Multi-UAV Node Placement Strategies for Meshed Field Coverage

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1 Introduction

The utilization of unmanned aerial vehicles (UAVs) ranges from commercial surveillance and reconnaissance missions to semi-professional and private applications. With ongoing improvements in the area of embedded automation systems and autonomous multicopter aircrafts, the quadcopter platform got more and more interesting in research and development. Advances in the wireless network communication technologies allow UAVs to not only communicate with dedicated controlling base stations but with each other as well as with other communication partners such as mobile handhelds, industrial sensor nodes and extending network bridges. While these and other communication devices are able to communicate wirelessly, a comprehensive layer is needed to provide connection over long distances and to translate between different technologies and protocols. A UAV is not only a simple relay node but a rather flexible platform with several kinds of communication hardware and measuring sensors applicable. A meshed Multi-UAV system can thereby be used to construct a comprehensive and stable communication backbone to achieve these goals while having the advantage of freely placeable aerial nodes and nearly no limitations introduced by the ground terrain.

At Ilmenau University of Technology the graduate school research group focuses on mobile communication systems for disaster scenarios. UAVs are able to aid in these scenarios and to create the backbone of the communication infrastructure needed. The creation and maintenance of Multi-UAV arrangements for this task is a crucial aspect of this research field. The presented paper aims to compare possible strategies of node placement for Multi-UAV arrangements in a structured grid as a basis for further research into maintenance processes. Requirements are comprehensive communication coverage of a specific area and the autonomous expandability without global knowledge while considering the intermeshing degree, failure tolerance and the node amount as indicator for mutual interference and resource needs.

After introducing the existent approaches, chapter 3 presents the general conditions under which the comparison was carried out. Chapter 4 defines the requirements and chapter 5 contains the comparison. Chapter 6 concludes the findings.

2 Related Work

In [1] the mathematical background on the basic two-dimensional arrangement patterns are presented. The nodes form a grid with triangular, square or hexagonal shape and uniform side length. Furthermore improved methods for arrangements under the goal of directed data collection rather than forming a meshed communication grid are presented

The aspects of relay node placement with focus on the relay quality was discussed in [2]. The authors take a closer look on the optimal distance between nodes, however their focus lies on constructed connections between particular nodes.

A good solution for comprehensive field coverage under minimal resource usage was presented in [3] named the connected coverage. It aims at relaying sensor data rather than interconnecting nodes but it holds some interesting ideas about how to cover an area while being connected and resource optimal.

In [4] the Voronoi tessellations and the Lloyd optimization method are presented to find optimal solutions while pursuing certain goals related to the communication needs.

The scope of our research lies in creating a network of UAV nodes comprehensively covering a specific area while achieving a good intermeshing degree in all directions. The presented methods have to be compared and evaluated to find a suited placement strategy.

3 Setup for meshed coverage

There are three kinds of communication objects. An unmanned aerial vehicle (UAV) should be called a node and acts as part of the constructed backbone network. A client is a probably earth-bound device, which uses the in-air UAV-based backbone. One or multiple base stations are located at the edge of the considered area and connect the constructed backbone with other network structures or for instance the global internet. For most scenarios base stations have the same meaning as clients, with the difference, that base stations are fixed in place and will always be available.

It is also needed to differentiate between the implemented node-to-node and node-to-client technology, since they typically will have different spreading and range properties. In order to determine the distance of possible communication without significant bandwidth loss between, one has to take the communication protocol, the communication hardware at both ends, external interference and characteristics of the area in-between into consideration.

The following assumptions are made throughout further discussion: Interference level and area-related influences are homogenous across the considered area. Communication protocol and hardware are the same for all node-to-node communication and the antenna technology is assumed to be omnidirectional. These assumptions result in being able to define the area of coverage per node as a circular area around it. One additional assumption should be, that the whole communication area is considerably bigger than the communication range of one single node, resulting in being able to concentrate on nodes in the centre rather than at the edges.

