Low-altitude Emergency Strategy Using Ad-hoc Radio Relay eVTOLs in Karst Topography and Game Analysis

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Abstract:

The low-altitude economy (LAE) represents a novel economic framework centered around low-altitude aviation activities. Electric Vertical Take-Off and Landing vehicles (eVTOLs) are emerging as the key instruments for LAE due to their quiet operation, scalability, environmental friendliness, efficiency, and autonomous capabilities. In regions with complex karst topography, such as the ASEAN border areas, leveraging eVTOL networks with radio relays can significantly enhance communication quality, logistics efficiency, emergency response, and tourism experiences, thereby offering a transformative development for regional LAE. We investigate the coverage of wireless base stations along a section of the Hechi Muluojia Canyon coastline in Guangxi, China, identifying challenges in achieving high-quality wireless communications. In response, we propose the Low-altitude Emergency Strategy (LES), which employs ad-hoc radio relay eVTOLs (ARR eVTOLs) in conjunction with GSOs to deftly counteract radio fading and interference, thereby improving communication accessibility and quality. To generalize the issue, we develop a differential evolutionary game model of LES, examining various game scenarios where participants face negative net gains and disregard costs. This study offers a theoretical contribution to addressing wireless network security challenges within the LES framework.

Keywords: low-altitude economy, eVTOL, wireless disturbance and counteract, ASEAN karst topography, open source SDR

INTRODUCTION

The emerging low-altitude economy (LAE), which leverages aviation activities below 1000 meters, spans various fields and industries, rapidly evolving into a new paradigm and a driver of innovation. The electric vertical take-off and landing vehicle (eVTOL) is increasingly becoming a key component of this economy, thanks to its benefits of low noise, scalability, environmental sustainability, high efficiency, and automation technology [1]. However, eVTOLs with radio communication remote control are vulnerable to interference. In December 2024, a significant number of eVTOLs lost control and crashed in Quanzhou, Fujian, and Jingzhou, Hubei, with their high-density lithium batteries sparking fires. Hence, ensuring the radio safety of the LAE is crucial.

From a technological standpoint, the widespread adoption of open source SDR (software-defined radios) has boosted the agility of technological innovation. However, it has also introduced challenges to spectrum management and communication security, such as spectrum disturbances, signal hijacking, fake nodes, and power attacks [2,3]. The dynamic nature of low-altitude vehicle wireless networks requires agility and robustness in their spectrum management mechanisms [4].

Geomorphological terrain poses an inherent challenge for low-altitude communications. Beyond the need to preserve the natural landscape, factors such as high calcium content, numerous cavities, rockfalls, and landslides [5] hinder the construction of large-scale wireless base stations. We investigate the coverage of wireless base stations along a section of the Hechi Muluojia Canyon in Guangxi (Figure 1). The area extends from 24°48′33″N, 107°52′31″E to 24°45′44″N, 107°53′51″E — approximately 5.667 km straight-line distance — with a total of four visually identified WBSs, located using GSO satellite coordinates. One notable section is between WBS_3 and WBS_4, which spans about 2.508 km with an elevation ranging from 480 to 520 m. As these WBSs are constructed on hillsides in consideration of preserving the natural landscape, the signal frequency at 5 GHz and 2.4 GHz is significantly attenuated or even lost due to limestone, vegetation, moisture, and surface scattering in this area.

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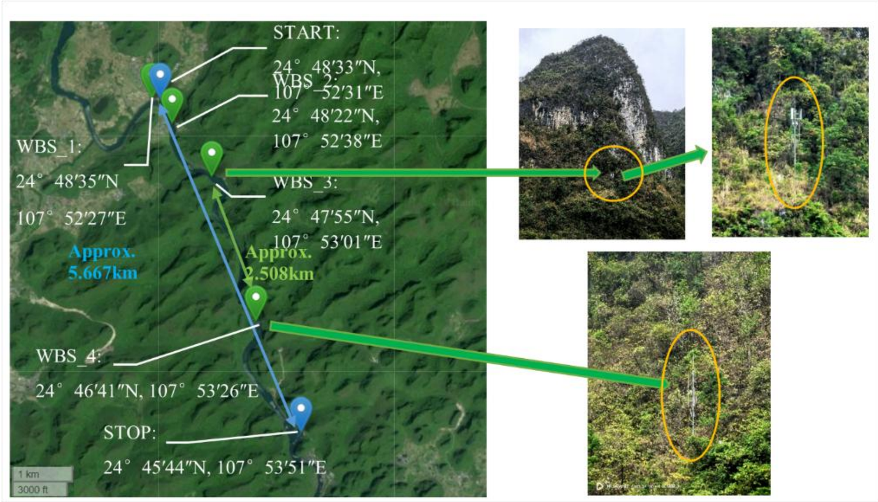


