

Using Public Network Infrastructures for UAV Remote Sensing in Civilian Security Operations

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ABSTRACT

Unmanned Aerial Vehicles (UAV) enable the in-depth reconnaissance and surveillance of major incidents. Uncontrolled emissions of liquid or gaseous contaminants in cases of volcanic eruptions, large fires, industrial incidents or terrorist attacks can be analyzed by utilizing UAV. Hence, the use of cognitive Unmanned Aerial Systems (UAS) for distributing mobile sensors in incident areas is in general a significant value added for remote sensing, reconnaissance, surveillance, and communication purposes. Police departments, fire brigades, and other homeland security organizations will have access to medium and small UAV in the near future and will be able to integrate UAV in their work flow. In this paper we focus on the civilian concepts of operations (CONOPS) for UAV, in particular for small-scale UAV. We present viable concepts at the systems level for leveraging public wireless communication networks for UAV-based sensor networks with respect to existing constraints and user requirements.

INTRODUCTION

As a result of advances in communication, computation, sensor and energy storage technologies, as well as carbon fiber-reinforced plastic materials, micro unmanned aerial vehicles (UAV) are available at affordable prices. On this basis many new application areas, such as the in-depth reconnaissance and surveillance of major incidents, will be possible. Uncontrolled emissions of liquid or gaseous contaminants in cases of volcanic eruptions, large fires, industrial incidents, or terrorist attacks can be analyzed by utilizing UAV (Figure 1). Hence, the use of cognitive Unmanned Aerial Systems (UAS) for distributing mobile sensors in incident areas is in general a significant value added for remote sensing,

reconnaissance, surveillance, and communication purposes.¹

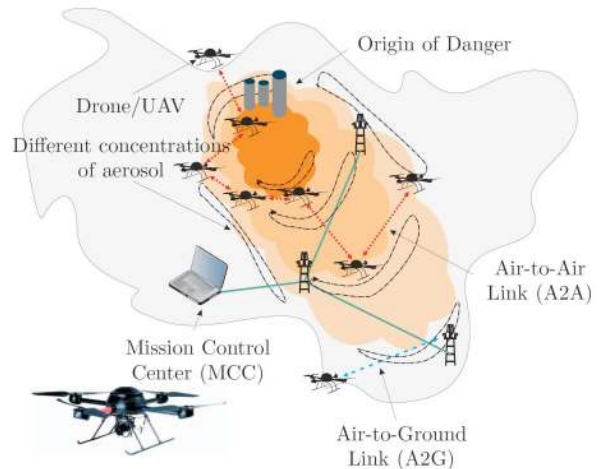


Figure 1: Deployment Scenario: Chemical Plume Detection with an Autonomous Micro UAV Mesh Network.

In the near future police departments, fire brigades and other homeland security organizations will have access to medium- and small-size UAV and will integrate them in their work flow. The use of non-military frequencies and civil communication technologies gains in importance for purposes of safety and security missions, since the frequency pool is limited and nearly exhausted. In particular, regionally organized public authorities and small rescue organizations like fire brigades often have insufficient access to frequencies and expensive communication equipment. Thus, using civil mobile communication systems is often the only effective workaround for homeland security organizations.

This is also one of the major issues for wireless communication in the area of unmanned aerial systems (UAS). Besides flight regulation, wireless communication is an important aspect of UAS as telemetry

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information (navigation, control, guidance) and sensor data usually have to be transmitted to a mission control center (MCC) in nearly real-time. Today, there is no viable alternative for this type of transmission besides using civil mobile communication networks. Unfortunately, there is no foreseeable solution in terms of frequency assignment for UAS. For efficient sensor coverage of large industrial and incident areas, fast and flexible strategies for collecting sensor data through an autonomous, reliably connected UAV need to be developed. In this article we focus on the civilian concepts of operations (CONOPS) for UAV, in particular for small-scale UAV. Viable concepts on the system level for leveraging public wireless communication networks for UAV-based cognitive remote sensing are presented with respect to both existing constraints and user requirements.

