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Peer-to-Peer Algorithms in Wireless Ad-Hoc Networks for Disaster Management

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Zusammenfassung

Ein Wireless-ad-hoc-Netzwerk (WAHN) ist ein Kommunikationssystem, das nicht von vorinstallierter Infrastruktur abhängt und kann vollständig dezentral aufgebaut werden. Mit Sensoren ausgestattet sind WAHNs zur Unterstützung des Katastrophenmanagements sehr gut geeignet.

Der Ort der Katastrophe ist in vielen Szenarien nicht vorhersagbar. Eine Katastrophe beeinflusst jedoch den Datenfluss innerhalb des Netzwerkes und kann auch Gruppen von benachbarten Knoten schädigen.

In dieser Arbeit werden P2P-Algorithmen in ressourcen-limitierten und irregulären WAHNs betrachtet, die effizient, skalierbar und fehlertolerant in Situationen arbeiten sollen, in denen eine räumlich benachbarte Gruppe von Netzwerkknoten simultan ausfällt. Es wird ein fehlertolerantes Replikationsschema zur datenzentrischen Speicherung betrachtet, und eine selbstorganisierende, skalierbare Berechnung von Datenaggregaten zur Lösung des Konsensproblems.

Existierende P2P-Algorithmen die Skalierbarkeit, Fehlertoleranz und Selbstorganisation in drahtgebundenen Netzen betrachten sind für die Klasse der WAHNs nicht geeignet weil sie Engpässe in WAHNs verursachen können. Außerdem berücksichtigt Replikation mittels dieser P2P-Algorithmen Netzen nicht die geographischen Positionen der Knoten, wodurch in Katastrophenmanagement-szenarien die Zuverlässigkeit der Daten nicht sichergestellt werden kann.

Die Verwendung von Informationen der geographischen Position von Knoten ist ein möglicher Weg, um die Effizienz und Skalierbarkeit von P2P-Anwendungen in drahtlosen Netzwerken zu verbessern. Die lokal verfügbaren Positionsinformationen von Knoten werden in existierenden Lösungen für ortsabhängige WAHNs benutzt, um Kommunikations-Overhead zu reduzieren. Jedoch wird Informationen über das geografische Gebiet des Netzwerks für Aufgaben der Allokation von Daten und Replikaten in den Zielszenarien erforderlich.

In dieser Arbeit wird ein neuer Ansatz vorgestellt, wie auf effiziente Weise 1) *Gebiet des Netzwerks*, das die geographische Ausbreitung seiner Knoten umfasst, und 2) *Gruppenzugehörigkeit*, wobei jeder Knoten zu genau einer Gruppe innerhalb eines einstellbaren Gebietes gehört, erzeugt werden kann. Dadurch können: 1) existierenden, skalierbare P2P Datenspeicheralgorithmen für WAHNs genutzt werden, 2) effiziente, fehlertolerante Replikation erstellt werden, 3) die Effizienz von geographischen Routing und der Suche nach Replikaten verbessert werden sowie, 4) Anwendungen auf einen bestimmten geographischen Bereich innerhalb des WAHN beschränkt werden (z.B. im Aggregationsprotokoll).

Die entwickelten Protokolle sind tolerant gegenüber Nachrichtenverlust und verwenden ausschließlich lokale Broadcast-Nachrichten. Das Protokoll wurde mit Simulationen untersucht, die auf realistischen Netzwerktopologien mit Anteilen an sehr spärlichen und sehr dichten Knotenansammlungen basieren. Die Protokolle können im Katastrophenmanagement und Umweltanwendungen verwendet werden, die Daten unter Verwendung drahtloser Ad-hoc-Netzwerke sammeln, speichern und verarbeiten.

Abstract

A wireless ad-hoc network (WAHN) is a communication system that does not rely on any preexisting infrastructure. WAHNs may be equipped with sensors and deployed in decentralized manner, without human assistance on site. As such, WAHNs are a good communication choice for a Disaster Management (DM) support.

Addressed DM tasks are characterized by an unknown a priori location of a disaster. Disaster however determines the network traffic, roles of individual network nodes and finally may damage a group of nearby placed nodes.

