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Guidebook on Network Organization

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1. INTRODUCTION

1.1 GENERAL

This document produced under the OSIRIS project (Contract number 033475) constitutes the deliverable D3130.

It reports on the activities and results of Work Package (WP3130) – Network Organization.

The WP3130 objective is to provide an overview on the selection of sensor network strategies that are suited to the requirements of use cases, phenomenon properties and sensor capabilities.

1.2 DOCUMENT STRUCTURE

This paragraph gives an overview of the document structure and the relationship between the different chapters.

Chapter 2 describes the scope of work for WP3130 and its relationship with other Work Packages within OSIRIS.

Chapter 3 presents the process that was used to achieve the stated objectives and describes the working approach and schedule for WP3130. This was based on the agreed process and on the overall schedule for OSIRIS.

Chapter 4 provides an introduction into the basic concepts and backgrounds that are related to the selection and design of sensor network strategies.

Chapter 5 provides an overview of different types of sensor network strategies.

Chapter 6 describes factors that are relevant to the selection and design of coverage strategies.

Chapter 7 describes factors that are relevant to the selection and design of communication strategies.

Chapter 8 illustrates the factors previously described by several guidelines and also shows exemplary how they can be applied to the OSIRIS scenarios.

Chapter 9 summarises the document and concludes the findings. It also describes lessons identified while performing WP3130.

1.3 GLOSSARY OF TERMS AND ABBREVIATIONS

Term	Meaning
APS	APS GmbH
FP6	6th Framework Program
GPRS	General Packet Radio Service
GPS	Global Positioning System (Satellite positioning)
GSM	Global System for Mobile Communications
GSN	Geosensor network
IfGI	Institute for Geoinformatics
OSIRIS	Open architecture for Smart and Interoperable networks In Risk management based on In-situ Sensors
TCF	THALES Communications SA
UAV	Unmanned aerial vehicle
UWB	Ultra wide band
WP	Work package
WSN	Wireless sensor network

1.4 APPLICABLE DOCUMENTS AND REFERENCES

Document	Description
Annex 1 of the OSIRIS contract	Description of work
D 3100	Inputs regarding various aspects of sensor organisation models

2. SCOPE OF WP3130: GUIDEBOOK ON NETWORK ORGANISATION

2.1 SCOPE OF WP3130

The objective of WP 3100 is to analyse network organization models with special consideration of sensor network coverage and connectivity.

Based on the results and experiences gained from WP 3100, in D 3130 a guidebook on sensor network organisation shall be delivered.

This guidebook aims at describing relevant factors for the process of designing or selecting sensor network organisation models (subsequently also referred as sensor network strategies). Thus this guidebook deals mainly with the presentation of three different types of influencing factors that need to be considered

- phenomenon specific factors
- sensor specific factors
- use case specific factors

This document is structured as follows. An introduction initialises the document with the description of elementary terms that are used within this guidebook two chapters are provided which present a selection of potentially relevant factors to the selection/design of coverage and connectivity strategies. Subsequently exemplarily guidelines that are relevant for designing and selecting sensor network strategies are presented. Finally the guidebook concludes with a summary that points out the most important findings of the work performed within WP 3130.

2.2 WP3130 RELATIONSHIP WITH OTHER WP

The results of WP 3130 are strongly influenced by the previous findings of WP 3100 and WP 3220. Thus these work packages are closely connected to WP 3130.

Furthermore the results of WP 3130 will be used as an input to the sensor tasking and maintenance protocol which is developed within WP 3300.

For the implementation of the different OSIRIS scenarios (WP 7000) the results of WP 3130 can be used for supporting the determination of sensor network strategies that are applicable to the scenarios.

3. PROCESS OVERVIEW AND WORK SCHEDULE

This document is the result of the collaboration of two of the OSIRIS partners. The distribution of work among them has been defined with respect to the DoW (Description Of Work), the exact share of the work was defined during common sessions.

This report has been initiated by the delivery leader, also having the responsibility of merging and harmonizing all contributions. The partners have been invited to take the responsibility of one or several chapters with the contribution of the others partners as shown in the following table (where the responsible is in bold).

	APS	**IfGI**
"Guidebook on network organisation"	x	**X**

Giving the process previously defined, the work was scheduled across the participants of this work package.

The work was performed using a number of multi-national workshops and 'homework' between workshops.

The workshops were organised around the steps of the process and the plan was as follows:

WP3130 Workshop #1		
Münster 22nd & 23rd March 2007		
Inputs	**Workshop Objectives**	**Homework**
Current status	Discussion about the objectives of WP 3130.	Delivery of inputs to WP 3130.
WP3130 Workshop #2		
Reading 22nd & 23rd June 2007		
Inputs	**Workshop Objectives**	**Homework**
Current status	Presentation current status of WP 3130.	Update of input and delivery of the final document.

4. GEOSENSOR NETWORKS

Geosensor networks are an important development for capturing various phenomena (Stefanidis 2006). Important use cases are for example the measurement of pollution in air or water and meteorological parameters. In this context it is necessary to define the term “geosensor”. Generally sensors convert an input (i.e. phenomena like temperature, humidity etc.) into measured values. A geosensor is a special kind of sensor that is characterized by the ability to assign the measurements with a spatial reference.

Besides conventional sensor networks that consist of stationary sensors, mobile sensor networks are a new development that is currently a very important research topic. This type of network is characterised by sensors that are capable of moving so that the sensor constellation can be dynamically optimised depending on the measurement or surveillance task of the network (Dantu et al. 2005).

Often a central control of the sensor network is not feasible. Reasons for this are for example that the connection between base station and sensors is only temporary or that the number of sensors makes it impossible to control them by only one central unit. Thus sensors are often designed as autonomous components that cooperate in order to fulfil the global aim of the sensor network (Estrin et al. 1999). The distinction between centralised and distributed sensor control is subsequently a very important topic of this guidebook.

4.1 SENSOR NETWORK STRATEGIES

In order to ensure that every sensor contributes to the completion of the geosensor network tasks, it is necessary to define its behaviour by the so called sensor strategies. Such a strategy describes how a sensor has to react on different influences. For example the sensor behaviour can be influenced by the positions and measurement results of other sensors or by the values the sensors detects itself. In this guidebook two different types of strategies are treated:

- coverage strategies which are used for optimising the sensor constellation in order to improve the coverage of the investigation area
- communication strategies (also referred as connectivity strategies) which describe for example which messages are sent by a sensor or if a sensor is relaying the messages it receives

This guidebook aims at providing information about the different practical influencing factors to the selection of sensor strategies. By taking into account the properties of the monitored phenomenon, the deployed sensors and the use case it is possible to select well suited strategies. Thus the identification of potential factors is of great relevance and will consequently form the main part of this guidebook. Later these factors are related to practical examples in order to illustrate and explain their influence.

4.2 UAV SYSTEMS

Besides classical ground based sensor networks also the research regarding UAV systems has become more important. A UAV (unmanned aerial vehicle) is an unmanned aircraft that is either flying remotely controlled or autonomously (U.S. Department of Defense 2002). UAVs can be equipped with sensors and cameras so that they can contribute additional overview information that is usable for enhancing the sensor network performance. Because of their importance to the OSIRIS project this guidebook contains also a short section about strategies for UAV integration into conventional sensor networks.

4.3 TECHNICAL CHALLENGES

Within the OSIRIS project and subsequently also in this guidebook wireless sensor networks are of central interest as this network type provides the highest flexibility regarding the sensor deployment and regarding the adaptability to changing conditions. As wireless sensor networks possess specific operational needs, they necessitate a special consideration within this guidebook:

- Energy supply: Most wireless sensors are equipped with batteries that provide the energy supply. Thus a limited energy supply must considered so that the energy consumption is reduced (Rahimi et al. 2003)
- Communication: Often the sensor network topology is influenced by sensor movements and by the addition/removal of sensors. Thus special routing algorithms are needed (Taherian 2004). Furthermore the communication range is in many cases limited due to limitations of the energy supply (Agre & Clare 2000).
- Localisation: The ability of determining the sensor position is an important prerequisite for relating measured values to space. Additionally the knowledge about the sensor position can be used for coordinating mechanisms within the sensor network.

Within the chapters 6 and 7 these special technical challenges will be investigated and different potential influences on the design and selection of sensor network strategies will be presented.

5. TYPES OF SENSOR NETWORK STRATEGIES

There are several ways how sensor network strategies can be classified. This chapter gives an overview of important distinctions that can be made. First it is necessary to differentiate strategies for sensor coverage and for sensor communication. Further properties that can be used for a distinction deal with the way different strategies work

- centralised vs. distributed strategies
- dynamic sensor networks vs. static sensor networks
- inputs to sensor strategies

A last special case consists of strategies for the integration of UAVs which will be dealt with in an additional subchapter.

5.1 COVERAGE AND COMMUNICATION STRATEGIES

In order to fulfil the tasks of a sensor network it is necessary to use strategies which define rules regarding the sensor placement and behaviour so that the network is customised and best suited to the scenario requirements.

Subsequently all aspects related to the sensor network behaviour and constellation will be denoted as strategies. The following section will give a more detailed insight into the field of sensor network strategies by presenting the terms “coverage strategy” and “communication strategy”.

5.1.1 COVERAGE STRATEGIES

The term coverage strategy is not generally defined. With regard to the coverage in mobile sensor networks also the terms “motion strategy” (Dantu et al. 2005), “mobility strategy” (Kesidis et al. 2003) and “move strategy” (Liu et al. 2005) are used.

Basically in this guidebook the following definition shall be used: A coverage strategy defines how sensors shall be distributed in space in order to fulfil the tasks of the geosensor network. Strategies for mobile sensors (mobility strategies) are an important subset of coverage strategies.

A coverage strategy usually takes into account several different factors that influence the desired sensor distribution. For example the following influences have to be considered:

- sensor position
- positions of other sensors
- previous positions of a mobile sensor
- results of measurements performed by the sensor itself
- results of measurements performed by other sensors

It has to be noted that the mentioned influences are only a selection of important factors. Other potentially highly specialised factors can be caused by specific needs of use cases and scenarios.

5.1.2 COMMUNICATION STRATEGIES

The term communication strategy (also referred as connectivity strategy) is mentioned in several sources (e.g. Nittel et al. 2004 and Rybski et al. 2004) for describing all kinds of sensor behaviour that is related to the communication that is performed by a sensor. However a universally valid definition cannot be found.

In this guidebook the term “communication strategy” comprises the following aspects and factors (this list is not exhaustive):

- Which communication capabilities does a sensor possess? Is it possible to send, receive and forward messages?
- Which sensors need to receive messages?
- Which messages need to be sent by a sensor?
- When are messages sent by a sensor?
- How can messages be transported through a sensor network that is characterised by a potentially dynamical changing topology? With regard to this question especially the aspect of multi-hop data transmission is interesting.

Besides the previously mentioned aspects it has to be added that a communication strategy must be adapted to the capabilities of the hardware platform that is used.

5.1.3 CONNECTIONS BETWEEN COVERAGE AND COMMUNICATION STRATEGIES

Although this guidebook uses a strong distinction between coverage and communication strategies, there are many connections between the two strategy types that must be considered.