Figure 1. Coverage of WBS along a section of Hechi Muluojia Canyon, Guangxi

Similarly, Nonggang National Nature Reserve (22°13′56″-22°39′09″N, 106°42′28″-107°04′54″E), situated along the Sino-Vietnamese border, is renowned for its Karst peak-cluster depression landscapes, with elevations ranging from 118 to 680 m [6]. These complex geological conditions pose significant challenges for management and coordination of radio frequencies by "The International Coordination of Frequencies for Terrestrial Radio Operations in Border Areas". Employing eVTOL as a radio relay offers a solution, providing mesh network support to the low-altitude airspace, thereby overcoming terrain limitations and interference risks. This approach enhances communication quality and logistical efficiency, bolsters emergency response capabilities, and introduces a new technological model for the development of the regional LAE.

We propose a Low-altitude Emergency Strategy (LES) for ARR eVTOLs in synergy with GSO, designed to mitigate wireless signal disturbance and power loss in challenging terrains while optimizing terrestrial and spatial resources to deliver efficient network services. The implementation of LES can be succinctly described as follows: ARR eVTOLs utilize satellite positioning to locate users and connect to terrestrial WBS, ensuring comprehensive signal coverage and data transmission in complex terrains (Figure 2). In essence, LES enables ARR eVTOLs to pinpoint user locations using GSO satellite positioning in difficult terrains and establish connections with ground WBS, providing stable and high-quality data services (Figure 2). The LES process is divided into the following three steps.

First step. Users actively search and request GSO satellite positioning. The longitude and latitude data of the user's location is provided by the GSO satellite to multiple ARR eVTOLs, meanwhile, provides Maidenhead Grid Locator verification through the frequency difference method.

Second step. Multiple ARR eVTOLs provide users with stable high-bitrate audio and video data transmission services.

Third step. ARR eVTOLs deliver stable high bit rate video and audio data transmission services to the user.

As shown in Figure 2, karst limestone, due to its complex structure and composition, easily scatters and absorbs electromagnetic waves in the UHF and SHF frequency bands, which are fundamental for high bit rate audio and video data transmission. The LES for ARR eVTOLs in synergy with GSO utilizes different frequency bands to meet the high bit rate communication needs between WBS and users in complex terrain environments. The 1-2 GHz L-band UHF is used for GSO positioning services. Its relatively low frequency provides strong penetration capability and is less affected by weather, ensuring reliable positioning services in rugged karst terrains. The 4-8 GHz C-band SHF is employed for high bit rate data services. Although it is more susceptible to terrain obstruction and absorption during propagation, ARR eVTOLs can circumvent terrain limitations by providing short.

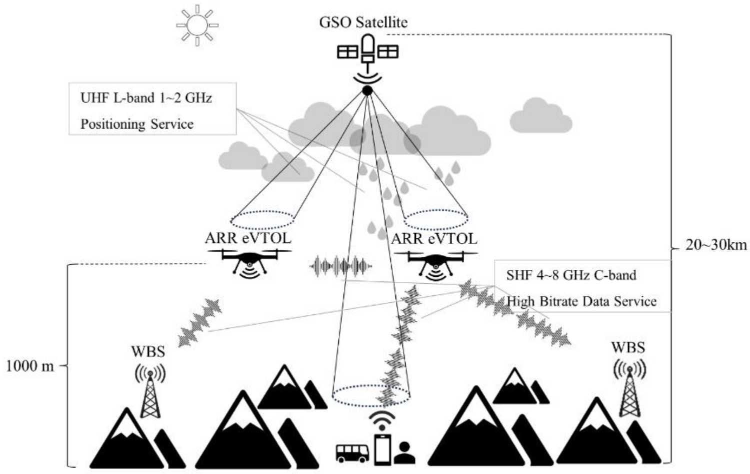


Figure 2. Low-altitude emergency strategy for ad-hoc radio relay eVTOLs with GSO.