This dissertation addresses the challenge of reaching efficiency, scalability and fault-tolerance by P2P algorithms for resource-limited and irregular WAHNs where a spatially correlated group of nodes may crash simultaneously. In particular, we consider a fault-tolerant replication scheme for data-centric storage for supplying data survivability and a self-organized, efficient calculation of localized data aggregates for solving the consensus problem.

There exists a variety of algorithms that address issues of scalability, fault tolerance and self-organization in wired networks. However, they are inadequate for the addressed systems, as physical communication in WAHNs causes' bottleneck in Peer-to-Peer algorithms designed for the wired systems. Moreover, replication in wired P2P algorithms that abstract from geographical location of replicas cannot supply data survivability in DM scenarios in WAHNs.

Incorporating information on geographical location of nodes is a recognized way to increase the efficiency and scalability of P2P applications in wireless networks. Locally available positions of nodes are used in existing solutions for location-aware WAHNs to reduce the communication overhead. However, information on the geographical area covered by the network is required for tasks of data and replica allocation in the target disaster scenarios.

This dissertation proposes to efficiently construct new position information in a location-aware WAHN, where each node knows its own location and location of its direct neighbors. The new information are: 1) *network area,* which expresses the geographical area covered by the network, and 2) *group membership*, where each node belongs to exactly one group that is placed over the area of a maximum defined size. This new position information enable the use of the existing, scalable P2P data store in WAHNs (Geographical Hash Table), allow design of efficient fault-tolerant replication for the assumed fault model, increase efficiency of georouting and replica search, and allow to limit the geographical extent of activity of any distributed application, as we show using an example of data aggregation protocol.

Proposed protocols tolerate message loss and use local broadcast only. They are evaluated by simulation over irregular topologies following the node placement of the existing, large wireless ad-hoc networks, which contain both very sparse and very dense network parts. The protocols can be used in disaster management and environmental applications that collect, store and process data with use of wireless ad-hoc networks.

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Chapter

1. Introduction

Rising frequency and damages caused by **natural disasters** drove the General Assembly of the United Nations to proclaim 1990s as the International Decade for Natural Disaster Reduction (IDNDR). The IDNDR program concluded, that the natural disasters are a major threat to social and economic stability and that disaster prevention is the main long-term solution to this threat [IDN99]. The United Nations International Strategy for Disaster Reduction[1] group (ISDR) collecting the work of hundredths of independent scientists and practitioners builds upon the experience of IDNDR and other guides to shift disaster management efforts *"from a culture of reaction to a culture of prevention".* [UN99]. Prevention and reduction of disasters are **Disaster Management** (DM) goals. While occurrence of natural hazards is unavoidable[2], DM aims to prevent and reduce the disasters by finding and taking actions that lower the impact of natural hazards on humans, like appropriate urban planning, introducing rules for building construction, developing and deploying early warning systems, creating and facilitating effective, planned relief and recovery actions, and preventing outbreaks of secondary disasters, capable of causing bigger damages than the originating event. The overall goal is to reduce the number of affected people and suffered economic damage, also in a long term.

Recent advances in the area of **wireless communication** including standardization of protocols and law regulating open radio frequencies compounded with progressing battery and memory chips miniaturization resulted in constantly growing scientific and industrial interest in wireless technology. Today, not only that almost every electronic device has a build-in wireless communication module, but also commercial wireless nodes, inexpensive and easy to program and deploy, are widely accessible. Wireless networks equipped according to the needs with dedicated applications, actuators and/or sensors are being used in the internet sharing communities, health care, production lines, military applications and environmental sensing. It is also the wireless technology that augmented visions of "smart cities" and the "internet of things". Wireless networks offer themselves as flexible and capable **support to the disaster management systems**, too.

A particularly interesting platform for the disaster management applications are **Wireless Ad-Hoc Networks** (WAHNs). WAHNs are fully distributed, self-organized and robust to the failures of individual links and nodes. WAHNs can be deployed without any preexisting infrastructure and detailed planning and out of inexpensive and homogenous nodes, through a decentralized process, which allows for easy deployment of networks that serve geographical areas of a significant size. In addition to communicating abilities WAHNs can be equipped with sensors and are capable of

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[1] http://www.unisdr.org/

[2] For discussion on global warming see section 1.1.1.2.

measuring, storing and processing environmental readings needed in DM applications, for disaster modelling or alarm systems. WAHNs can be designed to function and be deployed in a harsh environment where they collect usually inaccessible environmental data. They can be deployed rapidly on disaster sites and used for emergency communication systems.

