SEVERAL CHALLENGES ASSOCIATED WITH UAV COMMUNICATION NETWORKS

Luu Thi Hiep[(1)]

(1) Thu Dau Mot University

Corresponding author: hieplt@tdmu.edu.vn

DOI: 10.37550/tdmu.EJS/2024.02.545

Article Info

Volume: 6
Issue: 02
June 2024
Received: Mar. 23rd, 2024
Accepted: April 6th, 2024
Page No: 193-201

Abstract

In recent times, there has been a rapid surge in the advancement of technologies associated with Unmanned Aerial Vehicles (UAVs), particularly in the domains of sensors, networking, and processing. The evolution of design methodologies and the exploration of UAV systems have transitioned from single UAV applications to encompass multi-UAVs and cooperative UAV systems. These systems necessitate a heightened level of coordination and collaboration to execute tasks, demanding innovative networking models, approaches, and mechanisms tailored for highly mobile nodes, encompassing numerous intricate parameters and constraints. The present paper provides comprehensive insights and conducts a meticulous examination of UAV communication protocols, networking systems, architectures, and applications. Furthermore, the paper delves into UAV solutions while underscoring critical technical challenges and unresolved research issues that warrant further investigation and dedicated research and development endeavors. We study some problems and solutions for The Command and Control (C2) aspect of UAV communication systems. We also give some directions for research in near future.

Keywords: communication, solutions, system, the command and control, UAV

1. Introduction

Recent advancements in the design and enhancement of Unmanned Aerial Vehicles (UAVs) of diverse sizes and configurations, coupled with advancements in their communication capabilities, have been marked by swift progress. UAVs possess the capability to operate autonomously through integrated microprocessors or can be remotely controlled without the need for human intervention. Due to their adaptability, straightforward installation, cost-effectiveness in terms of maintenance, versatility, and relatively minimal operational expenses, the utilization of UAVs opens up novel avenues for applications across commercial, military, civilian, agricultural, and environmental sectors.

These applications encompass border surveillance (Akyildiz et al., 2007; Agmon et al., 2011), functioning as relays for ad hoc networks (Taherkordi et al., 2006; Han et al., 2009), wildfire management (Kanchanasut, 2007), monitoring disasters (Capitan et al., 2009), wind estimation (Rodríguez et al., 2007), traffic supervision (Caffarelli et al., 2003; Kontitsis et al., 2005), remote sensing (Herwitz et al., 2004), and engaging in search and destroy operations (Nygard et al., 2001).

Several of these applications necessitate the utilization of a singular UAV system, while endeavors such as monitoring hazardous environments encompass the deployment of multi-UAV systems. Despite the longstanding use of single-UAV systems, the exploitation of a fleet of small UAVs presents numerous advantages over relying on a solitary large UAV. In the realm of single UAV systems, each UAV functions as an independent node, restricted solely to communication with the ground node. Consequently, the UAV communication system relies exclusively on UAV-to-infrastructure communication, with inter-UAV communication facilitated through the infrastructure. The capabilities of a single UAV system are inherently limited when juxtaposed with the myriad advantages offered by multi-UAV systems. Firstly, missions undertaken by multi-UAV systems are generally accomplished at a reduced cost. Furthermore, the collaborative synergy among UAVs enhances overall system performance. Additionally, in a multi-UAV system, the failure of one UAV during a mission does not jeopardize the entire operation, as the remaining UAVs can seamlessly compensate, resulting in more expeditious and efficient mission completions.

Individual UAV systems serve the purpose of navigating and controlling the monitoring of distant targets, particularly in unfamiliar geographical areas and flight conditions, thereby mitigating the risk of pilot loss. The term “single UAV system” does not imply the exclusive presence of just one UAV within the network; instead, the network may encompass multiple UAVs. Within this system, each UAV functions as an independent node, as illustrated in Figure 1. The central node is positioned on the ground, facilitating direct communication between the UAVs and the ground node. Consequently, the UAV communication system relies solely on communication between UAVs and the infrastructure.