A few parameters have to be defined. The considered communication area A. The number of utilized nodes N and their individual positions $P_i(x, y, z)$. The maximum node-to-node distance r allowing communication of a thereby created circular area in height h above ground. The maximum node-to-client communication distance simplified to parameter d. The intermeshing degree D of a node describes the number of other nodes connected to the node and is thereby an indicator for the number of possible routes and for the robustness against node failure related communication interruption.

4 Requirements

In the considered research field of mobile communication systems for disaster scenarios, UAVs should be utilized to create a comprehensive backbone for network communication. One objective in finding a fitting placement strategy is a reasonably high intermeshing degree. Individual UAVs have a limited reach and will normally only be able to communicate with nodes in close distance. Additionally we expect the positions between communication partners to be randomly distributed in the considered area as a characteristic of the application field. These facts support the claim for the nodes to be closely connected in a meshed network. Redundant communication paths will also be beneficial in handling node failure.

Since this paper should be the basis for further research into maintenance processes, specifically energy management processes, energy consumption is another important aspect to be considered. The energy amount needed to transfer a data unit depends on the used communication hardware, the communication protocol and the transmission path. A network with high intermeshing degree will reduce the hop-count for the transmission path. One other aspect related to the node placement and energy consumption is the distance between communicating nodes. The maximum node-to-node distance r should not be mistaken with the physically possible distance. It is known, that the physically possible maximum communication distance is far from energy optimal and a reduced energy-optimal maximum distance can be found under the characteristics of the utilized hardware. The parameter r should be chosen under these considerations.

Another important goal for disaster applications where the operation area may differ over time, is the ability of the network to be easily expendable without the need for global knowledge.

Concluding, the absolute number of nodes should be held reasonable small. A high node amount not only increases the absolute number of needed UAVs on-site but will also have an effect on mutual interference and thereby reduces the effectiveness of the placement strategy.

To meet all these mentioned goals for Multi-UAV meshed field coverage, the following requirements have to be fulfilled by a fitting strategy:

1. Every client is able to communicate with at least two nodes.
$$\forall\, P(x, y, z) \rightarrow \exists\, P_a, P_b\colon (\overline{PP_a} < d;\ \overline{PP_b} < d)$$
2. The intermeshing degree D of each node is a minimal of three, preferably higher.
$$D \geq 3$$
3. Placement of a node near other nodes at the edge of the area while following the placement strategy is fairly simple.
4. The number N of utilized nodes is reasonably small.

5 Node placement strategy

In order to verify the first requirement, possible client positions must be compared to the node-to-node and node-to-client distances. The relation between these two parameters can be differentiated in four cases, illustrated in figure 1:

$$d < r/2 \qquad r/2 < d < r \qquad d \geq r \qquad d \gg r$$

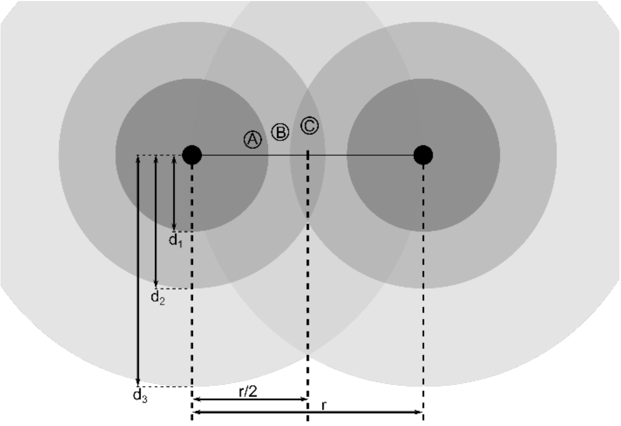

Figure 1 Node-to-node distance r in relation to the node-to-client distance d with possible client positions

With the node-to-client distance d_1 being smaller than half the node-to-node distance r, the first requirement is completely violated as the example client positions B and C in figure 1 are not in reach of any of the displayed nodes and position A is only in reach of one node. In the case $r/2 < d_2 < r$, the first requirement is at least partially violated as C is connected with two nodes but A and

B are only connected to at least one node. In the case $d_3 \geq r$ the first requirement is fulfilled completely as all three example positions are inside the reach of both displayed nodes. The case $d \gg r$ is of special interest because special complex structured placements may be applicable while meeting the requirements.