Realization of chosen disaster management tasks with use of wireless ad-hoc networks motivates this thesis. Envisioned DM applications in WAHNs should be **efficient** and **scale with system size**, i.e., as the number of nodes in the system increases, the system's total storage capacity should increase, and the communication cost of the system should not grow excessively, nor should any node become a concentration point of communication. In disaster management scenarios even a whole group of nodes might be destroyed simultaneously. DM applications should **tolerate** node crushes due to a disaster and be able to adjust to changing network topology and load, and to function in spite of unreliable communication. DM applications must also function without any a priori knowledge of traffic patterns, as this will depend on the disaster (e.g., time, amount and location of data sources and sinks). In other words for the realization of DM goals efficient, scalable and self-organized, Peer-to-Peer (P2P) applications for WAHNs are needed.

Design of scalable, fault-tolerant and self-organized P2P applications is a challenge in a fundamentally resource-limited wireless environment, and it is even more challenging in wireless ad-hoc networks deployed with a decentralized process, which results in networks with irregular topology. This thesis proposes to exploit in P2P algorithms in WAHNs **aggregated location information**. We propose to use the information on the **network area** which expresses network size and geographical location ('*where is the network?*') and we introduce the motion of the **extent of an application's activity**, which describes the geographical placement of nodes communicating within one instance of a given distributed algorithm ('*where the application works*?'). By supplying information on **network area** (network size and location) it is possible to load balance data in the network with the geographical hashing. Also, the costs of geographical routing are reduced. The same information enables structured replication (SR) in WAHNs, which supports data survivability in a disaster scenario. Limiting the **extent of an application's activity** reduces the number of nodes executing distributed algorithm and can lead to increased scalability of the applications. We propose a mechanism for group membership that executes network division. This mechanism allows to execute in WAHN any P2P application in a scalable way. We show how the **extent of an application's activity** can be used by an existing distributed algorithm and then in DM applications.

Our solutions are designed for static, location-aware WAHNs and have been tested over highly irregular, sparse topologies meeting the characteristics of real-life, wireless ad-hoc networks [Mil06]. Proposed protocols can be used for increasing scalability of P2P applications in WAHNs.

1.1. Natural Disasters

Natural disasters are caused by natural hazards, i.e., natural processes, like extreme weather and climate events which we cannot control. Natural hazards can be most generally classified into geophysical, climate-related and biological:

- **Geophysical hazards** are events originating from solid earth, classified as earthquakes (ground shaking and tsunami[3]), volcanic eruptions, and dry mass movements (rock fall, avalanche, landslides[4], and subsidence[5]).
- **Climate-related hazards** include climatological events like extreme temperatures, droughts and wildfires, hydrological events as avalanches and floods, and meteorological events like cyclones and storms surges.
- **Biological hazards** are disease epidemics and insect or animal infestations[6] and are out of the focus of the presented research.

A natural hazard may have a devastating impact on humans. It becomes a disaster when in its course people's lives and livelihoods are destroyed**.** According to the definition of the UN International Strategy for Disaster Reduction a disaster is a "*sudden, devastating event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources*"[7].

1.1.1. Impact

Natural disasters kill and injure people, destroy property and infrastructure, lead to devastation and intoxication of the environment, and have severe economic, social and political impact [UN99][Lin03][Kou12][Lea13]. A disaster's impact reaches further and lasts longer than the event itself and, can influence regions quite remote to it, if economically connected with the affected area.

To express the impact, strength scales are being used for some natural disasters, like the Moment Magnitude Scale (MMS) for expressing the size of earthquakes or the International Nuclear Event Scale (INES) for describing events with sources of ionizing radiation. These scales however only express the disaster's power and not the actual damages caused. Actual impact of a disaster depends on the location of the hazard, the time it strikes, level of preparation for a disaster of a given kind and on the quality of the immediate response actions taken. The most important metric scale expressing the severity of a disaster is the **death toll**. This can be extremely high (Table 1), as due to the floods of 1931 in China that killed at least 3,7 million people

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[3] Tsunami is a seismic sea-wave and can be caused by an earthquake, volcanic eruptions, submarine landslide or an underwater explosion.