Fig 1. Singular UAV systems (https://www.thedefensepost.com)

Singular UAV systems play a crucial role in overseeing distant targets by providing navigation and control, particularly in unexplored geographical regions and challenging flight conditions, with the primary objective of avoiding any potential harm to pilots. It's essential to clarify that the term “single UAV system” does not imply the exclusive presence of only one UAV; rather, the network may encompass numerous UAVs. Within this framework, each UAV functions autonomously as a distinct node, as depicted in Figure 1. The ground node is centrally located, facilitating direct communication between the UAVs and the ground node. Consequently, the UAV communication system is exclusively reliant on communication between UAVs and the infrastructure.

Multi-UAV (Unmanned Aerial Vehicle) systems are designed to leverage the collective capabilities of multiple UAVs, providing enhanced functionality and flexibility in various applications. Unlike single UAV systems, which may be limited in their scope, multi-UAV systems allow for simultaneous operation and collaboration among several unmanned vehicles. We list some key aspects and advantages of multi-UAV systems:

a) Cooperative Mission Execution:

Multi-UAV systems enable collaborative execution of complex missions. UAVs within the network can share information, coordinate tasks, and work together to achieve common objectives, such as large-area surveillance or search and rescue operations.

b) Increased Coverage and Efficiency:

The simultaneous deployment of multiple UAVs expands the coverage area and accelerates task completion. This leads to improved efficiency in tasks like monitoring, mapping, and data collection, where multiple perspectives enhance the overall quality of information gathered.

c) Redundancy and Reliability:

Redundancy is a built-in advantage of multi-UAV systems. In the event of a malfunction or failure in one UAV, others can seamlessly take over, ensuring continuous mission operation. This redundancy enhances the overall reliability of the system.

d) Flexibility in Task Allocation:

Multi-UAV systems offer the flexibility to dynamically allocate tasks based on real-time requirements and environmental conditions. This adaptability allows for optimized resource utilization and responsiveness to changing mission parameters.

f) Swarm Intelligence:

Some multi-UAV systems leverage swarm intelligence, where UAVs communicate and collaborate in a decentralized manner, mimicking natural swarm behavior. This approach enables self-organization, adaptability, and resilience in the face of dynamic challenges.

j) Enhanced Communication Networks:

Multi-UAV systems often utilize advanced communication networks, enabling seamless information exchange among UAVs and with ground control stations. This robust communication infrastructure is vital for real-time coordination and data sharing.

g) Scalability:

Multi-UAV systems are scalable, allowing for the integration of additional UAVs as needed. This scalability is advantageous in scenarios where the mission requirements or the size of the operational area may change.

h) Versatility in Applications:

Multi-UAV systems find applications across various sectors, including agriculture, environmental monitoring, disaster response, and defense. Their versatility makes them adaptable to a wide range of tasks and mission profiles.

i) Improved Data Fusion:

Multiple UAVs can capture diverse data streams simultaneously, facilitating improved data fusion. Combining information from different sensors and viewpoints enhances the overall accuracy and richness of the collected data.

j) Research and Development Opportunities:

The development of multi-UAV systems presents exciting opportunities for research and innovation. Addressing challenges related to swarm coordination, communication protocols, and autonomous decision-making contributes to advancements in the field of robotics and aerial systems.

2. Preliminaries

UAVs find applications across diverse scenarios and manifest in various configurations. As illustrated in Figure 2, numerous classification methods exist to categorize them accordingly. A common classification approach involves grouping UAVs based on their wing type into fixed-wing, rotary-wing, and flapping-wing categories. Weight-based classification divides UAVs into micro (< 1kg), miniature (1-25kg), and heavier (> 25kg) classes. Researchers outlined alternative classification methods, considering flight endurance/range, leading to categorizations of short (< 5h, < 100km), medium (5-24h, 100-400km), and long-range (> 24h, > 1500km) UAVs. Moreover, UAVs can be distinguished by their maximum flying height, classifying them as low altitude (< 1km), medium altitude (1-10km), and high altitude (> 10km) UAVs. It's worth noting that UAVs are not confined to aerial domains; they can also navigate water surfaces or operate underwater. Expanding this perspective, some research classified such UAVs into seaplane UAVs, submarine-launched UAVs, and underwater UAVs, thereby broadening the scope of UAV classification.