However, LES for ARR eVTOLs in synergy with GSO involves cost-benefit trade-off, both for the disruptor and the counteractor. In the third section, we build this trade-off into an LES disturbance – counteract differential evolutionary game (LES DC), study and discuss the evolutionarily stable strategy (ESS), and verify the ESS through simulation.

Our study contributes to the theoretical and practical strategies concerning the low-altitude economy. Firstly, by reviewing existing literature on the low-altitude economy, low-altitude technologies, and ecological risks in the ASEAN region's karst terrain, we identify research gaps and practical needs for building Ad-hoc emergency wireless networks with RR-equipped eVTOLs. Secondly, we propose the LES ARR eVTOLs in synergy with GSO and convert this issue into an LES disturbance – counteract differential game for analysis. A key contribution of our work is providing a theoretical foundation for the security issues of Ad-hoc RR eVTOL wireless networks.

RELATED WORKS

The emergence of low-altitude technologies and the transformation brought by eVTOLs have been significant. Drones entered the academic and practical realms through a transition from military to civilian and commercial use, marked by institutional changes [7] and the exploration of their potential and challenges in smart cities [8]. eVTOLs (Electric Vertical Take-off and Landing) are a technological branch of UAVs (Unmanned Aerial Vehicles). Pavel systematically analyzed the main features of eVTOLs, highlighting their use of high-density, high-capacity lithium batteries and multi-rotor control systems to achieve vertical take-off and landing [1]. This grants them advantages such as quiet operation, efficiency, and minimal space restrictions. Xu et al. noted that various countries are considering policy and technological measures to regulate eVTOL operations [9]. These studies outline the development blueprint of the low-altitude economy, showcasing the potential of eVTOL technology in future transportation systems and the economic and social changes they may bring. eVTOLs have demonstrated advantages in applications within urban air mobility [10,11], logistics and delivery [12,13], and emergency rescue operations [14-16].

In terrain constraints and geological protection restrictions, the value of low-altitude technologies becomes prominent. The southwestern region of China, bordering ASEAN, is characterized by complex karst topography [17]. Huang et al. and Pang et al. indicate the expansion of human activities in ASEAN region is leading to a decreasing trend in arable land, forests, and landscape areas [18,19]. Chang et al. developed a landslide risk assessment model to measure the vulnerability and susceptibility of the karst terrain in Beihai City, Guangxi [5]. Considering both ecological protection and safety threats, eVTOLs equipped with wireless relays offer agility for performing high-risk tasks such as production, logistics, research, and rescue in the karst terrains of ASEAN. Luo et al. tested the network performance of 530 MHz, 670 MHz, and 1.4 GHz frequency bands after penetrating karst caves and conducted loss modeling and bending modeling [20]. The limitation noted was the lack of testing in the 4-8 GHz C-band SHF frequency range, which is used for high bit rate data services.

Research on eVTOL networking and communication technologies is also gradually emerging. Al-Rubaye et al. noted that one of the challenges faced by Advanced Air Mobility (AAM) is insufficient wireless coverage, which affects the large-scale deployment of eVTOLs, especially in crowded urban and remote areas [21]. The unique trajectories of eVTOLs lead to changes in channel conditions, and controlling the carbon footprint and operational costs of 5G and next-generation networks remains a challenge when pursuing high spectral efficiency and communication performance. Aryendu et al. optimized the fairness and efficiency of spectrum resource use for multi-user eVTOL communication in the context of Citizens Broadband Radio Service (CBRS) and C-band applications by employing a bargaining game approach [22].

Further research is needed on low-altitude integrated wireless network attack and defense. Chen et al. improved the efficiency and safety of eVTOL operations in low-altitude airspace by utilizing a multi-model algorithm, dynamic conflict detection methods, and an improved artificial potential field method within a geographic coordinate system, providing a feasible basis for eVTOL maneuverability [23]. Xie et al. proposed a machine learning security active defense model (MLSADM) that enhances network security in the face of cyber threats [24]. Islam et al. analyzed different layers of denial of service attacks and their defense mechanisms in wireless sensor networks [25]. Manikanta et al. proposed an adaptive threat defense model that can quickly identify Wi-Fi network attackers and employ diversified self-defense strategies to counteract attacks and prevent hijacking [26]. Chen et al. explored the use of AI and 2.4GHz wireless networks to implement attack and defense command technologies in eVTOL swarm systems, enhancing defense capability and flexibility in low-altitude airspaces [27]. Alismail et al. proposed an IP and port hopping algorithm framework specifically designed for drone networks, which enhances network unpredictability by integrating moving target defense with 6G software-defined networks and increases drone network security using honeypot strategies to counter reconnaissance-based cyberattacks [28].