4 Landslide is a ground movements, such as rock falls, deep failure of slopes and shallow debris flows.

5 Subsidence (land subsidence) is a gradual settling or sudden sinking of the Earth's surface.

6 Pervasive invasion of insects or parasites affecting humans, animals, crops and materials.

7 Definition of United Nations ISDR, www.unisdr.org/we/inform/terminology.

or during the Black Death[8] that killed an estimated 40 to 60 percent of Europe's population[9] [Dis14]. Besides immediate deaths, disasters affect millions through **injury**, **disease** and **devastation**, which are much more difficult to estimate. Such as the memorable Haiti Earthquake in 2010 that killed 200 000 people and additionally left two million homeless, and further three million people in need of emergency aid. According to the International Disaster Database in Brussels, since the year 1900, earthquakes alone (ground shaking and tsunamis) killed over 2.5 million and affected over 181 million people world-wide.

The way the natural disasters devastate humans is connected with **property damage** and **economic devastation**. An example are the 2005 Gulf Coast Hurricanes, including famous hurricane Katrina, that are memorized as one of the worst disaster ever. Although these hurricanes killed "only" about 4,000 people, they caused economic loss of about $182 billion and influenced not only the life of citizens of New Orleans but also those of Louisiana and Mississippi. To incorporate property damage and economic devastation in disaster assessment the **economic damage** is estimated. It is important to realize, that economic damage experienced by communities goes beyond the immediate physical destruction cause by a disaster (**direct damage**) and incorporates long-term economic losses caused by indirect disaster impacts (**indirect damage**). **Direct damage** are harms to structures (houses, buildings), contents (inventory, productive capital, crops, and livestock), and infrastructure (farm equipment, telecommunication and power supply infrastructure, roads and bridges etc.) that occur as a direct result of the hazard. Direct damage include mortality and injury caused directly by the hazard and are complemented with costs of emergency response, such as evacuation and rescue and the clean-up costs, e.g., clearing debris from streets. **Indirect damage** are the consequences of the described direct damage. They refer to lost economic activity, such as loss of potential production, increased costs of production, loss in expected income and other welfare losses, which occur as a result of the initial damage. Companies may not be able to operate because their supplier fails, their workers are evacuated, or they lost power. A good example is the case of Toyota that reported a loss of $1.2 billion in product revenue from the Japanese earthquake in 2011 due to parts shortages that resulted in 150 thousand fewer cars manufactured in the United States, a reduction in production of 70 percent in India and of 50 percent in China [BI13]. Indirect damages include the multiplier effects from reductions in demand or supply (e.g., revenue loss of the other companies that supplied Toyota with materials and parts in the example above). In addition to business interruption, loss of infrastructure or other life-lines (e.g., power, sewage, or water) can cause households and businesses to adopt costly compensating measures, such as increased commuting time as a result of damaged roads or the extra costs of running a private generator when the electricity is out.

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[8] Also known as "the Great Mortality" or "the Pestilence", an epidemic that swept through Europe from 1348 to 1351.

[9] 130,000 to 200,000 people.

Other long term disaster impacts include epidemics and intoxication that cause further economic damages by mortality and morbidity.

Direct and indirect damage include also immeasurable **nonmarket impacts**, such as degeneration in the quality of life, loss of recreational amenities, destroyed cultural heritage like antic relics, and finally environmental degradation. An example of the latter is the radioactive pollution from the Fukushima nuclear disaster in 2011 that measured Level 7 on INES and was triggered by an earthquake and tsunami. The nuclear plant released substantial amounts of radioactive material, becoming the largest nuclear incident since the Chernobyl disaster. The cleanup process and environmental regeneration is expected to take decades [Lip13].

Economic damage of a natural disaster can be counted in billions of U.S. dollars (Table 2). However, presented statistics must be seen as estimates only because complete and systematic data on disaster impacts are lacking. According to a recent United Nation report [UN13], direct economic losses from natural disasters in years 2000-2012 are strongly underestimated, and they are in the range of \$2.5 trillion, a figure at least 50 percent higher than previous international estimates. There is no comparable information on estimation accuracy of indirect economic losses, but one can expect that they are even more difficult to assess and might be underestimated even more so. Often, they are not evaluated at all.