The article is structured as follows: we first present the current state of the art and related research activities in the area of UAS communication. Civilian concepts of operations (CONOPS) for purposes of homeland security are discussed in the next section. Subsequent sections address the requirements, concepts and solutions for Air-to-Air (A2A), Air-to-Ground (A2G), and UAS-backend communication. On this basis we then show a methodology for agent-based UAV-mobility for areas with insufficient communication. The article ends suggestions for future research.

RELATED WORK AND PROJECTS

Several research investigations have been done in the area of UAS. However, UAS communication aspects mostly address proprietary communication systems and usually do not consider public wireless infrastructures since these systems have been mostly deployed by military organizations in the past. Hence, we identify a demand for more in-depth contributions for UAS communication by means of public wireless networks.

Tiwari and others have studied the placement planning problem of an airborne network.² They offer a toolbox to optimize the ground coverage while maintaining a certain degree of reliability and connectivity. By

introducing practical scenarios for deployment, the interaction between communication design and mobility planning is shown. An active topology management for airborne networks is introduced in research by Krishnamurthi and others, aiming for the improvement of overall network throughput and efficiency by assigning optimal power, channel, and boresight direction to the airborne antennas with respect to the current airborne trajectories.³ Although the utilization of public networks is not mentioned in either of these articles, communication aware mobility methodologies are also suitable for public wireless networks, as we will discuss later.⁴

Distributing sensors as mounted UAV payload can be implemented by means of mobile agents for remote sensing and data gathering where connectivity constraints are discussed from a topology, transmitter, and protocol design perspective.⁵ Experimental results using an unmanned aircraft system are presented by Frew and Brown to show that meshed airborne communication is feasible and that meshed networking architectures will provide the needed communication for a large number of highly mobile and small aircrafts.⁶ Additionally, the ability of airborne networks to exploit controlled mobility for improving the performance is discussed. The deployment of aerial mesh networks requires routing protocols from civil WLAN networks. However, the applicability of ISM (industrial, scientific and medical) frequencies is not discussed for this approach.

A search algorithm for UAV swarms has been investigated Lidowski and others for a two-dimensional grid where A2A links are combined with geographic routing to improve search efficiency.⁷ Performance indicators in this context are the amount of total searches, distance traveled by UAV, and the minimization of UAV direction changes. A simulative study concerned with the location and UAV movement optimization of UAV to improve the connectivity of a wireless network is contributed by Han and others.⁸ An algorithm that tracks changes in the network topology is constructed. This generic approach opens up novel CONOPS for civil and homeland security networks, where ad hoc coverage can be provided with UAV from

higher altitudes. Rueetschi and others elaborate on the use of multiple airborne radios for a distributed cooperation scheme; the radios are able to cope with difficult channels resulting from an aerial wide area network, where improved channel prediction and channel estimations could perhaps provide an alternative for satellite-based or ground-level network-based relaying to overcome large distances.⁹

Looking at the physical layer, channel modeling approaches mostly investigate ground-level networks or, if aerial deployment is taken into account, focus on proprietary links. For example, Lee and Meng analyze the use of a low altitude air-to-ground channel over a sea surface in the tropical region at C band (300 MHz - 1 GHz, UHF) and compare this approach to a high altitude air-to-ground channel with a free space propagation condition.¹⁰