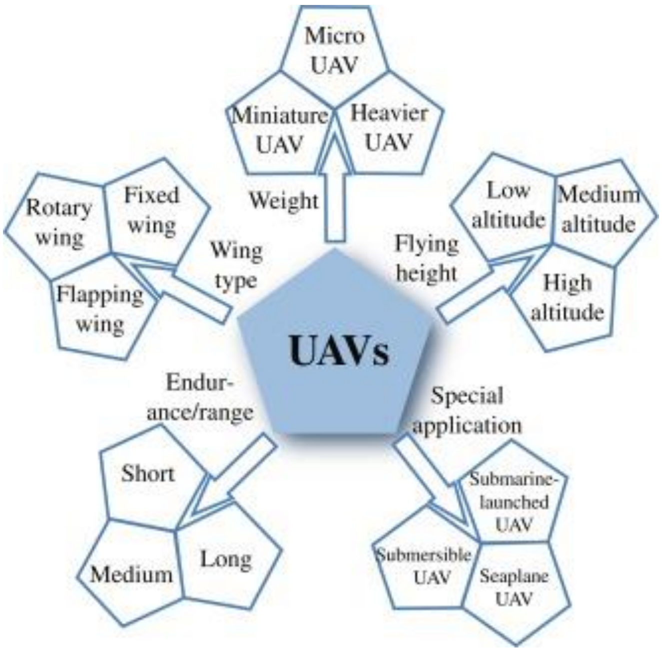

Fig 2. UAV classification (https://www.thedefensepost.com)

Unmanned Aerial Vehicles (UAVs), commonly known as drones, come in various types and sizes, each designed for specific applications. The classification of UAVs is based on their size, purpose, range, and operational capabilities. We list here several categories with detailed explanations of UAV systems.

a. Nano UAVs:

Size: Extremely small, typically less than 100mm in diameter.

Purpose: Nano UAVs are designed for tasks that require miniature dimensions, such as indoor surveillance, monitoring confined spaces, or biological research.

b. Micro UAVs:

Size: Small, typically between 100mm to 550mm in diameter.

Purpose: Micro UAVs are versatile and find applications in reconnaissance, surveillance, and hobbyist activities. They are suitable for short-range missions and are often used in urban environments.

c. Mini UAVs:

Size: Compact, ranging from 550mm to 1.5 meters in wingspan.

Purpose: Mini UAVs are commonly employed for surveillance, mapping, and monitoring. They offer increased payload capacity and endurance compared to micro UAVs, making them suitable for various commercial and military applications.

d. Small UAVs:

Size: Medium-sized, with a wingspan between 1.5 to 6 meters.

Purpose: Small UAVs are capable of carrying more significant payloads and can cover longer distances. They are employed in applications such as agriculture, environmental monitoring, and border surveillance.

e. Medium UAVs:

Size: Larger than small UAVs, with wingspans ranging from 6 to 20 meters.

Purpose: Medium UAVs have extended endurance and payload capacity, making them suitable for tasks like long-range surveillance, aerial mapping, and scientific research.

f. Large UAVs:

Size: Considerable size, with wingspans exceeding 20 meters.

Purpose: Large UAVs are designed for heavy payloads, extended endurance, and high-altitude operations. They are used in applications such as military reconnaissance, cargo transport, and scientific data collection.

g. Fixed-Wing UAVs:

Design: Shaped like traditional airplanes with fixed wings.

Purpose: Fixed-wing UAVs are known for their efficiency in long-endurance flights and covering large areas. They are commonly used in mapping, surveillance, and agriculture.

h. Rotary-Wing UAVs:

Design: Equipped with rotating wings or rotors, such as helicopters or quadcopters.

Purpose: Rotary-wing UAVs are versatile and can hover in place, making them suitable for tasks like aerial photography, surveillance, and search and rescue operations.

i. Vertical Takeoff and Landing (VTOL) UAVs:

Design: Capable of taking off and landing vertically.

Purpose: VTOL UAVs combine the advantages of both fixed-wing and rotary-wing designs. They are used in scenarios where a runway may be impractical, such as urban environments or maritime operations.

j. Hybrid UAVs:

Design: Combines features of both fixed-wing and rotary-wing designs.

Purpose: Hybrid UAVs offer the flexibility of vertical takeoff and landing along with the efficiency of fixed-wing flight. They are employed in applications requiring versatility, such as surveillance and reconnaissance in challenging terrains.