Table 1: The deadliest natural disasters since 1900, [Wik1].

Rank and Name	**Estimated Death Toll**	**Disaster type**	**Location**	**Year**
1. China Floods	3,7 – 4 mln	Floods	China	1931
2. Tangshan Earthquake	650,000	Earthquake	China	1976
3. Bhola Cyclone	500,000	Cyclone	East Pakistan[10]	1970
4. Indian Ocean Tsunami[11]	280,000	Earthquake and Tsunami	Indian Ocean	2004
5. Haiyuan Earthquake	273,400	Earthquake	China	1920
6. Typhoon Nina	229,000	Tropical Cyclone	China	1975
7. Haiti Earthquake	200,000	Earthquake	Haiti	2010
8. Yangtze River Flood	145,000	Flood	China	1935
9. Kanto Earthquake	142,000	Earthquake	Japan	1923

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[10] Now Bangladesh.

[11] Known also as Sumatra-Andaman Earthquake.

Table 2: The most expensive natural disasters since 1980 [WVM13].

Rank and Name	Estimated Economic Damage	Event	Location	Year
1. Honshu Tsunami and Tohoku Earthquake	$235 Billion	Earthquake	Japan	2011
2. Golf Hurricanes 2005: Katrina, Rita, Wilma	$182 Billion	Hurricane	United States	2005
3. Kobe Earthquake	$102 Billion	Earthquake	Japan	1995
4. Wenchuan Earthquake	$90 Billion	Earthquake	China	2008
5. North American Drought	$78 Billion	Drought	United States	1988
6. Heat Wave and Drought	$55 Billion	Heat and Drought	United States	1980
7. Hurricane Sandy	$50 Billion	Hurricane	United States	2012
8. Northridge Earthquake	$46 Billion	Earthquake	United States	1994
9. Niigata-ken Earthquake	$34 Billion	Earthquake	Japan	2004
10. Maule Earthquake	$31 Billion	Earthquake	Chile	2010
11. Izmit Earthquake	$29 Billion	Earthquake	Turkey	1999

1.1.1.1. The Effect of Rising Population

Earth’s population raises exponentially, and it has tripled since 1950[12]. This growth intensifies total costs of natural disasters. First factor is that a bigger population produces and owns **more wealth** (Fig. 1), so more goods and services are potentially destroyed in a disaster.

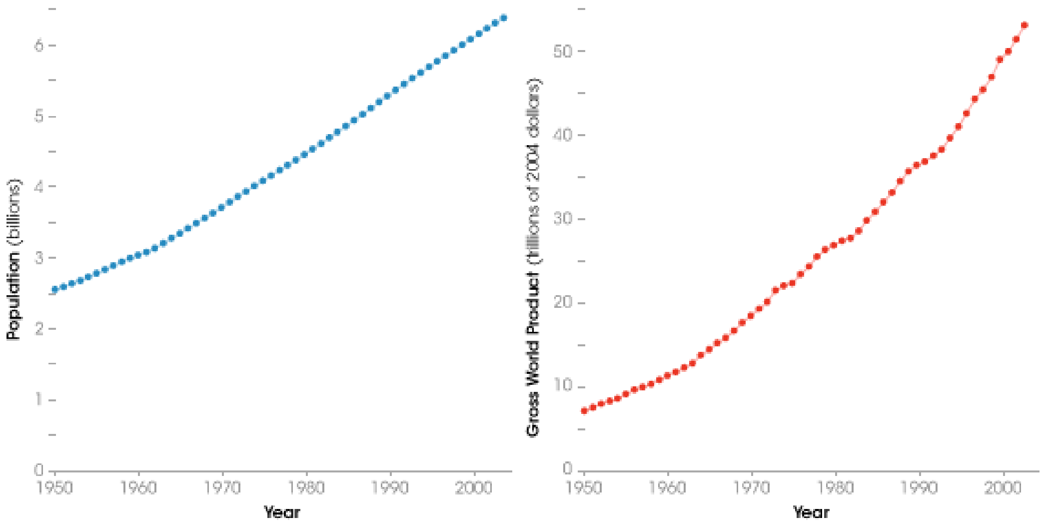

Fig. 1: Comparison of the increase of the Earth’s population and the increase of the global wealth, based on data provided by the U.S. Census Bureau (left) and the Worldwatch Institute (right), from [Rie05].