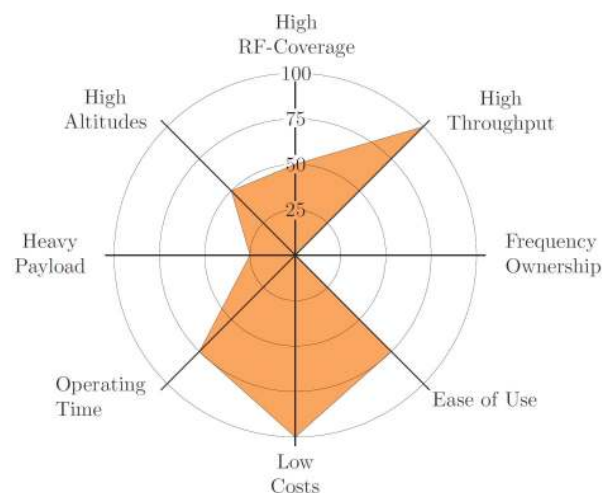


Figure 2: Civil CONOPS Requirements for UAVs

The most promising results for characterizing UAV A2G-links have been achieved by Feng and others,¹¹ where a statistical model for air-to-ground channels in an urban environment (Bristol, UK) is derived by ray tracing to operate at frequencies from 200 MHz to 5 GHz.

Based on these previous achievements we will extend the operational focus to non-military missions, where civilian public networks can fulfill the requirements of homeland security organizations.

CONOPS AND REQUIREMENTS FOR UAV NETWORKS

The requirements and preliminaries for the use of UAV in homeland security missions are basically different from those of military operations. An overview of selected requirements for civil UAV-CONOPS is depicted in Figure 2. Homeland security organizations are suffering from the lack of available frequency ownerships, on which basis UAVs could operate for telemetry and payload data transmission. Additionally, costs are typically a major issue for fire brigades and police departments as financial resources are usually very limited. However, the requirements regarding payload weight, operating altitudes, and range are comparatively low. We next introduce a selected CBRN-CONOPS and examine the communication-specific requirements of this CONOPS.

CBRN Reconnaissance

The clarification, containment, and combat of incidents that are caused by uncontrolled emissions of liquid or gaseous contaminants (dangerous gases and liquids or biological, chemical, and nuclear weapons) remain an emerging challenge. Instead of sending specially equipped forces with expensive transport and measurement devices into the contaminated area, an autonomous, wirelessly connected swarm of micro UAV, outfitted with lightweight mobile sensor systems (Figure 1), could be used in the future. Utilizing a MUAV swarm enables the calculation of gas concentrations on the one hand and allows for propagation forecasts on the other hand, which assist rescue forces in averting danger (e.g. evacuation) at a very early stage. Wide-spread chemical plumes can have a dimension of 20 km and more. Hence, coverage is a major issue which can be addressed by using several UAV in a swarm and assigning a relay functionality to each UAV or by using public wireless networks. Relevant incident areas are usually urban or metropolitan areas where infrastructures of cellular networks are available such as GSM, UMTS/HSPA (or in the future, LTE and Mobile WiMAX respectively). The advantages and issues for

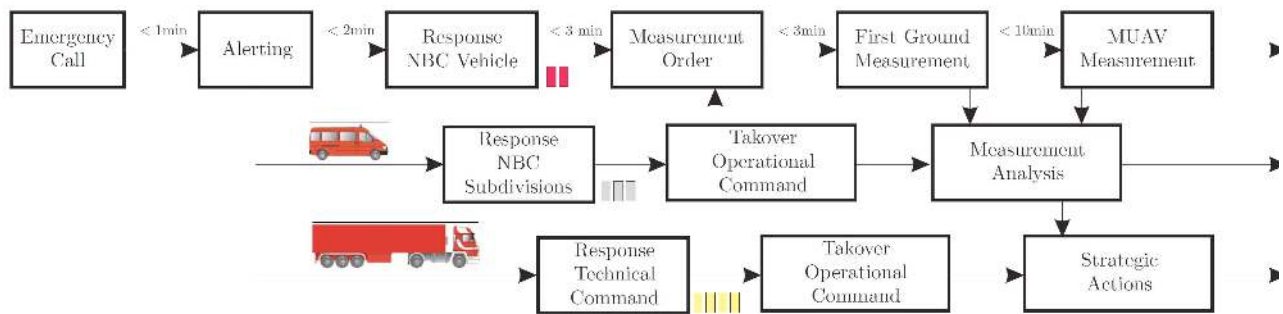


Figure 3: Generic Workflow for a CBRN rescue mission

using these networks for A2G-links will be discussed in the next section.