3. Main Results

(UAVs) rely on sophisticated communication systems to facilitate control, navigation, and data exchange between the UAVs themselves and their ground control stations. The communication architecture for UAVs encompasses various elements, each serving a specific purpose in ensuring reliable and secure operations. Command and Control (C2) Link is crucial for transmitting commands from the ground control station to the UAV and receiving telemetry data, including GPS coordinates, altitude, and system health. Typically established through radio frequency (RF) communication, satellite links, or a combination of both, depending on the UAV's range and operational environment. Encryption and authentication protocols are implemented to secure the C2 link against unauthorized access or cyber-attacks.

The Command and Control (C2) link is a critical component of Unmanned Aerial Vehicles (UAVs) communication systems, responsible for transmitting commands from the ground control station to the UAV and relaying real-time telemetry data back to the operators. The reliability and security of the C2 link are paramount for safe and effective UAV operations.

The most common method for establishing the C2 link is through RF communication. RF signals are transmitted between the ground control station and the UAV using dedicated frequencies and modulation techniques. In scenarios where the UAV operates over long distances or in remote areas, satellite communication may be employed to establish a C2 link. This ensures global coverage and beyond line-of-sight operations. C2 links often operate on specific frequency bands allocated for UAV communication. These frequency bands are regulated to avoid interference with other communication systems and to ensure a reliable and interference-free C2 link. Some UAV communication systems may utilize Industrial, Scientific, and Medical (ISM) bands, subject to regulatory approval. These bands offer flexibility but may be more susceptible to interference.

To enhance reliability, C2 links often incorporate redundancy by using multiple communication channels or protocols. This ensures continuous communication in the event of signal disruptions or interference on a particular channel.

Intelligent switching algorithms may be employed to automatically switch between primary and backup channels based on signal strength, quality, or predefined criteria.

Both the ground control station and the UAV may be equipped with directional antennas to establish and maintain a strong and focused communication link. This is especially important for long-range and beyond line-of-sight operations. Advanced systems use automated antenna tracking to maintain a consistent and stable connection by continuously adjusting the antenna orientation to track the UAV's position.

Encryption protocols are implemented to secure the C2 link against unauthorized access and cyber threats. Common encryption methods include Advanced Encryption Standard (AES) and secure key exchange protocols. Authentication mechanisms ensure that only authorized ground control stations can communicate with the UAV, preventing potential hijacking or tampering. Ground control stations often monitor the signal strength of the C2 link in real-time. If the signal strength drops below a predefined threshold, the system can take corrective actions or switch to a backup channel.

Error correction techniques are employed to detect and correct data errors that may occur during transmission, ensuring the integrity of the communicated commands and telemetry data.

From discussion above, we give the following problem and the solution. This is an issue that may arise in UAV activities, highlighting the importance of Command and Control, which needs to be extensively researched to accommodate UAV models ranging from simple to complex.

Problem 1: In a military operation, a ground-based command center relies on a satellite-based C2 link to communicate with deployed units in remote areas. However, intelligence reports indicate that adversaries are deploying sophisticated jamming devices in the vicinity, posing a significant threat to the reliability and security of the C2 link.

• Solution Approach:

• Step 1: We need to consider the identification of threats and vulnerabilities. Indeed, analyze intelligence reports and conduct on-the-ground assessments to identify potential jamming threats targeting the satellite-based C2 link.

Determine the frequency bands and modulation schemes used by the adversaries' jamming devices.

• Step 2: We must assessment of existing systems. We will check evaluate the satellite communication infrastructure and equipment deployed for the C2 link and assess the capabilities of the satellite communication system in detecting and mitigating jamming attacks.

• Step 3: After Steps 1 and 2, we have development of countermeasures. Then we need to design and implement signal processing algorithms capable of detecting and mitigating jamming signals within the satellite communication system andIncorporate frequency hopping and spread spectrum modulation techniques to make the C2 link more resilient against jamming attacks.

• Step 4: After Step 3, we need to check implementation of redundancy and diversity again by deploying redundant satellite links and ground-based communication relays to establish alternative communication paths in case of jamming-induced disruptions. Utilizing multi-path routing algorithms to dynamically switch between communication channels based on real-time jamming threat assessments.

• Step 5: Since implementation of redundancy and diversity is fixed, the deployment of encryption and authentication is an important step. Implement end-to-end encryption protocols to secure data transmitted over the C2 link, preventing unauthorized access and interception by adversaries. By Integrating authentication mechanisms to verify the authenticity of communication endpoints and prevent spoofing attacks, we can do implementation of redundancy and diversity completely.