For wireless network technology innovation, open-source SDRs are akin to a “double-edged sword”. Seal et al. transformed an SDR receiver into a complete pulse radar system for observing meteor reflection data in the atmosphere using open-source methods [29]. Perotini et al. developed a low-cost spectrum analyzer with open-source SDR, overcoming the limitations of hardware analog-to-digital converters [30]. Abdalla et al. experimentally validated the feasibility of establishing a low-altitude drone node cellular network using open-source SDR [31]. Palamà et al. utilized open-source SDR to establish a 5G positioning test environment, reducing testing costs [32]. Harianto et al. described FM communication simulations using GNU Radio and RTL-SDR, validated with a spectrum analyzer, achieving high accuracy in transmitter power and signal-to-noise ratio measurements [33], demonstrating the potential threats of SDR. Rugeles et al. reviewed vulnerabilities in IoT wireless technologies and the experience of using software-defined radio (SDR) to implement attacks, identifying the perception layer as the most vulnerable due to hardware limitations and device heterogeneity, which suggested enhancing future IoT security systems’ flexibility and adaptability by combining cognitive intelligence techniques and deep learning [2]. Achaal et al. demonstrated how to use low-cost equipment to carry out wireless attacks with software-defined radio (SDR), revealing the risk that attackers can easily disrupt and access various wireless communication services and networks, highlighting the threat SDR technology poses to wireless communication security [34]. Omar et al. demonstrated techniques for countering threats to radio security using SDR against low-altitude aircraft, which involved using replay attack techniques via SDR to intercept and replay signals between drones and their controllers, thereby disrupting or taking over drone control to prevent entry into restricted airspace [35].

The above studies indicate that despite the significant economic potential of eVTOL in low-altitude scenarios, comprehensive research on security strategies is needed for their application in emergency communications, particularly under complex terrains and SDR wireless network threats. Building on existing research, we transform the security issues of LES Ad-hoc RR eVTOLs with GSO into a differential game, analyzing stable strategies to support the secure application of the low-altitude economy.

MODEL ANALYSIS

Assumptions

This section employs the PAPI framework (Players – Actions – Payoffs – Information) [36] to provide a structured explanation of the game model.

Assumption 1: Players. In the LES ARR eVTOL in synergy with GSO game, the disruptor is denoted as participant D. The counteractor is denoted as participant C. Parameters are depicted in symbols and described in Table 1.

Table 1. Depicted symbols and descriptions

Symbol	**Type**	**Description**
θ	probabilistic	Probability of implementing {Disturbance}
ω	probabilistic	Probability of implementing {Counteract}
G_D	economical	Benefits gained by Participant D for implementing strategy {Disturbance}
C_D	economical	Costs consumed by Participant D to implement strategy {Disturbance}
S_P	probabilistic	Probability of Participant D's success in implementing {Disturbance}
G_C	economical	Benefits gained by Participant C from implementing the strategy {Counteract}
C_C	economical	Costs consumed by Participant C to implement the strategy {Counteract}
L_C	economical	Loss suffered by Participant C when Participant D's {Disturbance} is successful

Assumption 2: Actions. Participant D's strategy set is {D - Disturbance, ND - Not Disturbance}, and the probability of implementing {Disturbance} is $\theta \in [0,1]$. The strategy set of participant C is {C - Counteract, NC - Not Counteract} and the probability of implementing {Counteract} is $\omega \in [0,1]$. D acts first and C responds. The strategy space is obtained from the dynamic process of the game as ({D}×{C}, {D}×{NC}, {ND}×{C}, {ND}×{NC}) (Figure 3).