A CBRN-detection workflow of a fire brigade is depicted in Figure 3,¹² where three management levels of a fire brigade organization are involved each with different alerting stages where a response is initiated. Considering that different management levels have got fundamentally different information demands leads to a complex UAS architecture design as we will explain in more detail later.

CELLULAR NETWORKS-BASED AIR-TO-GROUND-LINKS

Installing A2G links on available public cellular networks has the advantages of

- high coverage,
- available frequencies,
- low efforts and expenses (low costs),
- existing interfaces to other networks (e.g. over IP).

For CBRN detection the requirements regarding throughput are low but the performance of public networks for payload data transmission is sufficient enough, if no images or videos need to be transmitted. Assuming that prioritization by means of QoS algorithms for rescue organizations ensure a reliable access to public cellular networks, homeland security organizations nevertheless are faced with several challenges. The delay for 2G-networks is not suitable for the transmission of telemetry data (approx. 0.5... 1s).

Lower round trip times can, however, be achieved with UMTS/HSPA (approx.200...

500 ms), Long Term Evolution (LTE) or Mobile WiMAX (approx. 50 ms). Besides, directional antenna characteristics of common sector antennas concentrate the TX-power to ground level (Figure 4). Thus, connectivity in higher altitudes cannot be assumed to be gapless and suffers from lower reliability.

The constraints can be overcome by introducing efficient failsafe and redundancy mechanisms. Areas with no reception can be compensated by using A2A links on the first backup level (as discussed in the next section). Combined with agent-based autonomy on the second backup level (as proposed in a later section), public wireless networks become a feasible communication technology for UAV. If all public networks are down due to a disaster or other catastrophe, WLAN in infrastructure mode or ad hoc Mobile WiMAX base stations offer promising solutions for rescue organizations at the third backup level. Unfortunately, they raise higher requirements for the A2A links to optimize the coverage for a region of interest.

ISM-based Air-to-Air (A2A) Links

Mesh networks have certain strengths regarding the key performance indicators: reliability and coverage. By contrast, well-known constraints are typically less realizable throughputs because of higher self-interferences and hidden station problems, respectively. Solving the hidden station problem by introducing RTS/CTS protocol