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[12] From 2.5 in 1950 to 7.5 million today [PRB14].

Second factor is **intense urbanization** of the areas prone to disasters. When such areas are urbanized, natural hazards that before had no impact on people cause casualties and/or economic damage. Specifically, we observe intensive urbanization of the attractive coastal areas, susceptible to strong winds and floods, where natural hazards can have a substantial damaging impact[13]. Another example is intensive land use that can escalate the impact of drought when water users like farmers, industry, and urban populations all draw from the same limited water supplies. Because of this, drought can impact everything from the availability and cost of food to the cost of electricity over a wide region.

Growing population invariably causes bigger environment degradation, which may increase the probability and harshness of natural disasters. An example is deforestation; deforested land can no longer anchor soil, and dirt washes into rivers, filling the river bottoms with silt and mud. A shallower river is able to hold less water, increasing the hazard of flood. However, the most dangerous ongoing environmental degradation that is generally accepted to have the greatest influence on the number of natural disasters [IPC14] is global warming.

1.1.1.2. The Effect of Global Warming

Global warming is unfortunately an inevitable and far-reaching environmental issue that influences the international community, including the intensity and number of natural disasters [IPC03][Rie05]. Warming of the climate is undeniable, and many of the observed climate changes are unprecedented. The atmosphere and oceans have warmed, the amounts of snow and ice have diminished and the sea level has risen [Hov13][IPC14]. This rapid recent rise in the average temperature of Earth's climate system is called *global warming*.

Life on Earth is possible because of the greenhouse effect, a natural warming process, in which the Earth’s atmosphere retains outgoing radiation, causing the overall temperature of the Earth to be warmer than it would otherwise be: without the natural greenhouse effect the present global mean temperature of +15 ° C would be –18°C [Hov13]. The greenhouse gases that make this effect possible are: water vapor, carbon dioxide (CO_2), methane, nitrous oxide, chlorofluorocarbons and ozone.

However, presence of too high amounts of greenhouse gases in the Earth’s atmosphere means that too much energy is retained, which in turn raises Earth’s surface temperature [Hov13]. Scientific observations of thousands of independent scientists[14] confirmed that it is humans’ industrial and technological activities that

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[13] For instance, according to Munich-Re, an insurance company, storms and floods accounted for two-thirds of the world’s insured losses in 2003 [MR03].

[14] In 1988, the Intergovernmental Panel on Climate Change (IPCC) was formed by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). It brought together a broad range of government and non-government experts to assemble and assess the most recent available scientific knowledge and to determine what is known and not known about the climate system and climate change. More than two thousand scientists contributed to the 1995 Second Assessment Report, which concluded that, “*The balance of evidence suggests a discernible human influence on global climate*” [IPC95].

brought imbalance to the Earth's greenhouse gases household by freeing excessive amounts of *carbon dioxide* [IPC95]. It has been ascertained, that prior to industrialization a steady balance of about 280 *ppmv*[15] was maintained in the concentration of carbon dioxide in the atmosphere. However, since the industrial revolution, more fossil fuels have been used to produce energy to support economic growth and concentrations of CO_2 have increased by about 30 percent to a current level of 360 *ppmv* [Hov13].

As scientific research gained momentum and the evidence found proved the effects of global warming, climate change was accepted as the inevitable outcome of increasing greenhouse gas emissions, and a number of important international and intergovernmental conferences were held from the mid-1980s onward. The significant Kyoto agreement was signed in Japan in December 1997, where 159 nations negotiated a treaty for the reduction in the concentration of greenhouse gases with the aim of slowing the rate of climate change. However, even with the reductions in greenhouse gas emissions agreed to in Kyoto, changes to the climate will continue to which nations will have to adapt. Computer projections using advanced climate models show that further increases in CO_2 concentration could reach 700 *ppmv* by 2100, which will increase global average temperatures by up to 4.0°C. Even if the level of the CO_2 concentration is kept at the current level (year 2014), an increase in the temperature of about 1.0°C till 2100 is expected [IPC14]. To picture what effect it might have on the ecosystem, consider that during the last glacial period[16] (last "ice age") the global average temperatures were only 6°C cooler than they are today.