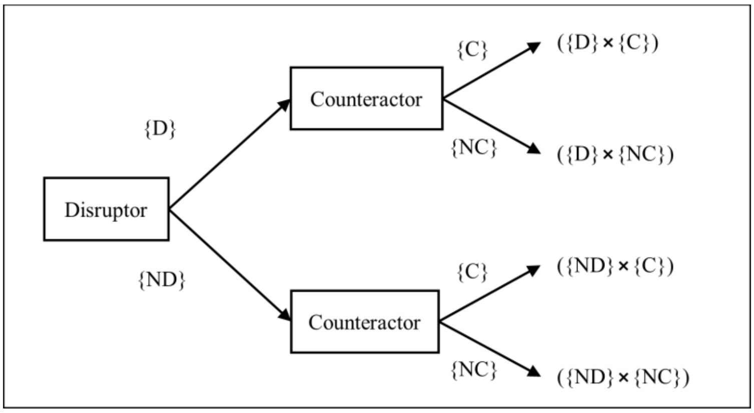


Figure 3. The dynamic extend form for LES ARR eVTOL in synergy with GSO

Assumption 3: Payoffs. Participant D employs the strategy {Disturbance} to achieve benefits such as acquiring base station information, disrupting the opponent's connectivity, and creating opportunities for their own side, collectively represented as G_D. The costs incurred include investments in hardware and software resources, denoted as C_D, and the probability of successfully implementing {Disturbance} is represented as S_P. On the other hand, Participant C uses the strategy {Counteract} to gain data value revenue from restoring connectivity, represented as G_C. The costs for Participant C include expenses for equipment, labor for signal modulation, and the power required to deploy the Ad-hoc RR on the eVTOL, denoted as C_C. Additionally, the losses in equipment and data value that occur when Participant C is affected by Participant D's {Disturbance} are represented as L_C. The payoff matrix depicted in Table 2.

Table 2. The payoff matrix

		Counteractor	
		Action: {C} Probability: ω	Action: {NC} Probability: $1-\omega$
Disruptor	Action: {D} Probability: θ	$-C_D$, $G_C - C_C - S_P \times L_C$	$G_D - C_D$, $-L_C$
	Action: {ND} Probability: $1-\theta$	0, $G_C - C_C$	0, G_C

Assumption 4: Information. The game information is complete, meaning that each participant's strategies and payoffs are public knowledge. When the game is represented in a dynamic extensive form (refer to Figure 3 above), Participant C makes decisions based on Participant D's strategies, thus the game is of perfect information.

Assumption 5: The strategies of both participants in this game are continuously time-varying.

Replicated Dynamic Equations

The expected gain from participant Disruptor taking {D} is denoted as π_D π_{t1}.s

$$\pi_D = \omega*(-C_D)+(1-\omega)*(G_D - C_D) \tag{1}$$

The expected gain from participant Disruptor taking {ND} is denoted as π_{ND}.

$$\pi_{ND} = \omega*0+(1-\omega)*0 \tag{2}$$

The Disruptor's average expected gain is denoted as $\overline{\pi_1}$.

$$\overline{\pi_1} = \theta*\pi_D + (1-\theta)*\pi_{ND} \tag{3}$$

The expected gain from participant Counteractor taking {C} is denoted as π_C.

$$\pi_C = \theta*(G_C - C_C - S_P*L_C)+(1-\theta)*(G_C - C_C) \tag{4}$$

The expected gain from participant Counteractor taking {NC} is denoted as π_{NC}.

$$\pi_{NC} = \theta*(-L_C)+(1-\theta)*G_C \tag{5}$$

The Counteractor's average expected gain is denoted as $\overline{\pi_2}$.

$$\overline{\pi_2} = \omega*\pi_C + (1-\omega)*\pi_{NC} \tag{6}$$

According to Assumption 5, the strategies of both participants are continuously time-varying, and therefore the replicator dynamic equations of this evolutionary game system can be derived in the form of differential equations.

$$\begin{cases} \Phi(\theta)=\dfrac{d\theta}{dt}=\theta*(\pi_D-\bar{\pi}_1)=\theta*(1-\theta)*[(1-\omega)*G_D-C_D] \\ \Psi(\omega)=\dfrac{d\omega}{dt}=\omega*(\pi_C-\bar{\pi}_2)=\omega*(1-\omega)*[\theta*[G_C+(1-S_P)*L_C]-C_C] \end{cases} \tag{7}$$

ESS and Simulation

Let equations in (7) equal zero, respectively, yields five equilibriums:

$$E_1(0,0), E_2(1,0), E_3(0,1), E_4(1,1), E_5\left(\theta^* = \frac{C_C}{G_C + L_C(1-S_P)}, \omega^* = 1-\frac{C_D}{G_D}\right) \tag{8}$$

Observe participant D's dominant strategy. When $\omega' \in (1-\frac{C_D}{G_D}, 1]$, {Not Disturbance} is participant D's dominant strategy. When $\omega' = 1-\frac{C_D}{G_D}$, participant D has no dominant strategy. When $\omega' \in [0, 1-\frac{C_D}{G_D})$, participant D has dominant strategy {Disturbance}.