The separation between strategies for coverage and communication allows a more systematic approach but, when selecting a strategy, it is necessary to ensure that the chosen coverage and communication strategies are compatible. This shall be illustrated by the two following examples.

Coverage strategies can have an influence on communication strategies. An example could be a strategy that maximises the distance between sensors by collecting information about the locations of all sensors in the network. A communication strategy in this context has to ensure that the positioning messages of all sensors are delivered to the sensor that is applying the distance maximisation strategy. Even if there is no direct connection between the sensors (e.g. because of limited communication range) the positioning messages must be delivered (e.g. by using multi-hop transmission).

Contrary also a communication strategy can have an influence on the coverage strategy of a sensor. In Li & Rus (2000), a strategy is presented that relies on sensor movement in order to bring sensors within communication range to each other. Thus in this case the sensor constellation (and by this also the coverage) is influenced by the needs of communication.

5.2 CENTRALISED VS. DISTRIBUTED APPROACHES

Sensor network organization models can be divided into two different classes:

- centralised approaches
- distributed approaches

These two groups will be compared in the following two sections. Additionally it is possible to combine the two models in order to develop strategies that are best suited for special scenarios. In this case different strategies would be applied in the same sensor network so that a distributed strategy might be used for those tasks which can be easily distributed whereas a centralised approach is used for those tasks of the sensor network in which global knowledge and coordination might be essential.

5.2.1 CENTRALISED APPROACHES

In a centrally organised sensor network, the sensor behaviour is mainly determined by a central control instance. This control unit uses the data received from the sensors and if available from other additional sources (e.g. simulation models) in order to calculate orders that are sent to the sensors. These orders are subsequently executed by the sensor. This means that there is no (at least no completely) autonomous sensor behaviour.

There are several advantages of a centralised sensor network control:

- If a central control unit is used the orders for the sensors can be based on a global knowledge of the sensor network. Thus the positions and states of all sensors can be taken into account. This allows using the sensors in a more efficient way.
- As the calculations related to the sensor behaviour are computed at a central station the sensor nodes can be designed simpler. The need for sensors to execute complex computations and coordination mechanisms is reduced.
- The use of more powerful central units makes it possible to use special simulation models for determining those areas where sensors need to be deployed or how the sensor network could be optimised (please see WP 3220 for further information about the integration of (simulation) models into the sensor network optimisation process).

Besides these advantages there are several limitations and drawbacks that make it sometimes impossible to apply completely centralised control mechanisms. The following list gives an overview of relevant limitations:

- Scalability (in this case: ability of a network to handle increasing (potentially very big) numbers of sensors) can become an issue in centrally controlled sensor networks. As the sensor data need to be send continuously to the control station and because the orders have to be transmitted to the sensors a big amount of data traffic is created. Especially in large sensor networks the bandwidth might not be sufficient for the transport of large numbers of messages.
- The number of sensors that can be integrated by a control unit is to some extend limited as the calculations of orders might become too complex. Depending on the complexity of the computations performed by the control station the number of sensors that can be handled might be limited.
- The response time of a sensor network to certain stimuli can be limited in case of centrally controlled sensor behaviour. As sensors must wait for orders they receive from the control station the time for responding to different stimuli (e.g. measured values above a threshold) can become too long.

5.2.2 DISTRIBUTED APPROACCHES

A distributed approach is mainly characterised by the fact that there is no central component for controlling the sensor network. Furthermore the different nodes of the sensor network usually do not have a global knowledge about the network and the whole investigation area. In most cases a node possesses only information about the locations of neighbouring sensors and the measured values in its neighbourhood.

Most distributed approaches rely on autonomous cooperation between sensors so that the individual sensor behaviour of a set of sensors reaches the global aim of the sensor network

(Estrin et al. 1999). Every sensor contributes to the fulfilment of the global task by performing smaller parts of that task.

There are three main advantages that are related to the use of distributed sensor network strategies (Makarenko et al. 2004):

- Scalability: The computation and communication load at the single network nodes is independent of the network size.
- Robustness: If one node fails the functionality of the sensor network usually remains intact.
- Modularity: The components (sensors) can be independently integrated into the network.

At the same time a distributed approach raises several problems which result in special requirements. In order to apply distributed sensor network strategies the following requirements must be fulfilled:

- Communication capabilities: Coordination mechanisms require usually an intensive message exchange. Thus it is necessary that sensors are able to send and receive messages.
- Computing capabilities: For performing coordination between sensors and for autonomously determining the tasks a sensor needs to perform, it is necessary that the sensor possesses sufficient computing capabilities. It is especially important that the sensor is able to store and analyse information about its environment.

5.3 DYNAMIC SENSOR NETWORKS VS. STATIC SENSOR NETWORKS

For sensor network strategies it is important to distinguish between dynamic and static sensor networks. The dynamics of a network can affect both aspects coverage (adaptability of the sensor constellation) and communication (e.g. need for special routing protocols).

5.3.1 DYNAMIC SENSOR NETWORKS

The dynamics of a sensor network can be influenced by two factors:

- changing constellation by addition and removal of sensors
- mobility of sensors

By the addition and removal of sensors it is possible to adapt the sensor constellation to the needs of the network. On the one hand it is possible to deploy sensors at those locations where the coverage needs to be improved and on the other hand additional sensors can be used for improving the connectivity by acting as new intermediary nodes for data transmission.

A more flexible way for adapting the sensor network constellation is to rely on the mobility of sensors. For example many phenomena which would not be detected by a stationary sensor network can be discovered by mobile sensors (Liu et al. 2005). This mobile behaviour of sensors requires special strategies.

Furthermore mobile sensors can be used for self healing purposes. In case of defective sensors the gaps in the network can be compensated by mobile sensors which move accordingly (Dantu et al. 2005).

The previously described advantages of dynamic sensor networks are connected with some challenges which shall be discussed subsequently.

The dynamic of the sensor network requires special routing protocols as the topology can change constantly. This makes it more complicated to deliver messages by multi-hop transmission.

Especially in case of mobile sensors also the energy consumption becomes a more important issue. As sensor movement requires relatively much energy it is necessary to perform optimisations regarding the mobility behaviour of sensors.

5.3.2 STATIC SENSOR NETWORKS

The challenges that arise in dynamic sensor networks are avoided by using stationary sensors. Especially problems like routing can be solved much easier.

However static sensor networks lack the ability to flexibly adapt to potentially continuously changing requirements influenced by the environment. Thus the sensor deployment has a much bigger importance than it has in case of dynamic sensor networks.

When deploying stationary sensors it is necessary to take all needs into account the sensor network has to fulfil. Especially the two following aspects need to be considered:

- The distribution of the sensors must ensure the connectivity within the whole sensor network. Especially if the transmission ranges of single sensors are limited, the sensor locations are essential for creating a multi-hop network topology. For determining the requirements regarding the sensor distribution it can be useful to integrate the results of radio transmission range simulation models.
- After the deployment the whole area of interest must be covered. As dynamic coverage optimisations are not possible in a static sensor network the sensor constellation must be chosen more carefully. Also for this aspect the use of simulation models improves the planning of the sensor distribution.

Additionally it can be practical to aim at redundancy during the deployment. As the replacement of defective sensors is not foreseen the sensor distribution should be designed in such a way that the failure of single nodes can be compensated. The importance of these aspects depends mainly on the reliability and durability of the sensors that will be used.

5.4 INPUTS

A sensor network strategy can react to different types of stimuli. Three important influencing factors will be presented in this subchapter:

- Phenomenon related influences
- Influences related to the geometry of the sensor constellation
- Influences related to the needs of the sensor network (e.g. the need to maintain connectivity)

These three factors must be analysed in conjunction with each other as a strategy can make use of several of these influences. For example a strategy can be based on the phenomenon and the geometry of the sensor constellation so that the sensors are moved to those areas with the highest phenomenon intensities while at the same time also ensuring that no part of the investigation area is uncovered.

5.4.1 GEOMETRICALLY INFLUENCED

Geometrically influenced strategies are using information about the sensor constellation within the investigation area for optimisation purposes.

This type of strategy can be mainly used for distributing the sensors evenly across the whole area of interest. On the one hand this provides a basic coverage as it is avoided that bigger parts are not covered by any sensors. On the other hand the even distribution of sensors ensures that there are no big holes in the network which could result in an interrupted connectivity between the sensors (this is only valid if there are enough sensors so that the average distance between the sensors in case of an even distribution is shorter than the maximum radio transmission range).

Basically this approach can take into account the following information:

- position of the sensor itself
- positions of other sensors
- history of past sensor positions (e.g. in order to avoid that a sensor visits some locations more often than others)
- shape of the investigation area

The advantage of this strategy type is that for example a relatively even sensor distribution can be obtained. However a disadvantage is that the real characteristic of the phenomenon is not taken into account so that the sensor constellation is not fitted to the actual distribution of the phenomenon or its intensity.

5.4.2 PHENOMENON INFLUENCED

This type of strategy is mainly influenced by the phenomenon that has to be monitored. This means that the values that are measured by the sensors (or even outputs of models simulating a phenomenon) are used for computing the sensor behaviour. Thus this strategy type can also be referred as data centric.

As the phenomenon is mainly relevant to the coverage of the sensor network phenomenon influenced strategies usually do not primarily deal with the connectivity of the sensor network.

The main advantage of a phenomenon influenced strategy is that the sensor constellation can be optimised by the real state of the phenomenon and not just based on geometrical assumptions. Often this generates a more efficient sensor distribution that reflects the phenomenon distribution.

There are several types of information which can be used within a sensor strategy:

- values the sensor measures itself
- values measured by other sensors
- values calculated by simulation models so that the phenomenon distribution is predicted

One potential disadvantage of solely phenomenon influenced strategies is the risk that sensors can become very clustered so that some parts of the investigation area could become uncovered. For example in a purely phenomenon based sensor strategy there is no mechanism which avoids that sensors move to a few locations where especially high phenomenon intensities can be measured. In this case the areas with lower values would be completely uncovered.

5.4.3 NETWORK CENTRIC

Network centric strategies are closely related to geometrically influenced strategies. The main difference is that the geometry has an indirect influence to the connectivity between sensors and thus determines the needs the sensor network has regarding the sensor constellation. But as the geometry is only one influence on the connectivity (e.g. it could also be influenced by other properties like obstacles and physical phenomena) it shall be treated as separate strategy type.

Mainly this strategy type allows adapting the sensor network constellation in a way so that the connectivity within the sensor network is ensured.

Important inputs to such a strategy are shown in the list below:

- qualitative information about the communication links (as an indication where the communication could be improved by additional intermediary nodes which act as relay stations)

- information about the communication load (can be used for determining those parts of the sensor network where additional sensors could be used for providing an enhanced communication bandwidth)
- status information of other sensors (for determining if there are indications that sensors need to be replaced)
- geometrical information about the sensor network constellation (as one input that enhances the purely network centric inputs)

Furthermore it is also possible that sensors perform coordination mechanisms in order to determine if it is possible to switch to some type of sleeping mode. This allows to reduce the energy consumption so that the lifetime of the sensor network is prolonged.