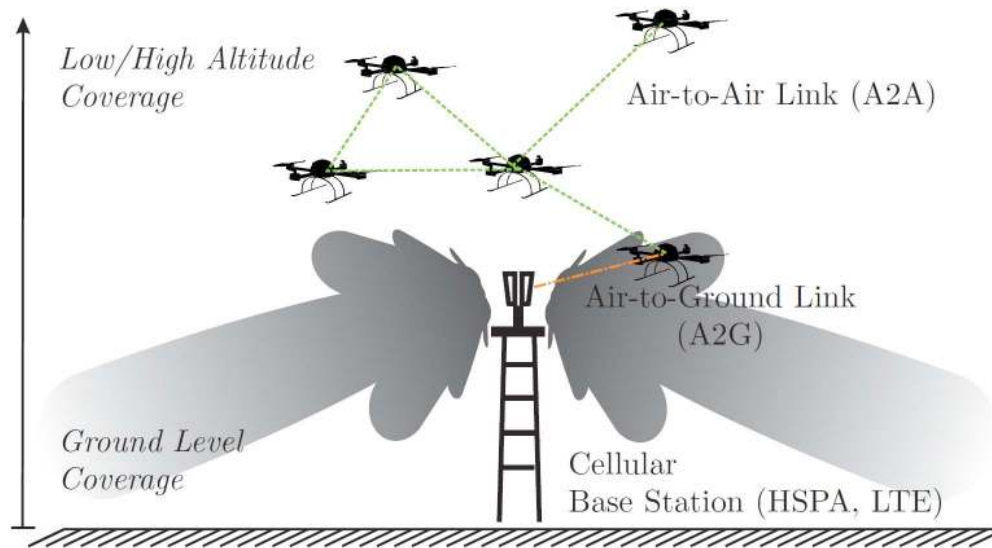


Figure 4: Insufficient Aerial RF-Coverage

will incur a higher overhead cost. The overhead for required routing protocols like AODV, OLSR or, hybrids deduced from them, reduces the total possible throughput in a mesh network. However, an aerial mesh network that is established with A2A links offers several advantages as proposed earlier. The tradeoff between coverage and throughput is acceptable if requirements regarding the throughput are low. And they are in case of CBRN reconnaissance, where only telemetry and payload data (sensor information) have to be transmitted. The aerial mesh network allows coverage of a large area and the calculation of a local gas concentration gradient (see Figure 1). Since it might happen that not all MUAV have a connection to the base station on their own (loss of A2G link), additional A2A links are used for routing those data to a neighboring relay-MUAV, which works as gateway to a ground station.

Military organizations have to cope with conscious jamming transmitters, which usually prohibit the use of off-the-shelf wireless technologies. This restriction plays a minor part in homeland security operations. Hence, for the implementation of A2A links different communication technologies and frequencies are available. ZigBee comes with good meshing capabilities, but is lacking a low coverage due to low transmit powers.

Routing protocols for WLAN such as OLSR have been well researched and are already available for embedded and low-weight devices which can easily be mounted to micro UAV. For WLAN, frequency bands at 2.4 GHz (EU, USA), at 5.2 GHz (EU, USA), at 5.5 GHz (EU), and at 5.7 GHz (USA) are available. Since frequencies at 2.4 GHz are very popular in the private sector, these frequency bands are usually overloaded and have high round-trip times due to higher backoff intervals caused by the CSMA MAC protocol.

At 5 GHz the interference situation for WLAN is better because the signal degradation for low transmission powers is high, due to the attenuation caused by matter – particularly in indoor environments. For this reason, 5 GHz is rarely used for indoor applications. Furthermore, it has been substantiated that interference is negligible at higher altitudes.¹³ For aerial deployment above 100 m, attenuation can be contained to free space attenuation. Besides, allowed transmit powers in this frequency band are higher (up to 1 W) and subsequently the possible region of interest to be covered can be larger. Thus, there is no counterargument to utilize 5 GHz for A2A links.

WIRELESS UAS-BACKBONE COMMUNICATION

As mentioned above, the workflows of homeland security organizations are very complex. Deviating workflows for different nations, states, and even cities further complicates this issue. Hence, we will describe the main communication aspects of backend architectures and protocols for UAS by introducing an example, also depicted in Figure 5. These agree with the CBRN detection purposes as introduced in a previous section. The backbone system has the following main functions:

- User Interface & Interaction;
- Managed UAV Control and Mission Planning;
- Information processing, automated analysis, forecasts, and decision support.

As it can be seen in Figure 5, the example of back-end architecture is organized as a distributed system. The colored bars correspond to the hierarchy of the rescue organization as introduced in Figure 3. Even though the operational command must have access to all relevant data, usually the NBC explorer is the first operational unit at the

scene of an incidence (Figure 3). This means that the back-end network topology changes over time, which leads to some specific challenges. The NBC explorer must have the capability to begin operation immediately upon arrival, but also must have the ability to pass control to operational command during the mission. For this reason, distributed services are implemented as target-oriented and adapted to the needs of the rescue forces.