For further research in this field, $d \geq r$ should be applied, i.e. d and r have to be chosen accordingly.

Based on basic mathematical patterns, in [1] three strategies and their properties were discussed and are illustrated in figure 2:

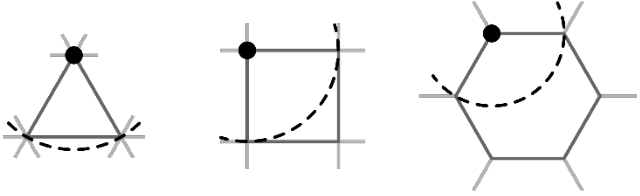

Figure 2 Placement strategies with distances $d = r$. (1) triangular, (2) square and (3) hexagonal

A Placement in a triangle like grid covers the area with a high intermeshing degree while being easily expandable due to the simple geometric characteristics. The hexagon shaped grid slightly reduces the node amount but also the amount of neighbouring nodes while in addition is not easily expandable due to its more complex structure. The square like arrangement is a compromise between the two arrangements. All three strategies meet the second requirement.

The connected coverage node placement strategy presented in [3] is an interesting strategy as it meets requirement 4 almost perfectly. The strategy creates a structured comprehensive coverage placement with an approximately optimal number of nodes. The nodes are connected in separated strips and are as those connected to the root nodes, i.e. the base stations. In order to fully meet requirement 1, the node-to-client distance is longer than the node-to-node distance ($d > r$). As all nodes are arranged in strips, the third requirement is also met as nodes can be easily attached to the end of strips or new strips can be created in order to expand the covered area. Requirement 2 is problematic with the connected coverage strategy. As all nodes are connected in strips, the intermeshing degree of nodes is only two. Connected coverage is designed towards the needs of wireless sensor networks (WSNs) and as such aims to connect all nodes with the base station rather than with each other. Although the strategy is interesting in some aspects and may be interesting for other research in the application field of disaster scenarios, it does not meet the predefined goals and requirements of the presented paper.

In addition to the structured node placement strategies discussed above, there are more complex strategies which aim to address the communication needs in the considered area in specific. Nodes are placed dynamically as a result of on-site client constellations and the directed communication needs. A good example are the Voronoi tessellations presented in [4]. As the presented strategies are situation specific and variable in many parameters, they cannot generally be verified against the defined requirements. Most advanced strategies are primarily designed for collecting sensor data in wireless sensor networks rather than building a comprehensive communication backbone, needed in the scope of this paper and are thereby not suited as placement strategies. More basic strategies are however able to fulfil the defined requirements. Table 1 collects the evaluation results:

Requirement:	*1*	*2*	*3*	*4*
Triangle pattern	✓✓	✓✓	✓✓	✓
Square pattern	✓	✓✓	✓	✓✓
Hexagonal pattern	✓	✓	✗	✓✓
Connected coverage	✓	✗	✓	✓✓✓
Specific WSN strategies	(✓)	(✗)	(n/a)	(✓✓)

Table 1 placement strategies evaluated against predefined requirements.

Even though the specific strategies cannot be evaluated in general, specific wireless sensor network node placement strategies have been evaluated under reserve. Since they are specifically designed towards WSN requirements, they are not fitting under the defined requirements in this paper. However specific optimal placement strategies for comprehensive meshed field coverage could be designed. This was however not the scope of this work. As result of discussion, the triangular and square node placement strategies were selected for further research.

6 Conclusion

We have discussed multiple node placement strategies from different fields of application. For the field of node placement for meshed efficient and failure-protected coverage special requirements were defined and multiple strategies were compared against these. Results of this paper are node placement information and recommendations and will be the basis for the ongoing research in maintenance processes this field.

7 References

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