• Step 6: To check Step 5, the testing and validation are very important. Conducting extensive field tests and simulations to evaluate the effectiveness of the countermeasures against various jamming scenarios, we can validate the resilience of the satellite communication system under realistic operational conditions and jamming threats.

• Step 7: To continue monitoring and adaptation, we need to have the followings:

+ Deploy monitoring systems capable of detecting anomalous signal patterns indicative of jamming attacks on the C2 link.

+ Implement adaptive strategies to dynamically adjust communication parameters and countermeasures in response to evolving jamming tactics employed by adversaries.

+ Training and Preparedness:

Provide training to personnel operating the satellite communication system on detecting and responding to jamming threats.

Develop contingency plans and emergency procedures to maintain communication continuity during jamming-induced disruptions.

Collaboration and Information Sharing:

Collaborate with satellite communication providers, defense contractors, and government agencies to share threat intelligence and best practices for mitigating jamming attacks.

Participate in joint exercises and information sharing initiatives within the defense community to enhance collective resilience against jamming threats.

• Step 8: We need to receive regular updates and evolution:

Stay abreast of advancements in satellite communication technology and jamming mitigation techniques.

Regularly update and enhance the satellite communication system's capabilities to adapt to emerging jamming threats and maintain a robust C2 link for military operations.

4. Conclusion

The Command and Control (C2) aspect of UAV communication systems is pivotal for ensuring effective and secure operations. It involves the transmission of commands from the ground control station (GCS) to the UAV, as well as the exchange of real-time telemetry data to monitor and control the UAV's flight. In this paper, we give some problems and solutions for The Command and Control (C2) aspect of UAV communication systems. We finish the’paper by providing some open problems and some hint for readers.

• Problem 1: The C2 link may have limited range, restricting the operational radius of the UAV.

• Solution for problem 1: Utilize high-gain antennas, satellite communication for beyond line-of-sight operations, and explore advanced communication technologies like mesh networks to extend the communication range.

• Problem 2: Insufficient data transfer rates may lead to latency issues and hinder real-time control and telemetry data exchange.

• Solution for problem 2: Upgrade communication equipment to support higher data rates, utilize modern communication protocols, and explore the use of advanced modulation techniques to improve overall bandwidth.

• Problem 3: Urban environments with tall buildings may block the line of sight, causing signal shadowing and communication disruptions.

• Solution for problem 3: Implement adaptive communication protocols, use relay stations or mesh networks to overcome obstacles, and consider deploying UAVs with the capability to maintain communication in non-line-of-sight conditions.

• Problem 4: The C2 link is susceptible to cyber threats, including unauthorized access, data breaches, and denial-of-service attacks.

• Solution for problem 4: Employ strong encryption algorithms, regularly update security protocols, and implement multi-factor authentication to protect against cyber-attacks. Conduct cybersecurity assessments and audits to identify and address vulnerabilities.

• Problem 5: Without backup systems, a single point of failure in the C2 link can lead to mission failure or loss of control.

• Solution for problem 5: Implement redundancy by using multiple communication channels, establishing backup ground control stations, and employing intelligent switching algorithms to automatically switch to alternative channels in case of signal degradation.

We list some aspects of communication for UAVs as follows. These are also problems to study in near future for fresh Ph.D or master students.

a) Telemetry links enable the continuous exchange of real-time data between the UAV and the ground control station, providing critical information about the UAV's status and performance. Telemetry data includes altitude, airspeed, battery status, sensor readings, and other relevant parameters. Utilizes RF communication, satellite links, or a combination to ensure seamless and continuous data flow.

b) Payload data links are dedicated to transmitting information captured by the UAV's sensors, such as cameras, LiDAR, or other specialized equipment. High-resolution images, video feeds, sensor readings, and other payload-specific data. Employ various frequencies and modulation techniques based on the requirements of the payload sensors.

c) In multi-UAV systems, communication between UAVs is essential for collaborative missions, coordination, and avoiding collisions. We Can involve ad-hoc networks, mesh networks, or direct communication links between UAVs, ensuring seamless information exchange. Utilize communication protocols and algorithms for collision avoidance, task distribution, and synchronization among multiple UAVs.