3D-visualization, UI for decision support and route planning, and person/street map search are directly accessible through the user and fed by information processing and control services such as route planning, decision support, geo-engine, sensor-web, and the propagation simulation. The required, but also gathered, information is written to several databases as depicted in Figure 5. The UAV directly access these databases through UAV communication service and a database access service in order to keep the processing delay low and in order to allow for real-time operation. Next to the hierarchy of rescue organizations, the relay and real-time requirements are crucial for the system design. For delay of critical communication a slim binary protocol is the most suitable, whereas for ground-level

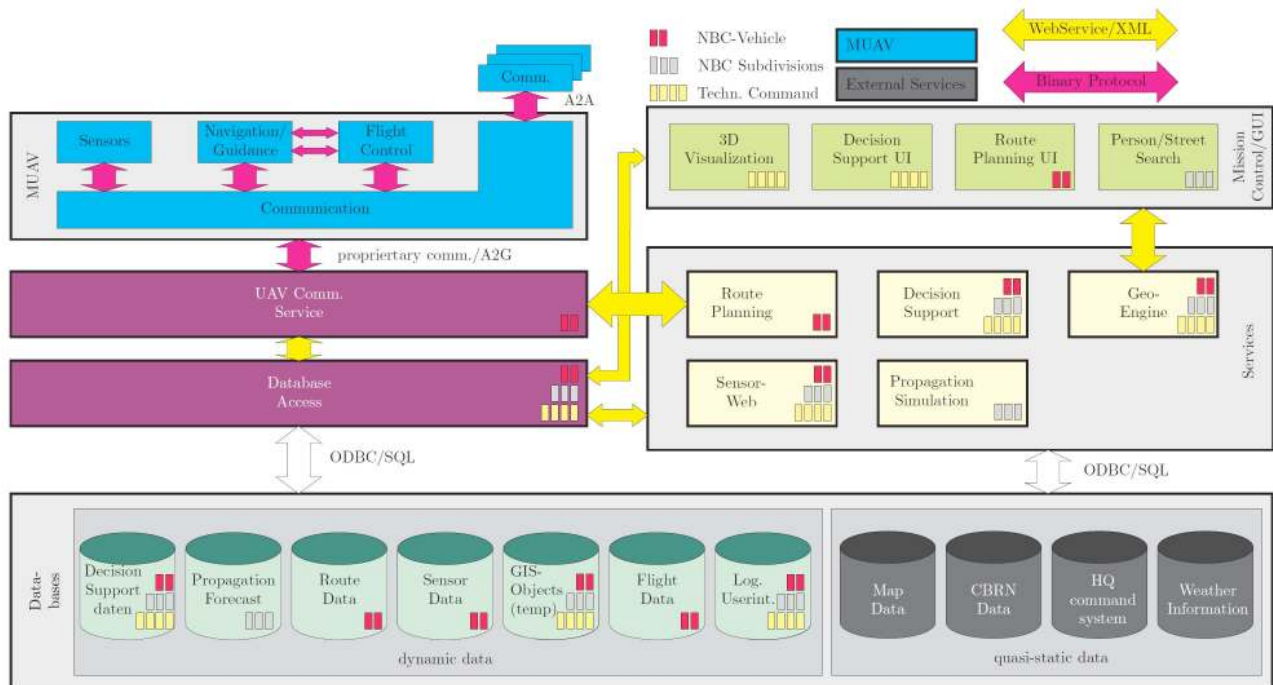


Figure 5: UAS Architecture for CBRN Reconnaissance

communication, web services offer more flexibility regarding interfaces and interoperability between heterogeneous and distributed systems. For the servers at ground level wireline communication is utilized (e.g. ADSL) that typically allows for IP communication. If wired communication is not available, directional ad hoc links have to be set up or again public networks (HSPA, LTE) can be used.

COMMUNICATION-AWARE DISTRIBUTION OF SENSORS WITH UAV

Leveraging public wireless communication infrastructures for UAV-based sensor networks causes reliability constraints such as possible connectivity losses due to poor coverage in higher altitudes. By giving UAV agent-based autonomy capabilities, UAV can manage mission goals even in cases of temporary connection problems. Working with UAV teams or swarms respectively increases the coverage and grants the overall viability. Swarming tasks are usually specified in terms of a small set of essential features, while the exact behavior of each node is not of primary interest.