As a conclusion it shall be mentioned that network centric strategies provide mainly means for creating a reliable completely connected sensor network. Thus the optimisation according to the needs of an optimised coverage is not taken into account. Because of this a sensor network strategy should be based not only on network centric influences but also on one of the two previously presented strategy types.

5.5 UAV STRATEGIES

Besides the previously mentioned strategy types those strategies that are used for UAVs and their integration into sensor networks form another important group.

There are several application possibilities for UAVs which require different specially developed strategies:

- **Support of ground based sensors**: In case of phenomena that are ground based (e.g. forest fires) the deployment of UAVs could provide an extension to the ground sensors. For example in Grocholsky et al. (2004) an approach is described in which UAVs provide a quick coarse overview of the area of interest. The overview data can be used for an optimised dispatching of ground vehicles in order to capture the phenomenon optimally.
- **Measurement of 3-dimensional phenomena**: In scenarios where a 3-dimensional distribution of the phenomenon must be detected UAVs can provide the needed sensing capabilities. An important example is the analysis of toxic clouds. It is possible to equip an UAV with gas sensors so that the gas concentration can be measured. By flying through the toxic gas cloud the UAV can deliver detailed information about the 3-dimensional distribution of the pollutant.

- **Deployment of sensors**: Zhao & Guibas (2004) describe a possibility of how UAVs can be used for deploying sensors by dropping them from the air. An important advantage of this approach is the possibility to quickly deploy large numbers of sensors in areas that might not be accessible on the ground.
- **Enhancement of communication ranges**: In Chaimowicz (2005) it is mentioned that UAVs can improve the connectivity within the sensor network. On the one hand it is possible to use UAVs as relay station to retransmit the messages sent by ground based sensors. On the other hand it is also possible to use UAVs for collecting the measured data from sensors which are not connected to other sensors or nodes of the network.

It has to be noted that especially those UAV strategies that aim at enhancing the functionality of ground based sensors must be supported by their strategies. For example a ground based sensor needs to be capable of integrating and using information that is generated by the overview data captured by an UAV.

Additionally the currently evolving research on cooperative behaviour of multiple UAVs shall be mentioned. This means that several UAV coordinate among them in order to reach a sharing of work so that the set of UAVs is used as efficient as possible.

6. INFLUENCING FACTORS FOR THE COVERAGE STRATEGY SELECTION

6.1 INTRODUCTION

This chapter aims at presenting factors that have to be taken into account when developing or selecting coverage strategies for geosensor networks. In this text both mobile and stationary sensors are addressed.

In order to provide a clear structure this chapter is divided into three sections dealing with elementary needs and influences that are related to geosensor networks:

- phenomenon specific factors
- sensor specific factors
- use case specific factors

All aspects that are subsequently presented have to be seen as potential factors of influence. When selecting a strategy these factors have to be investigated carefully so that their practical influence is determined. In many cases this can be done by analysing the use case and drawing conclusions. However in several cases the relevance of a factor must be evaluated by practical experiments. A tool for performing such experiments is the simulation framework that was developed within WP 3210 of the OSIRIS project.

Although it is not possible to include all theoretically existing influences that might only be valid for very specific sensors, sensor platforms, phenomena and use cases this chapter provides a comprehensive guide to those factors that are relevant for most use cases and especially for the OSIRIS scenarios.

6.2 PHENOMENON SPECIFIC FACTORS

The phenomena that are observable by a geosensor network may have very differing properties. Thus an overview shall be given which describes potentially relevant phenomenon properties that have to be taken into account when developing or choosing sensor network strategies. Additionally these phenomenon characteristics can be seen as a basis for optimising existing strategies with regard to the needs of specific use cases.

The description and analysis of phenomenon characteristics provides furthermore the foundation for developing a phenomenon classification that will facilitate the selection of appropriate sensor network strategies. This development is still an ongoing research topic. However in section 8 several basic rules are presented. A long term objective of this classification approach is also to allow an autonomous strategy selection by sensors depending on the current situation or phenomenon type they are dealing with.

As this chapter mainly aims at providing a collection of potentially important phenomenon characteristics and thus building the foundation for the development of a phenomenon classification the different properties are presented in a relatively abstract way. But for illustration purposes several of the characteristics presented will be explained by practical examples.

As far as the authors of this report are aware in the sensor network literature no comprehensive analysis of influencing factors to sensor network strategies is available. Most currently available approaches are based on specific phenomenon properties and describe how the optimisation to these factors can be reached.

The phenomenon properties that are presented in this section are divided into three categories as shown below in Table 6-1. Each of these categories is divided into more specific subcategories.

Table 6-1: Categories of influencing factors to the strategy design

Category	**Subcategories**
Shape and distribution	Discrete vs. continuous phenomena
	Geometry
	Distribution
	Dimension
Dynamic	Movement
	Changes of geometry
	Dynamic of values
	Distribution changes
	Number of phenomenon instances
	Temporal clusters
	Periodicity
Context	Scale level
	Spatial coherence
	Measurement process

It is important to note that a complete separation between these categories is not feasible. For example the shape of a phenomenon may change during the course of time. This would be related to both aspects shape and dynamic. However the presented division into categories provides a useful structure for analysing sensor network strategies so that it will be used throughout this section

6.2.1 SHAPE AND DISTRIBUTION

The following sections deal with all phenomenon characteristics that are related to the shape, size and distribution of one or more phenomena.

6.2.1.1 DISCRETE VS. CONTINUOUS PHENOMENA

Discrete and continuous phenomena can be differentiated according to their properties (see Table 6-2).

Table 6-2: Properties for differentiating between discrete and continuous phenomena

Subcategory	Property	Property values
Discrete vs. continuous phenomena	Discrete vs. continuous phenomena	Discrete
		Continuous
	Number of phenomenon instances	Minimum number known
		Maximum number known
		Exact number known
		Special case: Exactly one instance
		No information available

A first criterion is the ability to distinguish between single phenomenon instances within the area of interest. With regard to the strategy development two different cases have to be mentioned:

- Discrete phenomena
- Continuous phenomena

In case of a discrete phenomenon it is possible to distinguish between individual phenomenon instances within the area of interest. A further differentiation is to analyse if the minimum, maximum or exact number of instances is known that is occurring within the investigation area.

An example for this criterion is lightning strikes caused by a thunderstorm within a certain area and time period. The lightning strikes are a discrete multiple phenomenon. Every lightning strike is a individual phenomenon instance of which a multitude occurs during a thunderstorm. If there is no thunderstorm the exact number of lightning strike (obviously 0) can be predicted. During a thunder storm it is not possible to exactly predict how many lightning strikes will occur or what the maximum number will be.

A special case is when it is known that there is exactly one phenomenon instance within the investigation area. The following situation is an example for this: The operator of a sensor network wants to detect a wild animal (e.g. a bear) in a given area and it is known that only one exemplar of the animal exists. This knowledge can be used for developing a specialised strategy that takes exactly this knowledge into account (e.g. if the bear is detected no other areas need to be observed).

A continuous phenomenon is characterised by the fact that a subdivision into single phenomenon instances is not sensible or even not possible. An example for this is the determination of the particulate mater concentration by a sensor network. The phenomenon “particulate matter” exists everywhere, only the measured values are varying. Thus it is not possible to distinguish between “particulate matter instances”. However it is possible to “convert” this continuous phenomenon into a discrete phenomenon. In this case the phenomenon would not be any longer “particulate matter” but “particulate matter clouds”. This makes it possible to distinguish between different particulate matter clouds which can be seen as a discrete phenomenon.

6.2.1.2GEOMETRY

The geometry of a phenomenon is a very important factor that may influence sensor network strategies.

Table 6-3: Properties related to the geometry of phenomena

Subcategory	Property	Property values
Geometry	Shape	Compact
		Stretched
		Irregular
	Predictability	Predictable
		Unpredictable
	Absolute size	Centimetres
		Metres
		Kilometres
	Relative size	

In case of discrete phenomena the geometry of the single phenomenon instances is relevant. This is not applicable for continuous phenomena because there are no individual instances. Instead the geometry of for example areas with extreme values can be analysed. With regard to the geometry the following two aspects will be presented more closely:

- shape
- size

The shape of single phenomenon instances can be extremely manifold. Thus a classification according to the phenomenon shape is relatively difficult. However some important classes of phenomenon shapes can be identified and shall be mentioned. A very important differentiation can be made between evenly shaped compact phenomena and phenomena with a stretched shape. For example a single thunderstorm cell usually has a compact form whereas a cold front has a long stretched shape. Additionally it can be relevant if the shape and size of a phenomenon is predictable (e.g. dispersion models could be used for predicting the geometry of a air pollutant cloud).

A second important aspect with regard to the geometry is the phenomenon size which has two facets:

- absolute size
- relative size

The absolute size for example provides information if the phenomenon to be monitored has a diameter of a few metres or of several kilometres. This directly influences the detectability of the phenomenon and has consequently to be taken into account. For example the detection of a toxic gas cloud with a diameter of several kilometres probably needs a different strategy than the recognition of a small vehicle that intrudes into a prohibited area.

The previous example also suggests that the relative size of the phenomenon in comparison to the size of the investigation area is important. The smaller a phenomenon is compared to the area of interest the more the probability of a quick detection is reduced.

6.2.1.3 DISTRIBUTION

As previously stated it is necessary to distinguish between discrete and continuous phenomena. Thus with regard to the distribution two cases have to be mentioned (see Table 6-4).

- distribution of phenomenon instances
- distribution of continuous values

Table 6-4: Properties related to the distribution of phenomena

Subcategory	Property	Property values
Distribution	Distribution of phenomenon instances	Density
		Number of clusters
		Size of clusters
		Shape of clusters
	Distribution of continuous values	Appearance of the value surface
		Number of areas with extreme values
		Size of areas with extreme values
		Shape of areas with extreme values

The distribution of phenomenon instances can be described by a density function which represents the number of phenomenon instances per unit of area. An example for this is the number of lightning strikes per hour per unit of area. The distribution of continuous values cannot be described by such a density function. Instead the values that vary throughout the area of interest are relevant. The variation of values can be described on the one hand throughout the whole area of interest. On the other hand it is also possible to describe the distribution of values within phenomenon instances (e.g. varying concentration within a pollutant cloud).

If the distribution of discrete phenomenon instances is investigated it is especially interesting to look at a potential clustering. For example during a thunderstorm lightning strikes occur more frequently in those areas that are within the path of the thunderstorm whereas in other areas no strikes can be observed. With regards to clustering especially factors like number, size and shape of clusters are relevant.

When analysing the distribution of continuous values especially the distribution of areas with extreme values can be investigated when deciding for a strategy. The determination of areas that are most affected by an air pollutant cloud is one example where areas with extreme values are important. Similarly to clustering also in this case especially number, size and shape of extreme value areas are potentially important factors for choosing sensor network strategies.

Finally it has to be remarked that there is some kind of parallel between the geometry of single phenomenon instances and the geometry of clusters/geometry of areas with extreme values. Thus there might be some common basic influences that allow the reuse of sensor network strategies in different scenarios.