Observe participant C's dominant strategy. When $\theta' \in (\frac{C_C}{G_C+L_C(1-S_P)}, 1]$, participant C has dominant strategy {Counteract}. When $\theta' = \frac{C_C}{G_C+L_C(1-S_P)}$, participant C has no dominant strategies. When $\theta' \in [0, \frac{C_C}{G_C+L_C(1-S_P)})$, participant C has dominant strategy {Not Counteract}.

Taking the partial derivatives of equation (7), we obtain the Jacobian matrix. By substituting the five equilibrium points from equation (8) into this matrix, we can calculate the eigenvalues corresponding to each equilibrium. Observe the inequality constraints (9)~(13) below implied by the economic significance of the variables within these eigenvalues to determine the Evolutionarily Stable Strategy (ESS) as presented in Table 3.

$$G_D - C_D > 0 \tag{9}$$

$$G_C + L_C\left(1 - S_P\right) - C_C > 0 \tag{10}$$

$$G_D - C_D < 0 \tag{11}$$

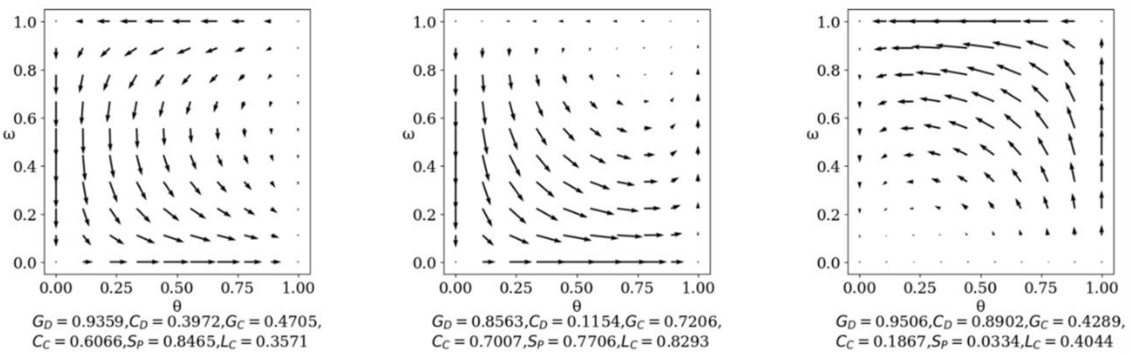
$$G_C + L_C\left(1 - S_P\right) - C_C < 0 \tag{12}$$

$$C_D < 0 \tag{13}$$

Table 3. Eigen value and ESS determination based on five equilibriums

Equilibrium Point	$\boldsymbol{\lambda_1}$	$\boldsymbol{\lambda_2}$	**Condition 1 (9), (10)**	**Condition 2 (10), (11)**	**Condition 3 (11), (12)**	**Condition 4 (10), (13)**	**Condition 5 (12), (13)**
$E_1(0,0)$	$-C_D + G_D$	$-C_C$	$+,-$ → **NS**	$-,-$ → **ESS**	$-,-$ → **ESS**	$+,-$ → **NS**	$+,-$ → **NS**
$E_2(1,0)$	$C_D - G_D$	$-C_C + G_C + L_C(1-S_P)$	$-,+$ → **NS**	$+,+$ → **Saddle**	$+,-$ → **NS**	$-,+$ → **NS**	$-,-$ → **ESS**
$E_3(0,1)$	$-C_D$	C_C	$-,+$ → **NS**	$-,+$ → **NS**	$-,+$ → **NS**	$+,+$ → **Saddle**	$+,+$ → **Saddle**
$E_4(1,1)$	C_D	$C_C - G_C - L_C(1-S_P)$	$+,-$ → **NS**	$+,-$ → **NS**	$+,+$ → **Saddle**	$-,-$ → **ESS**	$-,+$ → **NS**
$E_5(\theta^*, \omega^*)$	0	0	0,0 → **NS**	0,0 → **NS**	0,0 → **NS**	0,0 → **NS**	0,0 → **NS**

Condition 1 indicates that when both participants consider a positive net payoff from their strategies, there is no Evolutionarily Stable Strategy (ESS) in the game (Figure 4).