In our work we focus on the so-called inverse problem for swarm behaviors, the design of individual steering behaviors to achieve a desired macroscopic objective through the motion of UAVs on the microscopic level.¹⁴ Our goal is to find efficient agent algorithms for a UAV-swarm that are rich enough to accommodate high coverage in space and are accurately interconnected for the transmission of both payload (sensor) information and real-time critical telemetry at the same time. The accuracy of the steering behavior in these terms is represented by the coherence of the swarm, which has to be ensured concurrently while optimizing connectivity and coverage within a region of interest.

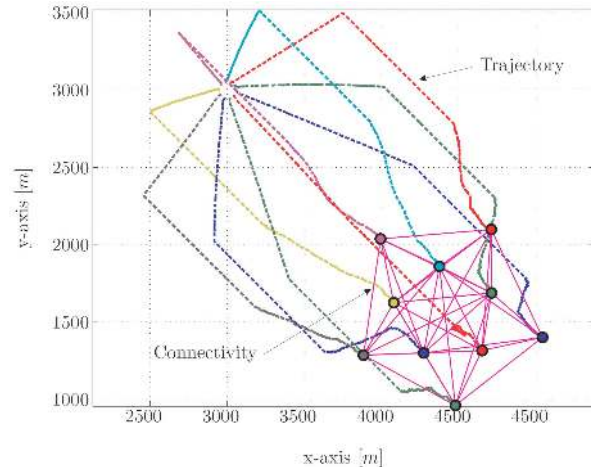


Figure 6: Trajectory and Network Topology for a MUAV Swarm

The interdependencies between swarm mobility on the one hand and network topology on the other hand are shown in Figure 6. Next to the initial growth of coverage the nearly equal spatial distribution of the UAV is highlighted in this figure. This configuration is established fully autonomously by the UAV agents based on their perception and RSSI-measurements respectively. The RSSI-measurements enable the agents to react cognitively to the channel variations. Figure 6 shows a topology contraction and that the swarm size and network topology shrinks: The UAV gather if noise or lognormal fading with $\text{std}=4$ dBm is suddenly added to the channel after 600 s (Figure 7). The results clearly show the equilibrium of these two orthogonal optimization goals. Good spatial coverage is achieved by the cost of weak RSSI links and vice versa.

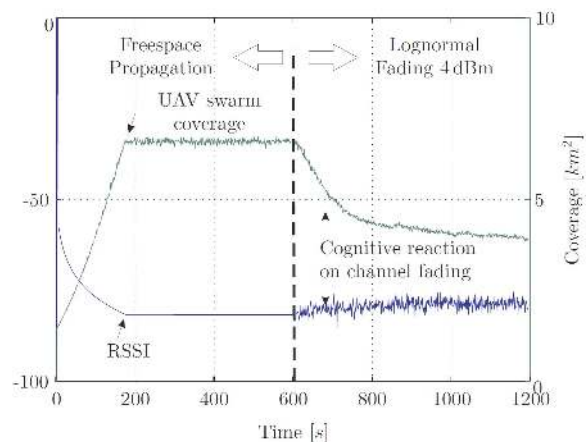


Figure 7: Relationship between RSSI and UAV swarm coverage

CONCLUSIONS AND FUTURE WORK

Leveraging public wireless communication infrastructures for UAV-based sensor networks for purposes of homeland security is a feasible approach under certain circumstances. Several advantages such as high coverage, existing infrastructures, and frequencies can be combined with different failsafe and redundancy approaches in order to overcome delay and reliability constraints. Based on CONOPS coping with CBRN reconnaissance, we have shown in this article that communication awareness and autonomous UAV are particularly able to improve the rescue workflow even with minor expenses. In our future work we will focus on aerial channel modeling and network graph-based mobility algorithms.

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