6.2.1.4DIMENSION

A further fundamental aspect related to the phenomenon shape is the dimension. It is possible to distinguish between 0-dimensional (e.g. animals that are modelled as points), 1-dimensional (e.g. rivers), 2-dimensional (e.g. forest fires) and 3-dimensional (e.g. toxic gas cloud) phenomena.

Table 6-5: Properties related to the dimension of phenomena

Subcategory	Property values
Dimension	0-dimensional
	1-dimensional
	2-dimensional
	3-dimensional

The question of the dimensionality is relevant as sensors must be able to sense all needed dimensions of a monitored phenomenon. For example a 3-dimensional phenomenon like a gas cloud may need sensors that are able to fly through the air so that every part of the cloud is covered.

6.2.2 DYNAMIC

The aspect “dynamic” comprises all topics that deal with phenomenon changes during the course of time. In the following sections several properties will be presented that are related to the dynamic of phenomena and that may have an influence on the sensor network strategy design / selection.

6.2.2.1MOVEMENT

The movement of phenomena is an important factor of influence when it comes to the development or selection of sensor network strategies.

Table 6-6: Properties related to the movement of phenomena

Subcategory	Property	Property values
Movement	Absolute speed	Special case: Stationary phenomena
	Relative speed compared to the size of the investigation area	
	Relative speed compared to the speed of sensors	Slower
		Equal speed
		Faster
	Movement direction of phenomenon instances	Uniform direction
		Different direction
		Special case: Movement on certain tracks
	Changes of movement directions (temporally caused)	Speed changes
		Direction changes
	Changes of movement directions (spatially caused)	Speed changes
		Direction changes
	Predictability	

A basic distinction has to be made between mobile and stationary phenomena. In case of mobile phenomena several factors may become relevant which are presented below.

First the speed of phenomenon instances has to be mentioned. On the one hand the absolute speed is important. But on the other hand also the speeds relative to the size of the investigation area and to the sensor speed have to be presented. If for example a fast moving phenomenon is measured it is a decisive factor for the strategy selection whether the sensors are fast enough to follow the phenomenon or not.

If a monitored phenomenon moves it is also important to investigate the direction of movement. The simplest case would be a constant movement into one direction. For example a toxic gas cloud usually moves in the direction of wind so that in case of a constant wind direction the movement would occur constantly in the according direction. Other phenomena might perform irregular movements so that the direction is random or is underlying variations.

Even if these variations are caused by certain measurable influences the rules that cause those variations might be unknown so that the movements appear to be random. A third case consists of phenomena that move along fixed paths (e.g. busses) but even in this case it might be unknown which path is selected from a set of possible routes.

Another aspect related to the phenomenon movement deals with temporally or spatially caused movement changes affecting speed and/or direction. For example the direction of wind may change during the course of time which would also indirectly affect the movement of clouds. With regard to spatially caused movement changes the different speeds of the current in a river can be given as an example. Depending on the position during the course of the river flotsam might be transported with different speeds.

Finally the predictability of the phenomenon movement (i.e. direction and speed) needs to be mentioned. As shown before the trajectory of toxic clouds is influenced by wind speed and direction. In this case a prediction is possible. However in other scenarios such a prediction might not be possible either because the movement is random or the rules determining the movement are unknown.

6.2.2.2CHANGES OF GEOMETRY

Changes of geometry can be divided into two subtypes: Changes of size and changes of shape during the course of time.

Table 6-7: Properties related to changes of geometry

Subcategory	**Property**	**Property values**
Changes of geometry	Changes of size	Shrinking
		No changes
		Growing
	Changes of shape	

Many phenomena are subject to growing or shrinking processes. For example forest fires usually start at a small spot and may grow to an expanded size. Besides growing processes also shrinking and constant phenomena may occur. Even phenomena with an oscillating size exist.

Like the size also the shape of phenomena can be subject to changes. For this also a forest fire can be given as an example. Depending on changes of the wind direction a forest fire may grow into different directions. Subsequently this causes a continuously ongoing change of shape.

6.2.2.3 DYNAMIC OF VALUES

There are several ways how the dynamic of values can influence the selection and design of coverage strategies. Several important aspects are shown below in Table 6-8.

Table 6-8: Properties related to the dynamic of values

Subcategory	**Property**	**Property values**
Dynamic of values	Changes of rational scaled values	Decrease
		No change
		Increase
	Changes of interval scaled values	Decrease
		No change
		Increase
	Changes of ordinal scaled values	Decrease
		No change
		Increase
	Changes of nominal scaled values	

The values of a phenomenon can change during the course of time. Rational, interval and ordinal values allow a comparison so that it is possible to distinguish between increasing and decreasing processes. For example radioactive substances lose their radioactivity during the course of time. Opposed to this nominal scaled values may also change but it is not possible to define an increase or decrease. For example the land use in a monitored area may change during the course of time but this is nothing which could be quantified in order to distinguish between increase and decrease.

6.2.2.4 DISTRIBUTION CHANGES

The distribution of single phenomenon instances and of minima/maxima can be subject to changes during the course of time.

Table 6-9: Properties related to distribution changes

Subcategory	**Property values**
Dynamic of values	Development of clusters
	Movement of clusters
	Dissolving of clusters
	Development of extremes
	Movement of extremes
	Dissolving of extremes

For example clusters may develop, relocate and the dissolve. An example for this is the life-cycle of a thunderstorm cell. Such a cell develops moves and then dissolves. If not the thunderstorm is analysed itself but the lightning strikes it is possible to see a connection between clusters of lightning strikes and the trajectory of the thunderstorm.

Another example is the distribution of air pressure in the atmosphere. There are different high pressure and low pressure areas that are constantly relocating. Thus this can be seen as an example for developing, relocating and dissolving extremes.

6.2.2.5 NUMBER OF PHENOMENON INSTANCES

As mentioned before the number of single phenomenon instances is a potentially relevant factor of influence to the selection and development of sensor network strategies.

Table 6-10: Properties related to the number of phenomenon instances

Subcategory	**Property values**
Number of phenomenon instances	Decrease
	No change
	Increase

For example in an area of interest the number of wild animals that are observed can change during the year.

Closely related to this aspect are also the two subsequently presented criteria “temporal clusters” and “periodicity”. Temporal clusters describe sporadic increasing numbers of phenomenon instances whereas periodicity deals with periodic variations.

6.2.2.6 TEMPORAL CLUSTERS

Temporal clustering describes changing phenomenon intensities during the course of time. This relates mainly to temporally increasing numbers of single phenomenon instances or to increasing measured values whereas in other time periods the intensity of the phenomenon is significantly lower.

An example for this are once again lightning strikes. During a thunderstorm a high activity can be observed whereas during other time periods no strikes occur. Thus lightning strikes occur temporarily clustered during thunderstorms.

This can be used for sensor network strategies by controlling the sensor activity: The sensors could be activated during the occurrence of a temporal cluster while they could be switches off during the other times.

6.2.2.7 PERIODICITY

Periodicity means that the phenomenon activity repeats itself during the course of time in regular patterns. The knowledge about such a periodicity could be used as an input for optimising sensor network strategies. A typical periodical phenomenon is the occurrence of thunderstorms in the inner tropical convergence zone which regularly can be observed during the late afternoons.

6.2.3 CONTEXT

The term context shall summarise potential influences on the sensor strategy design that result form the measurement process that needs to be applied and from the type of values that are used for describing the phenomenon.

6.2.3.1 SCALE LEVEL

As shown in the table below there are four different scale levels that have to be distinguished (Bahrenberg et al. 1999).

Table 6-11: Properties related to the scale level

Subcategory	Property values
Scale level	Nominal
	Ordinal
	Interval
	Rational

In case of a nominal scale the measurement of a phenomenon results in qualitative properties. For example aerial images can be analysed in order to determine the land use which is usually described by a set of qualitative categories. Furthermore it is not possible to rank these categories.

In contrast to this an ordinal scale allows the ordering of categories. An example could be the description of contamination loads by categories like “low contamination”, “medium contamination” and “high contamination”. With regard to sensor coverage strategies this would allow approaches where sensors use the ordered category values for moving to those areas where the highest contamination occurs.

Both the interval and rational scales allow the calculation of ratios between measured values. For a sensor strategy this would allow to compute the strength of change in value. Subsequently the gradient of the phenomenon might be determined so that it becomes possible to move to those areas where extreme values occur. The main difference between the interval and the rational scale is that the interval scale does not posses a zero-point.

6.2.3.2SPATIAL COHERENCE

The spatial coherence becomes especially important in those cases in which sensor coverage strategies are designed to make assumptions about the change of values in surrounding areas. If there is a strong spatial coherence a sensor is able to reason about the values in its neighbourhood. In contrast a low spatial coherence makes such assumptions impossible.

An example for a phenomenon with a low spatial coherence are convective rainfalls. Usually such rainfalls occur only at regionally and temporally limited places. Consequently the rainfall is subject to strong variations within very limited areas. Opposed to this the variance of rainfall in conjunction with a warm front is more continuous which results in a strong spatial coherence.

6.2.3.3MEASUREMENT PROCESS

A last criterion that shall be mentioned in conjunction with the measured variable is the measurement process that is applied. For example phenomena that can only be measured in long lasting procedures might need different strategies than phenomena that can be captured by ad-hoc measurements.

The rate of lightning strikes in a thunderstorm for example can only be determined by counting the strikes during a longer time interval. Opposed to this the measurement of temperatures can be executed without needing any special amount of time.

For coverage strategies that are based on mobile sensors the waiting times that are needed for performing longer lasting measurements is something that needs to be taken into account.

6.3 SENSOR SPECIFIC FACTORS

Besides the properties of the measured phenomenon also the characteristics of the deployed sensors or sensor networks can influence the choice for the best suited strategy. Several potential factors regarding the sensor characteristics will be described in the following sections.

6.3.1 MOBILITY

For executing movement strategies it is important that the sensor (platform) possess some kind of mobility. As there are several distinguishing properties regarding the mobility the selection of a movement strategy is strongly influenced by the type of mobility the sensor platform provides.

Table 6-12: Properties related to the mobility of sensors

Subcategory	**Property**	**Property values**
Mobility	Relative speed in comparison to the phenomenon speed	Slower
		Equal speed
		Faster
	Relative speed in comparison to the size of the area of interest	
	Limitations regarding the manoeuvrability	

Concerning the sensor speed two properties are relevant. On the one hand the relative speed in comparison to the size of the area of interest determines for example how much time a sensor needs to cross the investigation area which influences the maximum time a sensor needs for relocating. On the other hand the relative speed in comparison to the phenomenon speed decides if a sensor is able to follow the movement of phenomenon instances. Depending on this factor it might be necessary for example to develop some kind of interception mechanism that allows slower sensors to reach the trajectories of moving phenomenon instances.

Furthermore the manoeuvrability of sensors may be limited. For example an airplane is not capable of turning intermediately in any direction as it might be necessary to fly large curves for performing heading changes. Another example are ground vehicles which are limited by certain minimum turn radii. It is important that a movement strategy takes such limited manoeuvrability into account.