d) Satellite communication provides a robust and global communication solution for UAVs operating in remote or international areas. Enables long-range missions, beyond line-of-sight operations, and continuous communication even in challenging terrains. Bandwidth limitations and latency may be factors to consider when relying on satellite communication.

e) Mesh networks enhance communication reliability by allowing UAVs to act as both data sources and relays, creating a self-healing network. Redundancy, increased coverage, and improved resistance to communication disruptions. Particularly useful in urban environments or areas with obstacles that may obstruct direct communication links.

g) In autonomous UAVs, the ability to make decisions based on communication data is crucial for adapting to dynamic situations. Utilizing AI algorithms for decision-making, path planning, and autonomous response to changing conditions. Implementing communication protocols that can adapt to varying levels of autonomy and decision-making authority.

Acknowledgements

The authors would like to thank Thu Dau Mot University for the financial support. The authors thank the anonymous referees for their valuable suggestions which helped improve the report.

Referrences

Agmon, N., Kaminka, & G.A., Kraus, S. (2011). Multi-robot adversarial patrolling: facing a full-knowledge opponent. *Journal of Artificial Intelligence Research, 42(1),* 887-916.

Akyildiz, I.F., Melodia, T., & Chowdhury, K.R. (2007). A survey on wireless multimedia sensor networks. *Computer Networks. 51(4),* 921-960.

Caffarelli, L., Crespi, V., Cybenko, G., Gamba, I., & Rus, D. (2003). Stochastic Distributed Algorithms for Target Surveillance. *Intelligent Systems Design and Applications, 23,* 137-148.

Capitan, J., Merino, L., Caballero, F., & Ollero, A. (2009). Delayed-State Information Filter for Cooperative Decentralized Tracking. *Proceedings – IEEE International Conference on Robotics and Automation, Kobe International Conference Center, Kobe, Japan, 2009* (3865-3870).

Curtis, J.W., & Murphey, R. (2003). Simultaneous area search and task assignment for a team of cooperative agents. *AIAA Guidance, Navigation, and Control Conference and Exhibit, 11-14 August 2003, Austin, Texas, AIAA 2003-5584, 2003*(1-6).

Darrah, M., Niland, W., & Stolarik, B. (2006). UAV cooperative task assignments for a SEAD mission using genetic algorithms. *AIAA Guidance, Navigation, and Control Conference and Exhibit, 21 - 24 August 2006, Keystone, Colorado, AIAA-2006-6456*.

Han, Z., Swindlehurst, A.L., & Liu, K.J.R. (2009). Optimization of MANET connectivity via smart deployment/movement of unmanned air vehicles. *IEEE Trans. Veh. Technol., 58(7),* 3533-3546.

Herwitz, S.R., Johnson, L.F., Dunagan, S.E., … , & Brass, J.A. (2004). Imaging from an unmanned aerial vehicle: agricultural surveillance and decision support. *Computers and Electronics in Agriculture, 44,* 49-61.

Kanchanasut, K. (2007). Dumbonet: A Multimedia Communication System for Collaborative Emergency Response Operations in Disaster-Affected Areas. *Int'l J. Emergency Management, 4(4),* 670-681.

Kontitsis, M., Valavanis, K. P., & Garcia, R. (2005). A simple low cost vision system for small unmanned VTOL vehicles. *Conference: Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on, 2005* (1-7).

Nygard, K.E., Chandler, P.R., & Pachter, M. (2001). Dynamic network flow optimization models for air vehicle resource allocation. *Proceedings of the American Control Conference, Arlington, VA June 25-27, 2001* (1853-1858).

Rodríguez, A.F., Andersen, E., Bradley, J.M., & Taylor, C.N. (2007). Wind estimation using an optical flow sensor on a miniature air vehicle. *AIAA Guidance, Navigation and Control Conference and Exhibit, Hilton Head, South Carolina, 2007*(1-8).

Schumacher, C., Chandler, P., Pachter, M., & Pachter, L. (2004). UAV task assignment with timing constraints via mixed-integer linear programming. *AIAA 3rd "Unmanned Unlimited" Technical Conference, Workshop and Exhibit, 20 - 23 September 2004, Chicago, Illinois, AIAA-2004-6410, 2004*(1-15).

Taherkordi, A., Taleghan, M.A., & Sharifi, M. (2006). Dependability Considerations in Wireless Sensor Networks Applications. *Journal for Networks, Academy Publisher, 1(6),* 28-35.