(a) Not Stable in $E_2(1,0)$ (b) Not Stable in $E_4(1,1)$ (c) Not Stable in $E_0(0,0)$

Figure 4. Vector field simulation on condition 1

Condition 2 indicates that when participant D can tolerate a negative net payoff from their strategy, they tend to implement {Disturbance}. The game fluctuates around the saddle point $E_2(1,0)$ and stabilizes at $E_1(0,0)$ (Figure 5).

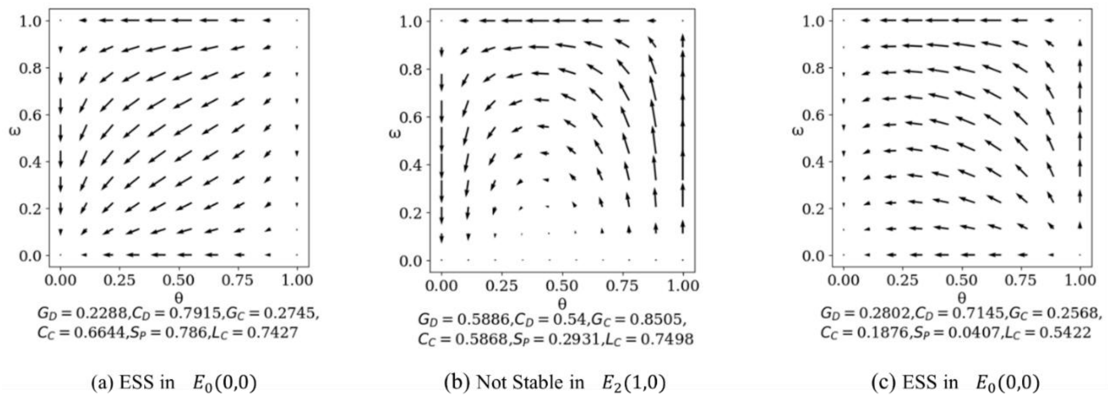


Figure 5. Vector field simulation on condition 2

Condition 3 indicates that when participant C can also tolerate a negative net payoff from their strategy, they tend to implement {Counteract}. The game fluctuates around the saddle point $E_4(1,1)$ and stabilizes at $E_1(0,0)$ (Figure 6).

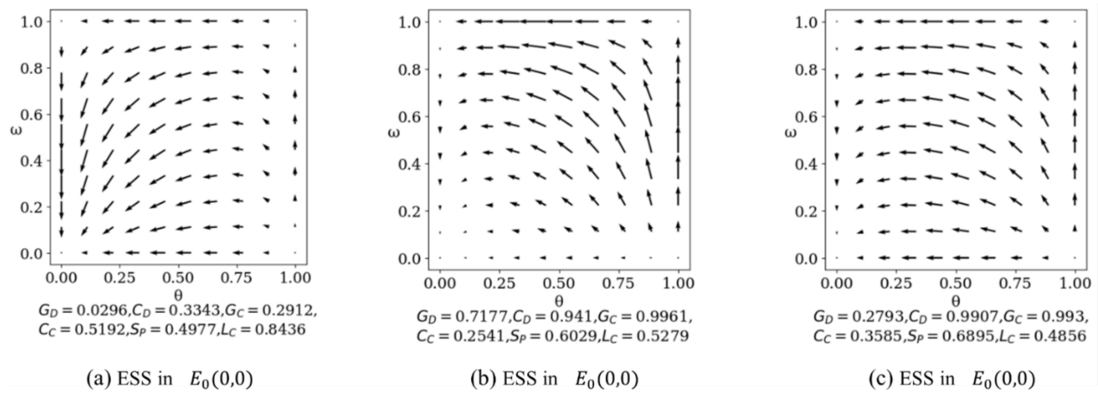


Figure 6. Vector field simulation on condition 3

Condition 4 indicates that when participant D can implement {Disturbance} without considering the cost, participant C tends to proactively implement {C} if they are considering a positive net payoff. As a result, the game fluctuates around the saddle point $E_3(0,1)$ and stabilizes at $E_4(1,1)$ (Figure 7).