6.3.2 COMMUNICATION

As stated before there is a close connection between connectivity and coverage strategies. Thus the communication capabilities of a sensor can have a strong influence to the design and selection of coverage strategies.

Table 6-13: Properties related to the communication capabilities of sensors

Subcategory	Property values
Communication	Sending of messages
	Receiving of messages
	Communication range in comparison to the size of the investigation area
	Communication range in comparison to the average distance between sensors
	Latency
	Bandwidth
	Reliability

For example most coverage strategies need to receive messages from neighbouring sensors so that the capability of sending and receiving messages is essential. This is a requirement for nearly all sensor strategies that rely on the coordination between sensors.

The next factor to be presented is the communication range. The communication range in comparison to the size of the investigation area is the first factor to be evaluated in this context. This property determines if a sensor is able to have a direct communication link to all other sensors within the area of interest or if it is necessary to rely on more complex communication protocols for message forwarding and routing. Secondly the communication range in comparison to the average distance between sensors has to be checked. If the communication range is significantly shorter than the average distance between sensors it is very probable that sensors are often without any connection to other sensors.

Further potentially important aspects that shall be mentioned are latency, bandwidth and reliability of communication. The latency determines the time a message needs to be transmitted from one sensor to another. Limitations resulting from bandwidth influence the amount of information that can be exchanged by sensors for coordination purposes. Reliability describes the guarantees that are given for the message delivery.

Additionally it shall be mentioned that the existence of relay stations can have a direct influence on the communication capabilities. One variant for deploying relay stations could be the use of UAVs or specially equipped ground vehicles that enhance the communication range within the sensor network.

6.3.3 COMPUTING POWER AND MEMORY

Computing power and memory are further determining factors for the strategy design and selection. The memory capacity influences how big the amount of information is that can be processed during the execution of a strategy. For example the memory capacity limits the number of received messages from other sensors that can be buffered for gaining an insight into the past sensor constellations (history). The computing power influences the complexity of computations that can be performed when a movement strategies is used.

6.3.4 ENERGY SUPPLY

The energy supply of sensors is the next factor to be presented. It has a decisive influence on the amount of movement, communication and computing that can be performed in the process of strategy execution.

Table 6-14: Properties related to the energy supply

Subcategory	Property	Property values
Energy supply	Availability of energy	Unlimited
		Limited energy supply
		Temporary availability
		Regeneration phases without energy supply
	Capacity of the energy supply	

The simplest case is an energy supply that always provides enough power. However to assume such an energy supply is not realistic. The most common case is the use of battery powered sensors that are limited by the battery lifetime. As their energy supply is limited it is necessary to enhance the sensors lifetime by developing strategies that minimise the energy consumption (Slijepcevic & Potknojak 2001). Solar powered sensors are another commonly used sensor type. For these sensors it is important to take into account that the energy supply is usually limited to certain time periods (i.e. if the sun is shining).

Other sensors ensure their energy supply by visiting special base stations where their batteries can be recharged. Such strategies need to take into account that there are phases in which the sensor is not available due to the time that is needed for recharging. Additionally it is necessary to plan the sensor movement carefully so that there is always enough energy left for returning to a recharging station.

Besides the limitations of the energy reserve it is also interesting to look on the power which can be provided at one moment. For example a battery or solar powered sensor can only provide a limited amount of maximum power. This causes limitations for the traction and communication power.

6.3.5 LOCALIZATION

The question if a sensor is able to determine its position is important as the knowledge of sensor positions is a key issue for many coverage strategies. Also the precision of the positioning data has to be considered.

Table 6-15: Properties related to the localization capabilities of sensors

Subcategory	Property	Property values
Localization	Type of positioning	Absolute positioning
		Relative positions to other sensors
	Precision	
	Duration of the positioning process	
	Communication costs	

Regarding the type of positioning information two scenarios must be distinguished. The most comprehensive positioning variant is the determination of the absolute sensor position. This means that the sensor is able to locate itself within the area of interest. An example for this is the mounting of GPS receivers on sensor platforms. Opposed to this there are also positioning approaches that provide relative positioning information. Examples for this positioning type are data about the distance or direction to neighbouring sensors. Such an approach is described in Batalin & Sukhatme (2002). For both types of positioning data it is also often relevant to consider their precision.

Sometimes also the time a sensor needs for calculating its position is significant. Several positioning methods require some time before a position is available. These waiting times have to be considered in the design of sensor strategies.

Another aspect that shall be mentioned is the amount of communication that is needed for determining the sensor position. Some methods are based on measuring the signal strength of the communication links between a sensor and its neighbours. During the positioning process a sensor sends requests to its neighbours and waits for the responses for measuring the signal strength so that a triangulation can be performed. As it may take some time until enough neighbours have answered the positioning process can be delayed. Furthermore it is often not possible to execute this request-response-scheme continuously in order to avoid an overload of the communication system. This imposes additional restrictions which result in a limited update rate of the positioning data.

6.3.6 DETECTION RANGE

The term detection range describes the area/radius around a sensor in which the sensor is able to perform measurements. In this context an important differentiation has to be made between in-situ and remote measurements (Botts 2006). An in-situ sensor performs measurements only at the location it is placed whereas remote sensors are capable of measuring at distant locations. An example for an in-situ sensor is an air pressure sensor. Remote measurements are for example typical for radar sensors which determine the rainfall in a larger surrounding area around the sensor location. The knowledge about the phenomenon values in a sensors neighbourhood can be used for designing strategies in which sensors move to those areas with the highest phenomenon intensity.

Another aspect of the detection range is that sensors exist which have a limited field of view. Thus these sensors are only able to observe a part of their environment that can usually be described by a characteristic angle. A typical example for this is a camera which in most cases is only able to monitor a certain field of view. This limitation must be taken into account when distributing sensors so that a complete coverage can be ensured.

6.3.7 COMPLEX SENSOR CAPABILITIES BY COMBINING DIFFERENT FACTORS

If the previously described factors are not only considered as independent characteristics several additional capabilities can be discovered. By combining different basic factors it can be evaluated if there are also more complex tasks that could be executed by a sensor.

As an example the combination of the factors communication, computing power/memory and localization shall be presented. By these three factors the degree to which a sensor is able to create maps of its neighbourhood is strongly influenced. An precise localization unit enables a sensor to georeference the measured values. The size of the area that can be mapped is mainly influenced by the memory capacity. A powerful communication link would allow the sensor to also integrate the measurements performed by other sensors into the creation of a map.

This short example shows that by combining several basic factors it is possible to create more sophisticated sensor functions which could enhance the functionality of specifically designed sensor network strategies.

6.4 USE CASE SPECIFIC FACTORS

The last big complex regarding influencing factors for the design of coverage strategies deals with use case specific circumstances. This category summarises all requirements, properties and conditions that are influenced by the aims of the sensor network and by the technical characteristics of the use case.

6.4.1 AIMS OF THE SENSOR NETWORK

Depending on the aims of the sensor network different mobility strategies can be deployed. An important aim is for example the fast detection of phenomenon instances. Depending on the use case it may sometimes be sufficient if a phenomenon instance is detected only once for a short time whereas other scenarios need a long lasting continuous detection is needed. Another potential application is to use the sensor network for measuring values that are needed as inputs to simulation models.

Table 6-16: Properties related to the aims of the sensor network

Subcategory	**Property values**
Aims of the sensor network	Fast detection
	One-time detection
	Continuous detection
	Input into simulation models

6.4.2 NUMBER OF SENSORS

It can be expected that the number of available sensors is very important for the selection and design of coverage strategies.

Table 6-17: Properties related to the number of sensors

Subcategory	**Property values**
Number of sensors	Absolute number
	Sensor density

On the one hand the absolute number of sensors might influence for example the scalability of the sensor network. In this case it is necessary to ensure that the communication channels are able to transport all messages a certain coverage strategy needs in order to work with a given number of sensors. A sensor network that can only use a limited bandwidth while at the same time a very large number of sensors has to be integrated requires specially optimised strategies. Such strategies would minimise the number and size of messages that need to be transmitted for coordination purposes.

Besides the absolute number of sensors also the sensor density must be considered. The density is determined by calculating the ratio of the number of sensors compared to the extent of the investigation area.

6.4.3 OBSTACLES

The existence of obstacles creates limitations to the freedom of movement of sensors. Sometimes it might be necessary for sensors not to use the direct way in order to circumvent obstacles. A specialization of this case is the limitation of sensors to follow only predefined paths. For example cars that are equipped with sensors need to stay on roads.

6.4.4 CENTRALISED CONTROL VS. AUTONOMY

The existence of a central control station can be used for designing efficient sensor coverage strategies.

Table 6-18: Properties related to the type of network control

Subcategory	**Property**	**Property values**
Centralised control vs. autonomy	Capacity	
	Task	Data collection
		Delivery of additional information
		Computation of control commands

In case of a very powerful control station with a high capacity for handling sensors it would be possible to centrally calculate control commands which are subsequently transmitted to the sensors. On the one hand this would reduce the autonomy of the sensors but on the other hand the global knowledge of the sensor network that can be used for the calculation allows often more efficient decisions. But it is also possible that a central control station only provides additional information to all sensors which can be used by them individually during the execution of autonomous strategies. This would enhance the autonomy while a global knowledge is still used to some extend. A total autonomy of sensors would be the case if a central station is only used for data collection purposes so that it has no direct influence on the sensor behaviour.

6.4.5 SENSOR DEPLOYMENT

Depending on the type of sensor deployment additional requirements may arise. For example sensors might be deployed at one central location so that it is necessary to perform movements in order to reach an even distribution across the investigation area. Other possibilities are a deployment of sensors at random locations (e.g. by dropping them from an airplane) or a planned regular distribution pattern in conjunction with manual sensor deployment.

Table 6-19: Properties related to type of sensor deployment

Subcategory	Property values
Sensor deployment	Clustered
	Random
	Evenly distributed

6.4.6 OPERATIONAL CONDITIONS AND RELIABILITY REQUIREMENTS

A last aspect related to the use case are the operational conditions with a special focus on the requirements for reliability.

Table 6-20: Properties related to the operational conditions

Subcategory	Property
Operational conditions and reliability requirements	Importance of reliability
	Feasibility of redundancy
	Probability of failures

First it is important to analyse the importance of reliability for the given use case. For example a military surveillance system is likely to have much higher needs than a weather monitoring system that is operated by amateur meteorologists. This influences the strategy design and selection to what extend for example self healing techniques must be applied for ensuring that a complete coverage is maintained even in case of node failures.

Furthermore the feasibility of relying on redundancy must be considered. If sensor nodes are for example very cheap it might be preferable to deploy a lot more sensors than needed for a basic coverage. This facilitates self healing technologies as the replacement of defective sensors becomes much easier by just activating redundant sensors.

Finally also the probability of failures has an influence. This determines for example how often sensors need to be replaced and which amount of redundancy is necessary.

7. INFLUENCING FACTORS FOR THE COMMUNICATION STRATEGY SELECTION

7.1 INTRODUCTION

In this chapter factors that could have an influence on the development and selection of communication strategies are discussed.

