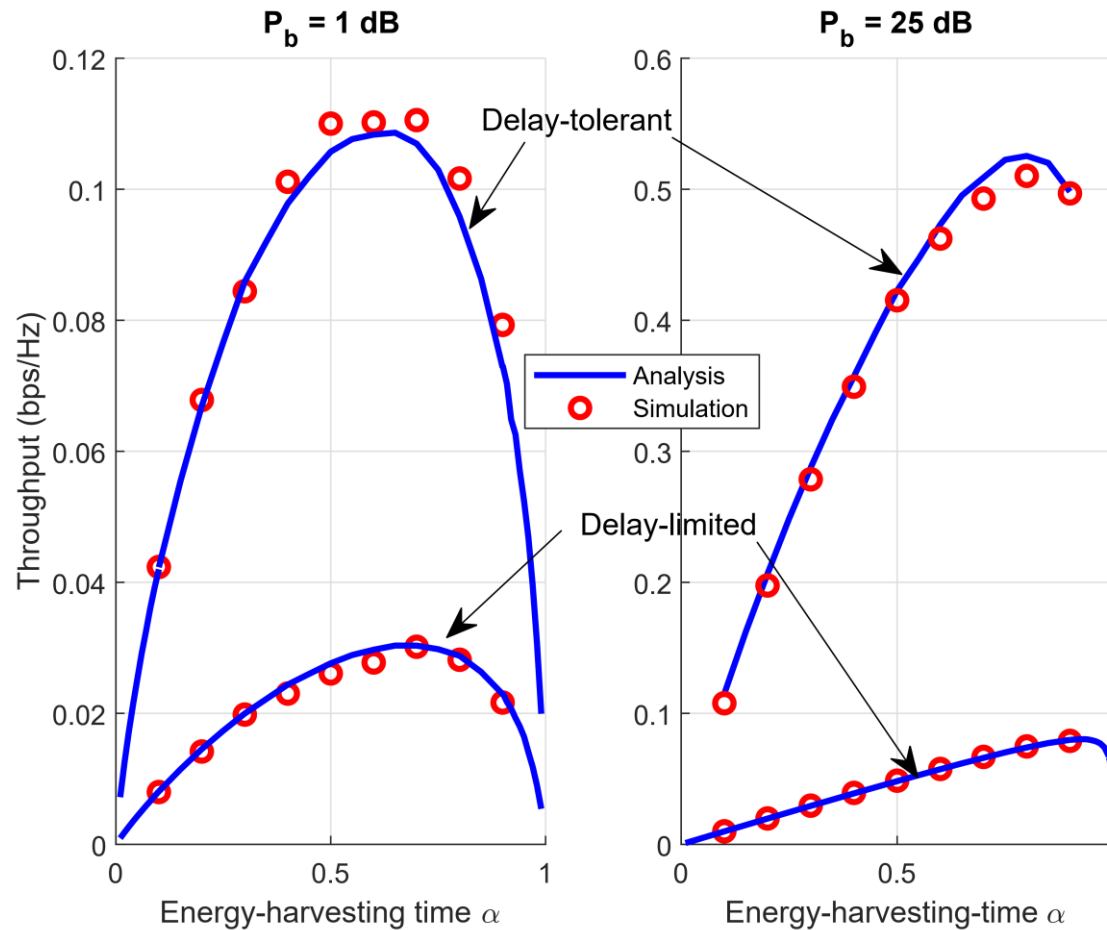
Simulation Results (4)

- ❖ Localization error and system throughput under different fading channel conditions



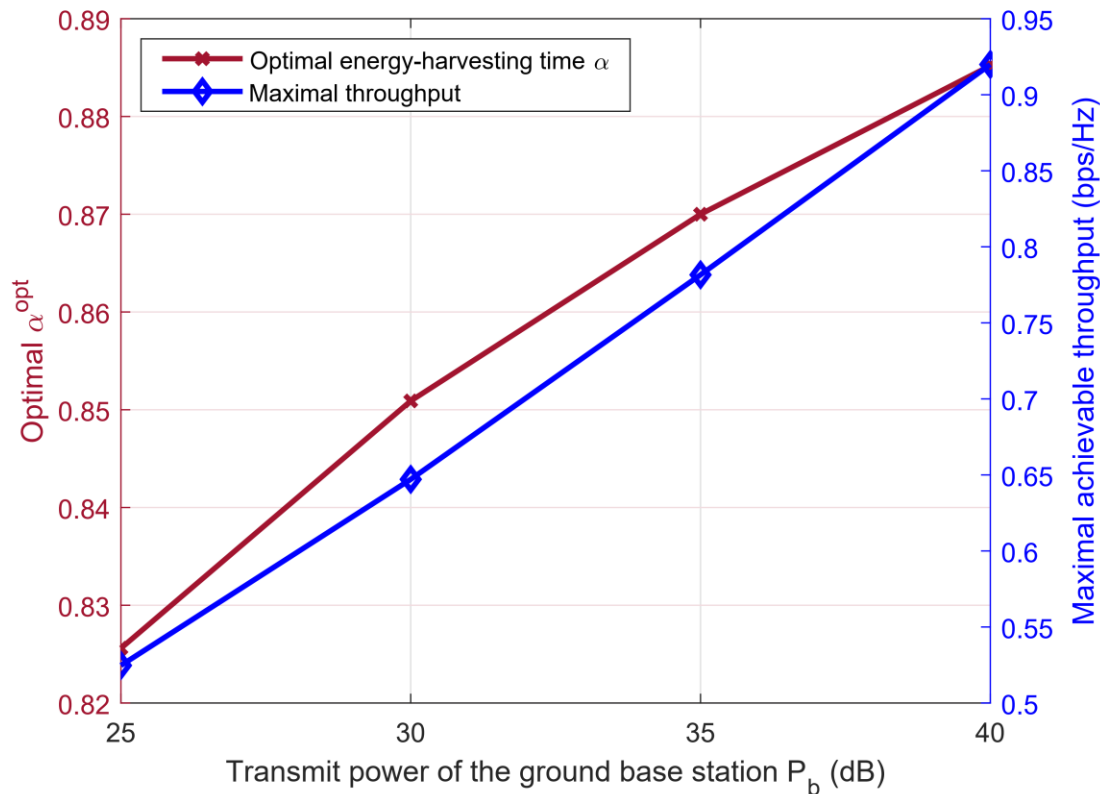
Simulation Results (5)

❖ System throughput versus energy-harvesting time



Simulation Results (6)

- ❖ Optimal energy-harvesting time and maximal throughput (delay-tolerant system) versus transmit power P_b



Conclusions and Future Works

□ **Energy-harvesting UAV for localization and communication:**

- ❖ Analyzed performance of RSS-based localization under correlated shadowing via the CRLB.
- ❖ Performed theoretical analysis of outage probability, ergodic capacity and achievable throughput.
- ❖ Provided useful insights into the system design and implementation:
 - Impacts of the number of waypoints and the altitude of the UAV.
 - Impacts of channel environments (correlated shadowing and small-scale fading).
 - Optimal energy-harvesting time.

□ Future works:

- ❖ Designing optimal UAV trajectory using a learning machine approach.
 - UAV's position for the optimal localization-communication performance trade-off.
- ❖ Combining the RSS-based method with other localization methods (e.g., TOA and AOA) for improved performance.

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Thank you!