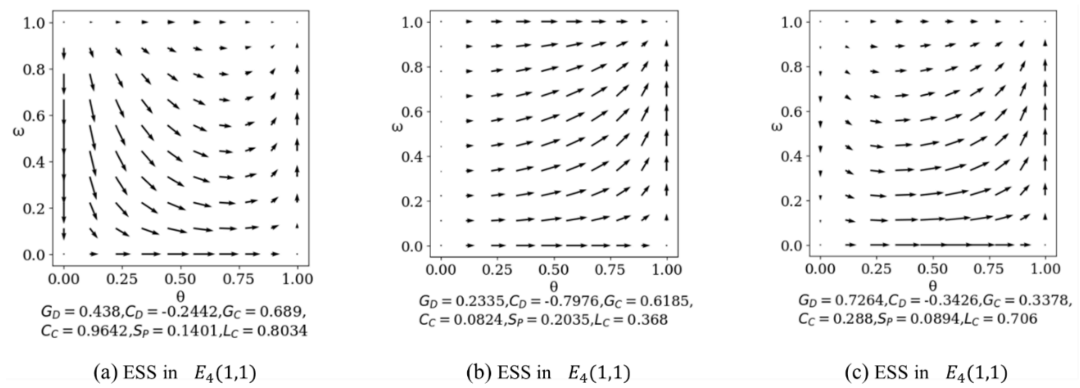
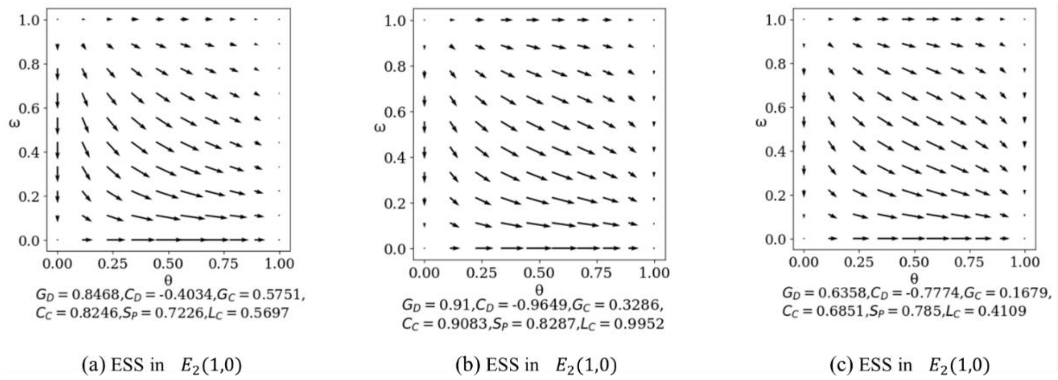


Figure 7. Vector field simulation on condition 4

Condition 5 indicates that when participant D can implement {Disturbance} without considering the cost, participant C tends to adopt {Not Counteract} if they can tolerate a negative net payoff. The game then has an evolutionarily stable strategy at $E_2(1,0)$ (Figure 8).



(a) ESS in $E_2(1,0)$ (b) ESS in $E_2(1,0)$ (c) ESS in $E_2(1,0)$

Figure 8. Vector field simulation on condition 5

CONCLUSION

This paper reviews recent research trends in LAE, eVTOL technology, karst topography, and open source SDR wireless security, highlighting the use of Ad-hoc Radio Relay eVTOLs in synergy with GSO to counteract radio disturbance and enhance communication accessibility and quality under terrain constraints.

We examined the coverage of coastal wireless base stations from 24°48′33″N, 107°52′31″E to 24°45′44″N, 107°53′51″E along Hechi Muluojia Canyon coastline in Guangxi, China, with a straight-line distance of approximately 5.667 km. We identified issues regarding high-quality radio communications in similar areas or terrains, which are crucial for low-altitude wireless security in remote and border karst regions amidst current trends in LAE development. Consequently, we proposed the Low-altitude Emergency Strategy (LES) for Ad-hoc Radio Relay eVTOLs with GSO, detailing a three-step implementation process. This LES is realized through the synergetic information between users, ARR eVTOLs, and GSO, allowing for agile disturbance mitigation, which constitutes the theoretical contribution of this paper.

To generalize the problem, the cost-benefit of both disruptor and counteractor is considered, and an LES Disturbance-Counteract differential evolutionary game model is developed, with five equilibrium points obtained. The ESSs are obtained based on the conditions of whether participants can endure a negative net payoff and whether they can disregard costs, thereby providing a theoretical basis for security issues involving low-altitude eVTOL ad hoc network interference mitigation.

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