This chapter is divided into three sections dealing with elementary types of influencing factors that occur in the context of geosensor networks:

- phenomenon specific factors
- sensor specific factors
- use case specific factors

The factors shown below shall be seen as influencing factors that can be relevant depending on the scenario so that they are not necessarily always important. However all those factors should be analysed carefully regarding their relevance when the selection or design of a communication strategy is performed. Mostly this can be done by closely investigating the description of the scenario. If this is not possible another solution is to use simulation environments like the one proposed in the OSIRIS WP 3210.

Although it is not possible to include all theoretically existing influences that might only be valid for very specific sensors, sensor platforms, phenomena and use cases this chapter provides a comprehensive guide to those factors that are relevant for many use cases and especially in the OSIRIS scenarios.

7.2 PHENOMENON SPECIFIC FACTORS

The following subchapters deal with phenomenon specific factors that can influence the strategy selection. Compared to the corresponding chapter in the section about coverage strategies the influence of the phenomenon on communication strategies is significantly lower.

Two aspects related to phenomenon specific properties have been identified:

- dynamic
- data type of the measurements

7.2.1 DYNAMIC

The dynamic of a phenomenon can have an indirect influence on the requirements that are posed to a communication strategy. A fast changing phenomenon usually requires a higher frequency of measurements. This directly influences the message rate of a sensor as more measurement results need to be transmitted.

An example for this could be the monitoring of the groundwater quality over a long time period. For this purpose the measurement rate might be two measurements per day so that only very few messages need to be transmitted. Opposed to this the monitoring of a toxic cloud that is moving with the wind might require much more measurements per time which would subsequently result in a higher message rate.

7.2.2 DATA TYPE

The second phenomenon specific influence to communication strategies is the data type in which a phenomenon can be measured.

Table 7-1: Properties related to the data type of measurements

Subcategory	Property values
Data type	Vector data
	Raster data

Basically in this guidebook it is differentiated between phenomena measured as vector data (e.g. temperature at a certain point) and phenomena captured by raster data (e.g. rainfall that is captured by radar).

The different data types result in very different bandwidth requirements. While vector data require usually a fairly low amount of bandwidth the transmission of raster data creates very high requirements.

7.3 SENSOR SPECIFIC FACTORS

In this section an overview of sensor properties is given that can influence the feasibility of strategies for different scenarios. The following aspects will be analysed:

- sensor mobility
- communication capabilities
- operating mode
- computing power and memory
- energy supply
- localisation

7.3.1 MOBILITY

The mobility of sensors influences primarily the dynamic of a sensor network.

Table 7-2: Properties related to the mobility of sensors

Subcategory	Property
Mobility	Absolute speed
	Relative speed in comparison to the transmission range and the average distance between sensors
	Relative speed in comparison to the size of the area of interest

Depending on the sensor movement the topology of the network can continuously change. This would require routing protocols which can cope with this kind of dynamic network.

Furthermore the relative speed of a sensor in comparison to the transmission range and the average distance between sensors determines how fast the topology changes. If the relative speed is high the neighbouring nodes a sensor is able to reach change more frequently. Subsequently a sensor network strategy is needed which is able to deal with such frequently occurring topology changes.

Finally the relative speed of sensors compared to the size of the area of interest needs to be mentioned. This speed influences how quickly mobile sensors can be moved to locations where additional sensors are needed in order to ensure the connectivity.

7.3.2 COMMUNICATION

The communication capabilities of a sensor belong obviously to the most important influences that determine which communication strategy has to be selected for a sensor or how such strategies need to be designed.

Table 7-3: Properties related to the sensor communication capabilities

Subcategory	Property values
Communication	Sending of messages
	Receiving of messages
	Wireless or wired communication
	Communication range in comparison to the size of the investigation area
	Communication range in comparison to the average distance between sensors
	Latency
	Bandwidth
	Reliability

The two first basic properties are if a sensor is even able to send and/or receive messages. If these two functions are not provided by a sensor the communication strategies that can be applied are very limited.

Another elementary property is the medium the network is based on: This can be either wireless or wired. While in wired networks topics like energy supply and limited connectivity/communication range are less important they become very relevant in wireless sensor networks. Especially the following two aspects are mainly only applicable to wireless sensor networks.

For determining the need of multi-hop data transmission the comparison of the communication range to the size of the investigation area or respectively to the maximum distance to the data sink needs to be considered. If the communication range of a sensor is shorter a direct communication link cannot always be established so that multi-hop data transmission becomes necessary.

Additionally the communication range compared to the average distance between sensors shows if it is necessary to take into account that sensors might not be continuously connected. For example it is possible that sensors move so that they are not within communication range to any other sensor. If this is the case communication strategies could provide caching mechanisms which buffer messages until the connection to other sensors or the rest of the sensor network is restored so that the messages can be delivered.

Further basic factors are latency, bandwidth and reliability of the communication system the sensor network is build on. Besides this, these factors can also be seen as requirements that must be fulfilled by communication strategies.

7.3.3 OPERATING MODE

The term operating mode identifies all properties that concern the way a sensor is controlled.

Table 7-4: Properties related to the operating mode of sensors

Subcategory	Property	Property values
Operating mode	Push or pull data delivery	Push
		Pull
	Autonomy	
	Coordination capabilities	

First the mode of data delivery is important. This determines if a sensor needs to send data only on request or independently by itself. In the latter case a communication strategy must specify in which situations (e.g. time intervals, exceeded thresholds) a sensor must start a data transmission. Whereas the first variant could be practical for relatively uncritical phenomena (e.g. measuring meteorological data) the second variant is especially important for alerting mechanisms. For example a fire detector must send alerts by itself and should not wait until it is requested about alerts.

As described in chapter 7 in connection with coverage strategies, the autonomy of sensors can be very different. With regard to the communication strategy of a sensor, it is for example possible that there is a centrally determined routing table so that every sensor receives orders which messages have to be forwarded in a multi-hop routing protocol. Another option in a centrally controlled network would be to select sensors which are set into a sleeping mode for conserving energy. Opposed to this in a network consisting of autonomous sensors every sensor must be able to individually determine its communication related behaviour.

A further aspect is the extent to which sensors are able to coordinate among themselves. For example sensors might execute coordination mechanisms for determining sensors which are put into a standby mode and which sensors must participate to multi-hop data transmission.

7.3.4 COMPUTING POWER AND MEMORY SIZE

The computing power and memory that is available for executing communication strategies directly influences the complexity that can be handled.

For example the memory size determines how big routing tables can be. Depending on this factor a sensor might use a global knowledge about the sensor network within its communication strategy or it might have to rely only on local knowledge. In this context is shall be noted that not only the absolute memory size is relevant as it needs to be considered in connection with the size of the sensor network (i.e. the number of sensors).

Other factors that can be influenced by the computing power and memory size are the complexity of distributed data aggregation algorithms or the possibility to use the whole sensor network as a distributed data store.

7.3.5 ENERGY SUPPLY

The energy supply of a sensor strongly influences the types of applicable communication strategies.

Table 7-5: Properties related to the energy supply

Subcategory	**Property**	**Property values**
Energy supply	Availability of energy	Unlimited
		Limited energy supply
		Temporary availability
		Regeneration phases without energy supply
	Capacity of the energy supply	

The availability of energy on the one hand limits the message rate as the energy consumption rises with the amount of data that is transmitted. This means that a limited energy supply often leads to specially optimised communication strategies which allow an efficient message transport.

A temporary limited energy supply (e.g. sensors equipped with solar panels that only work during daylight times) might also be relevant. In this case the communication of a sensor must be scheduled to those times in which sufficient energy is available.

The capacity of the energy supply has an influence on the communication range of sensors (e.g. by influencing the maximum sending power). This factor in conjunction with the average communication distances can influence the need for multi-hop data transmission protocols.

7.3.6 LOCALISATION

Even the localisation capabilities of a sensor can be important for the choice of a communication strategy. The information about the position of a sensor can be used for several communication and data transmission algorithms.

Table 7-6: Properties related to the localization capabilities of sensors

Subcategory	**Property**	**Property values**
Localisation	Type of positioning	Absolute positioning
		Relative positions to other sensors

If the positions of sensors are known it is relatively easy to perform routing algorithms that are based on geometrical knowledge. For example a sensor would be able to determine based on its own position, the position of the sender and the position of the target if is likely that the sensors is part of the route between sender and target.

Furthermore geometrical knowledge can be used for performing aggregation mechanisms on the data that is measured within the sensor network. There are several approaches that use this kind of information for reducing the amount of data that has to be transmitted within the sensor network.

7.4 USE CASE SPECIFIC FACTORS

In this section an overview of influences shall be given that are related to the use case. This comprises all factors that arise from user needs, operating conditions and the environment. The following topics will be analysed in this chapter

- aims of the sensor network
- number of sensors
- terrain
- type of data collection
- sensor deployment
- operational conditions and reliability requirements

7.4.1 AIMS OF THE SENSOR NETWORK

Regarding the aims of the sensor network it is necessary to distinguish between constant monitoring and alerting if predefined conditions are matched.

Table 7-7: Properties related to the aims of the sensor network

Subcategory	**Property values**
Aims of the sensor network	Continuous monitoring
	Alerting in case of critical values

A monitoring system that is designed for long lasting observations (e.g. long term observation of the particulate matters concentration) usually does not need very fast data delivery. Often the data might even be collected for a longer time period at the sensor so that it can be send bundled. This would result in a relatively low message rate with low latency requirements.

Opposed to this e.g. a fire alerting system needs very quick reaction. Thus there are special needs for a low latency data transport. Furthermore the existence of an alert condition might create a burst of many alert messages sent by multiple sensors within a short time.

7.4.2 NUMBER OF SENSORS

The number of sensors is important in two ways: The absolute number of sensors and also the number of sensors compared to the size of the investigation area (= sensor density) must be considered.

Table 7-8: Properties related to the number of sensors

Subcategory	**Property values**
Number of sensors	Absolute number
	Sensor density

The absolute number of sensors can be important for several criteria:

- Scalability: A high number of sensors within the network leads to high scalability requirements. Especially the coordination mechanisms between sensors should use as few messages as possible. This can be illustrated by the following example: If a sensors needs to send a coordination message to every other sensor the number of needed messages rises with the power of 2. This would create more scalability problems compared to coordination mechanisms in which a sensor only needs to send a fixed number of coordination messages.

- Bandwidth: As a higher number of sensors leads to more measurements the transmission of these additional measurements need to be handled by the communication system. Thus a higher bandwidth is needed. However an alternative might also be the design of efficient algorithms which aggregate data so that the bandwidth requirements are reduced to some extend.

A second aspect is the number of sensors in relation to the size of the investigation area. This is also termed “sensor density”. The higher the sensor density is it might be more feasible to temporary turn off single sensors in order to save energy. This could be implemented by specifically adapted communication protocols that allow the decision which sensors can be turned off while maintaining at the same time a sufficient connectivity (in case of multi-hop data transmission) within the sensor network.

7.4.3 TERRAIN

The presence of obstacles in the investigation area can influence the design of communication strategies. For example the presence of high mountains might create the requirement to send messages via intermediary nodes so that it is routed around these obstacles. Thus a specialised strategy might rely on knowledge about the terrain.

Another aspect could be the integration of special (potentially airborne) relay stations into the network. This would be another possibility for dealing with obstacles that obstruct direct communication links.

Closely related to the presence of obstacles is also the medium in which a sensor moves. For example high flying airborne sensors are nearly unaffected by obstacles whereas this might be a big challenge for ground based sensors.

Table 7-9: Properties related to the terrain

Subcategory	**Property**	**Property values**
Terrain	Obstacles	No obstacles
		Obstacles limiting the connectivity
	Medium	Airborne sensors
		Ground based sensors
		Sensors under the water surface

7.4.4 TYPE OF DATA COLLECTION

The type of data collection can be differentiated into two types: Delivery to data sink(s) and using the sensor network as a distributed data store.

Table 7-10: Properties related to the type of data collection

Subcategory	**Property values**
Type of data collection	One data sink
	Multiple data sinks
	Sensor network as data store

The more common case is that the measured data are delivered to one or more data sinks. These data sinks possess databases, direct connections to the internet or the application that uses the data. In this case it is necessary to use data transmission protocols which perform a routing so that the data is transmitted to the according data sinks.

However the previously described approach is not always feasible. Because of scalability reasons it is sometimes not possible to transmit all collected measurement data to data sinks. This could especially be the case in networks consisting of thousands of sensors. Thus an approach is chosen which is oriented on peer-to-peer mechanisms. This means that the data is stored at different nodes across the network and is only delivered to data consumers if it is requested. In connection with this solution special communication strategies are needed in order to allow the requesting of data, discovery of data and transmission of data to those nodes at which the data is requested.

7.4.5 SENSOR DEPLOYMENT

The way sensors are deployed influences the degree to which self organization capabilities of the sensors are needed.

Table 7-11: Properties related to type of sensor deployment

Subcategory	**Property values**
Sensor deployment	Deterministic
	Stochastic

For example in a deterministically the network topology is basically known a-priori. In this case the routing of data transmissions can be performed using predetermined routes. This reduces drastically the need of self organised routing mechanisms.

Opposed to this in a stochastically deployed network the topology is widely unknown. This makes it necessary to integrate coordination mechanisms that work on an unknown topology or which allow to determine the network topology so that data transmission routes can be established.

7.4.6 OPERATIONAL CONDITIONS AND RELIABILITY REQUIREMENTS

Finally also the operational conditions and the requirements for reliability shall be presented as an influencing factor.

Table 7-12: Properties related to the operational conditions

Subcategory	Property
Operational conditions and reliability requirements	Importance of reliability
	Feasibility of redundancy
	Probability of failures

Especially in multi-hop sensor networks the reliability of single nodes are a very important issue. In such a network it could happen that the failure of one single node leads to a breakdown of the complete or at least of parts of the communication network.

Another reliability related aspect is the use case specific need for an uninterrupted continuous availability of the complete communication system. For example a military application is likely to have a much higher need for reliability than a privately operated weather monitoring network. In case of high reliability requirements techniques like self healing networks become important.

Redundancy is a relatively simple solution for improving the reliability of a sensor network. However it is not always possible to deploy enough redundant sensors for reaching a sufficient level of redundancy (e.g. because the costs of sensors are too high). If only a few additional sensors are available more complex self healing solutions like mobile sensors could be feasible.

As a last aspect also the probability of failures shall be mentioned. The higher the likelihood of failures is the more important become self healing mechanisms and redundancy.

8. BASIC GUIDELINES AND EXAMPLES FOR THE STRATEGY SELECTION

As shown in the previous chapters, the influences to the selection and design of sensor network strategies are very manifold. Thus there are a nearly infinite number of phenomenon-sensor-use-case combinations so that the selection of a strategy needs to be made individually for each application. Furthermore the influencing factors have to be seen in combination so that it is not feasible to analyse every factor in an isolated way.

However several general rules can be given that are based on experiences of the authors of this report. An overview of such rules will be given in the first subchapter. The rules presented rely primarily on the differentiation between strategy types that was given earlier within this report.

The second subchapter will illustrate the factors presented before by showing how they can be applied to the practical scenarios that are dealt with in the OSIRIS project.

8.1 GUIDELINES FOR THE STRATEGY SELECTION

At the beginning of this document several approaches for classifying sensor network strategies were given. With regard to this coarse classification now several hints are given which strategy type is likely to be suited to which types of phenomenon/use case.

This has to be seen to some extend as exemplary illustrations as it is impossible to deal with the infinite number of potential scenarios. Thus the following guidelines provide a more valuable approach than overly specific solutions.

Furthermore no specific strategies are referred because most strategies are optimally fitted to very specific needs. However the classes of strategies that are used allow to identify potentially suited strategies which can subsequently analysed so that a good solution for specific scenarios can be found.

As this chapter relies on the outcomes of the previous chapters the most relevant aspects will be taken up once again. In this chapter the factors previously presented will be analyzed from a different perspective. This means that it is presented which strategy type is suited for which kinds of phenomena. Opposed to this the previous two chapters gave a list of potential influencing factors without relating them to concrete strategy types. Although some influencing factors described before are repeated this section they need to be mentioned again in order to give a clearer view which strategy type is especially suited for certain scenarios.

8.1.1 CENTRALISED VS. DISTRIBUTED STRATEGIES

8.1.1.1 CENTRALISED STRATEGIES

Centralised sensor network strategies are especially interesting for those cases where global information is available that can be used for optimising the sensor network. For this case two examples shall be given:

- An UAV is monitoring a wide area and delivers overview data. This overview data might be coarse and not completely accurate but it allows to identify those areas where phenomena occur that should be monitored more detailed (e.g. infrared data might be used for identifying hot spots that indicate a high risk of forest fires). Subsequently ground based sensors could be deployed at those locations which have been identified as hot spots so that a more detailed and accurate analysis can be performed. This deployment could be relatively easily realised by a centralised control mechanism.
- Another example is the use of sensor networks to deliver input for statistical models. For example a sensor network could be used for monitoring the air pollutant concentration throughout an investigation area. By performing statistical analysis it is possible to identify locations where sensors should be placed so that they can deliver additional information that reduces the uncertainty within the model (see WP 3220 for more details). As the statistical model needs a global knowledge it can only be applied in a centralised approach.

Furthermore often a global approach is likely to produce a more efficient sensor constellation than distributed solutions. This is especially important if only a low sensor density is available. For example the global knowledge of all sensor positions allows a geometrical approach to identify the biggest gaps in the sensor network which can subsequently be closed. Another possibility is that simulation models might be used to compute, based on the sensor measurement results, those areas where the highest phenomenon intensity occurs. If these areas shall be monitored more closely than others, the global models can be used to send sensors to those place with the highest phenomenon intensity (e.g. when monitoring certain air pollutants it is often desired to get more information about those areas with critical values than about locations where no pollution occurs).

Additionally a central control is needed in those cases in which sensors with only low or no significant computational capabilities are used. In this case the sensors would not be able to calculate complex cooperative behaviour patterns.

A drawback of centralised strategies is that the central computation of orders that are sent to the sensors can take more time which results in delays (because of the data transmission which could be performed via slow multi-hop networks). Thus adaptations to changing requirements might be less quick than a direct autonomous reaction by the individual sensors.

Furthermore a centralised strategy is mostly only feasible if the number of sensors is limited. The central control of a very big sensor network can become difficult because of two reasons:

- if the centrally performed computations need to deal with too many sensors they may take too much time
- the information transport between the sensors and the central control unit becomes an issue in very large networks with potentially low bandwidth communication systems

8.1.1.2 DISTRIBUTED STRATEGIES

Distributed sensor network strategies are especially needed in those scenarios where a central control is impossible because of scalability issues. In this case sensors can determine the behaviour by themselves or could execute cooperation mechanisms with other sensors. This avoids especially that large amounts of data must be sent to a central control instance. Thus this type of strategy usually provides a better scalability.

Furthermore a distributed sensor network strategy is often able to provide a quicker adaptability. As the sensor behaviour is determined locally it is not necessary to wait until an updated order from the central control station is received. Because of this distributed strategies are likely to deliver a better performance than centrally controlled sensors if highly changing phenomena need to be monitored.

However in order to apply distributed approaches for sensor network strategies it is necessary that the sensors are at least capable of performing a minimum amount of computations.

Also a distributed approach may lack the integration of a global knowledge about the current situation. This can lead to a sensor constellation which is suboptimal. But even if a sensor constellation is not optimal in many cases, it can be sufficient for the intended purpose. Furthermore if a high sensor density is available the importance of reaching the most efficient sensor distribution is reduced.

8.1.2 APPLICATION OF DYNAMICS WITHIN SENSOR NETWORK STRATEGIES

8.1.2.1 STATIC SENSORS

Basically strategies for stationary sensors must be applied in all those cases where mobility is not feasible. This might be because of financial reasons (if very large sensor networks are deployed the costs for mobile platforms would be too high), technical reasons (e.g. deployment of sensors in a terrain which makes movement impossible) or practical reasons (e.g. mobile sensors cannot move within the traffic on the streets). Also a low energy supply can make it impossible to apply mobility.

Another application for static sensor network strategies is the monitoring of low dynamic phenomena while a basic coverage by the static network is ensured. In this case the distribution of the phenomenon intensity is unlikely to change so that adaptations of the sensor constellation are not necessary.

Also if the sensors are initially optimally distributed it is not necessary to perform coverage adaptations. If sensors can be deployed deterministically so that an optimal predetermined coverage is reached no adaptations of the coverage would be necessary. For example official weather stations are distributed across a country so that the measurements are representative. In this case constellation changes are not needed. In fact they might even not be desirable if the development of a phenomenon at a fixed location during the course of time is to be measured.

Finally sensor networks with a high density can make mobile strategies unnecessary. Often a high sensor density provides a sufficient coverage so that sensor movement for closing gaps is not needed.

With regard to communication strategies it shall be noted that this case is relatively easy to handle as there is no need to deal with a changing network topology. The biggest challenge in this case are multi-hop routing protocols which are necessary in all cases where the communication range of sensors is lower than the maximum distance between potential communication partners.

8.1.2.2 ENABLING CONSTALLATION CHANGES IN STATIONARY SENSOR NETWORKS

The next case deals with static sensor networks with the difference that the sensor constellation can be modified by adding or removing sensors.

Basically this approach can be used if coverage adaptations are needed but the deployment of mobile sensors is impossible. This could be the case if sensors are very expensive so that they cannot be deployed in such a number that a sufficient coverage is automatically reached. Thus this approach is especially suited for low density stationary sensor networks.

Coverage adaptations as described before are especially needed in case of dynamic phenomena. If a toxic gas clouds is dislocated by the wind the according sensors for detecting the pollutant concentration must be moved if the gas cloud should be traced. But in an urban environment for example it is not possible to use sensors which move automatically (e.g. because of traffic security or legal reasons). Thus these sensors need to be relocated manually by removing them at their old spot and deploying them somewhere else.

Another scenario in which the deployment of additional sensors is needed is the replacement of defective sensors in order to maintain the coverage or connectivity within the network.

For applying a sensor network strategy that is based on the mechanisms described above it is necessary that the deployment of additional sensors is possible. Thus the area where the sensors have to be deployed must be accessible (at least for a controlled deterministic deployment). If this is not the case an alternative would be the mass deployment of sensors by dropping them for example from an airplane. However this approach requires more sensors as the deployment is usually not very precise.

Like in the previous case communication strategies in this context are relatively simple as the topology changes are only limited to the addition and removal of nodes. This aspect is already integrated in many common routing protocols so that it shall not be further analysed in this report.

8.1.2.3MOBILE SENSORS

The third variant in this subchapter is the application of strategies that rely on sensor mobility. However this requires first the availability of mobile sensor platforms for the given use case and second often limitations to the sensor mobility (e.g. obstacles, no-go-areas) must be included in the according algorithms. Furthermore the sensors must be relatively highly developed as sensor mobility requires more complex computations.

A very important use case is the application of mobility strategies in sensor networks that have a very low sensor density so that the sensors must be used very efficiently. For example a mobile sensor is able to cover a bigger area than a static sensor. In case of stationary phenomena it is possible to detect a higher percentage of phenomenon instances if a mobile sensor network is used. This aspect is also related to the requirement of a high adaptability. If the sensor density is relatively low it might, in case of a mobile phenomenon, be necessary to move sensors to those areas with the highest phenomenon intensity. If no additional sensors can be applied (inaccessibility of the investigation area, high costs of additional sensors) the sensors must move automatically to the according areas.

Finally special coverage types shall be mentioned which can only be realised by using mobile sensor strategies:

- Sweep lines: In this strategy sensors form a barrier that moves across the investigation area. This allows detecting (stationary) phenomenon instances with a high detection rate.
- Pursuit of phenomena: Sensors can pursuit phenomenon instances in order to provide a long lasting detection. This allows subsequently analysing the development of a phenomenon instance during the course of time.
- Interception of phenomena: If sensors are too slow to follow a phenomenon instance it is necessary to send other sensors on an interception course. This allows also a longer lasting phenomenon detection even if sensors might be slower than the phenomenon.
- Aligning of sensors around phenomenon instances which are dynamically changing: This allows to determine more precisely the shape and size of phenomenon instances. An application could be to determine the border of a toxic cloud so that for example evacuations can be performed more precisely.

With regard to the network connectivity also self healing mechanisms can rely on sensor mobility. Especially in case of a high probability of sensor failures it can become necessary to use sensors which automatically relocate in order to close disrupted communication links.

Another connectivity related aspect is the special challenge that may arise from the continuously changing network topology that is induced by the sensor movement. Especially in case of short communication ranges compared to the size of the investigation area relatively complex routing mechanisms are needed that are able to cope with the changing topology.

8.1.3 INPUTS TO SENSOR NETWORK STRATEGIES

8.1.3.1 PHENOMENON RELATED INPUTS

A sensor network strategy that belongs to this category is primarily characterised by the integration of any kind of information about the phenomenon. In this sections several approaches shall be presented in which a strategy that relies on phenomenon specific inputs can be used.

If the border of a phenomenon instance has to be determined by a sensor network so that a placement of the sensors along the border is wanted the integration of phenomenon data is necessary. Only be relying on the measured values it is possible to determine if a sensor has reached the border or if not. Furthermore by comparing neighbouring measurement values it is possible to determine the gradient of the phenomenon so that sensor can move into the direction of higher phenomenon intensities.

Also the tracking (pursuit) of moving phenomenon instances relies on the measured phenomenon data. As previously mentioned the determination of the gradient can also be used for indirectly following phenomenon instances.

If a sensor network is used for delivering inputs to statistical models the sensor constellation needs mainly to be adapted in a way that there are as few areas with a lack of information as possible. To determine the best sensor positions the lack of information can statistically be computed by analysing the phenomenon data that are measured.

Furthermore it may also be desirable to have a higher sensor density in those places with a higher phenomenon intensity (for example when monitoring the dispersion of toxic air pollutants it is mainly interesting to observe the areas with critical values). The adaptation of the sensor density can be performed by analysing the measured data so that the critical regions are identified. Subsequently additional sensors can be relocated in these areas so that the measurement quality is improved.

8.1.3.2 GEOMETRIC INPUTS

Besides using information about the phenomenon it is also possible to base the sensor network optimisation on geometrical criteria.

One possibility is a regular coverage (e.g. grid) that can be predefined. A deterministic strategy could be used for implementing such a coverage. An application for this coverage type might be the delivery of input for simulation models.

Another aim that can be realised by a geometrical approach is an even sensor distribution. This can be reached by a distributed (or centralised) sensor strategy that computes repulsive forces between sensors. Subsequently the sensors would be pushed apart so that the coverage becomes more evenly. The number of applications for this kind of strategy is relatively big as the even sensor distribution allows in many scenarios a relatively good detection of phenomena.

However all approaches that rely only on geometrical considerations are not able to adapt the sensor constellation to the distribution of the phenomenon intensity. Thus they should only be used if the sensor constellation needs to be independent from the phenomenon or if at least no adaptation is required (e.g. if a sufficiently high sensor density is available so that adaptation would bring no improvements).

Finally it has to be mentioned that there are many approaches of hybrid strategies which rely on phenomenon related and geometrical influences. These strategies combine the advantages so that the sensor constellation is for example adapted to the phenomenon while the geometrical component avoids an extensive clustering of sensors.

A further use of geometric information is in the area of communication strategies. The information about the positions of senders and receivers allows the use of routing protocols that decide about message forwarding based on the geometric relations between the different nodes.

8.1.3.3 NETWORK RELATED INPUTS

Network related inputs are mostly relevant for strategies that are needed for ensuring a sufficient connectivity within the sensor network. Subsequently two important applications shall be mentioned:

Network oriented sensor strategies can be used for repairing disrupted communication links within the sensor network. This type of strategy can especially be used for optimising the sensor constellation in low density networks in which sensors only posses a relatively short communication range. Subsequently the sensor constellation can be optimised so that the communication via multi-hop links is ensured.

In case of high sensor densities a communication strategy must be adapted to avoid scalability problems. One solution that can be applied in this case are communication strategies which allow an intelligent data aggregation so that the amount of data transmitted is reduced. An enhancement to this could also be to scale the degree of data aggregation based on the amount of network traffic that is occurring.

8.2 APPLICATION TO THE OSIRIS SCENARIOS

As a more detailed analysis of the different OSIRIS sensor systems is performed within D3100. This guidebook will only contain a few interesting aspects that illustrate how the different decision criteria can be applied to the OSIRIS scenarios.

8.2.1 CENTRALISED VS. DISTRIBUTED STRATEGIES

Within the OSIRIS scenarios mostly centrally controlled strategies are applied. This is mainly because the number of sensors that are deployed is relatively small and often the sensors are connected via a direct communication link to the central station. Important examples for this are the sensors in the water pollution scenario and the bus mounted air pollution sensors which are connected via a direct GPRS/GSM-link. In these cases no complex communication strategies are needed.

More complicated communication strategies are needed in the following cases

- Industrial risk scenario: The communication system must be able to deal with the potential failure of nodes (e.g. because of fire) as this can change the network topology.
- Positioning sensors in the forest fire scenario: In this case a multi-hop communication strategy which is able to cope with the addition and removal of nodes is needed. Basic reasons for this are the limited communication range and the need that arises from the use case to adapt the network connectivity to the constantly relocating positions of the firemen. Furthermore this scenario requires a coverage strategy that allows determining those locations where new sensors need to be deployed in order to ensure connectivity.
- Wireless cameras in the forest fire scenario: The data delivered by the cameras requires a fairly high bandwidth. Furthermore the communication range of the nodes in connection with the potentially high distances that need to be bridged makes the use of multi-hop transmission (relay) necessary. The complexity of this problem is addressed also in WP 5000.

With regard to the coverage strategy it can be stated that nearly all scenarios require deterministic and thus centrally controlled sensor deployment. For example the water pollution sensors or the fire sensors in the industrial risk scenario are deployed at locations that are predetermined. This is mainly because the sensor locations are determined by specialist expertise so that the use of automatic coverage strategies provides no significant advantages or is even less optimal.

8.2.2 APPLICATION OF DYNAMICS WITHIN SENSOR NETWORK STRATEGIES

Within the OSIRIS scenarios the use of sensor dynamics is limited. However in some areas interesting applications can be found.

The positioning system is an example for a static sensor network that is adapted to changing connectivity requirements by the addition and removal of nodes. Because of the terrain, practical limitations and also because of the cost the use of mobile nodes is not feasible. Furthermore the number of sensors is limited due to the costs per unit so that the directed deployment of sensors is the best solution.

A more complex integration of dynamic behaviour are the UAVs used in the forest fire and the air pollution scenarios. Both UAVs can execute movement strategies which take into account the changing localisation of the phenomenon that has to be observed.

8.2.3 INPUTS TO SENSOR NETWORK STRATEGIES

In this section one example for each type of input that is used within the OSIRIS scenarios is given.

Phenomenon specific input that is applied in a sensor strategy is used for calculating the trajectory of the UAV in the air pollution scenario. In this example the information about the pollutant cloud is used for computing those areas which require monitoring. Another example for the use of phenomenon specific input is the deployment of water quality sensors in the water pollution scenario according to the assumed phenomenon distribution.

Geometric input to a strategy can be observed in the industrial risk and forest fire scenarios as the cameras for the surveillance are placed by geometric criteria. The application of solutions to the art gallery problem (see D3100) as a deployment strategy is purely based on the geometry of the room that has to be observed and the camera locations. Also the trajectories of the bus mounted sensors in the air quality scenario can be given as an example for phenomenon independent strategies that rely only on geometrical assumptions (i.e. the geometry of the bus routes).

An example for a strategy that is based on network related inputs is the deployment of additional positioning sensors in the forest fire scenario. In this case new sensors need to be deployed in order to ensure the connectivity within the network. Thus the connectivity is the decisive input for deciding where new sensors need to be deployed.

9. SUMMARY AND CONCLUSIONS

9.1 KEY ISSUES ADDRESSED

This guidebook addressed several aspects that are important for the selection and design of sensor network strategies.

In order to give an overview of relevant sensor network organisation models an overview of different strategy types was given:

- Coverage and communication strategies
- Centralised vs. distributed approaches
- Dynamic vs. static approaches
- Approaches that are characterised by different input types to sensor strategies
- UAV-related strategies

Subsequently an extensive overview of potential influence factors for the selection of coverage and connectivity strategies was given. This overview in connection with the strategy classification was used to describe exemplary several guidelines that can be applied during the design/selection process of sensor network strategies.

As a final illustration a very short discussion of the different guidelines with regard to the OSIRIS scenarios was given.

9.2 LESSONS IDENTIFIED

The most important lesson that became evident during the production of this report is the big manifold of different factors that can influence the design/selection of sensor network strategy. It became quickly evident that it is not useful to define inflexible rules that claim to be universally valid.

As a conclusion it has to be stated that the design/selection of a sensor network strategy needs to be performed in an individually adapted way that takes the very specific needs of the scenario into account. The factors presented within this guidebook deliver guidelines that allow to decide which factors have to be analysed during this process.

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