Changes in climate caused by the excessive emission of the greenhouse gases not only affect *average temperatures*, but also *extreme temperatures*, *air humidity*, and *sea levels*. Many regions will experience higher temperatures and less precipitation. Warmer temperatures will gradually cause polar ice to melt. Combined with the expansion of ocean water due to warmer water temperatures, sea levels could rise to a level that will threaten coastal areas and small island nations. In addition, with more thermodynamic energy in the global system, there is an increased probability of extreme weather events, leading to threats to human safety and property damages. The likelihood of weather-related natural disasters, like tropical cyclones, storm surges, coastal flooding, rainstorms, floods, droughts, wildfires and crop hazards will increase.

1.1.2. Management

Disaster Management (DM) is a developing domain of research and activities concerning disasters. The overall goal is to provide best prophylactic, preparative and response measures to avoid the disaster when possible, shorten its duration, lower

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[15] *ppmv* = parts per million by volume.

[16] The last glacial period lasted from approximately 110,000 to 12,000 years ago, and caused among others glaciation of northern Europe, inclusive part of today's Germany.

the number of affected people and induced economic damage and prevent secondary disasters.

DM has multiple sub-tasks in different time periods ranging from time before, during and after a disaster, creating a Disaster Management Cycle (Fig. 2). Disaster Management Cycles reflect life-cycles and repeating occurrences of disasters and has phases of mitigation, preparedness, response, and recovery. Phases do not occur in isolation but they overlap, and their length, order and specific tasks greatly depend on the kind and severity of the disaster. DM sub-tasks are grouped into phases based on their concrete goal and time of execution relative to the disaster. For example, **mitigation** and **preparedness** phases take place in anticipation of a disaster event and together establish strategies to prevent and mitigate (lessen) disasters and prepare for them. Mitigation includes all efforts, usually taken well in advance of a disaster, to identify the risk and eliminate or reduce the probability of disaster occurrence, or reduce the effects of unavoidable disasters. Examples of mitigation tasks are the development of building codes[17] to provide safe constructions and ensure integrity during a disaster, zoning[18] policies for settlement plans for areas prone to hazards, public education, and vulnerability analyses. Also research on hazards, disasters and disaster management, as well as disaster modeling and development of supporting systems belong to the mitigation phase. The Preparedness phase provides concrete plans on how to respond, what to do, where to go, or who to call for help. It includes emergency exercises and training, implementation of early warning/actuator systems, installing smoke detectors, or preparation of disaster kits with essential supplies.

As a disaster occurs disaster management actors, in particular humanitarian organizations, become involved in the **immediate response** and **long-term recovery** phases. The Response phase minimizes the damages created by a disaster. Immediate response includes the mobilization of the necessary emergency services and the first responders in the disaster area, which supply core emergency services, like search and rescue, to provide immediate assistance to maintain life, improve health and support the morale of the affected population. Such assistance may range from providing specific but limited aid, such as assisting refugees with transport, temporary shelter, and food, to establishing semi-permanent settlement in camps and other locations. It also may involve initial repairs to damaged infrastructure. The focus in the response phase is on saving lives, meeting the basic needs of the people until more permanent and sustainable solutions can be found. Humanitarian organizations are often strongly present in this phase of the disaster management cycle. To be able to respond effectively, these agencies must have experienced leaders, trained personnel, adequate transport and logistic support, appropriate

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[17] Set of rules that specify the minimum standards for constructed objects. The purpose is to provide minimum standards for safety, health, structural and mechanical integrity, fire prevention and control, and energy conservation. The building code becomes law of a particular jurisdiction when formally enacted by the appropriate governmental or private authority [Hag08].

[18] Authorities control of the use of land, and of the buildings thereon. Areas of land are divided by appropriate authorities into zones within which various uses are permitted.

communications, and guidelines for working in emergencies. If the necessary preparations have not been made, the humanitarian agencies will not be able to meet the immediate needs of the people. The Recovery phase continues the relief efforts and aims to restore population’s lives and the supporting infrastructure to normal. There is no distinct point at which immediate relief changes into recovery and then into long-term sustainable development and mitigation. There will be many opportunities during the recovery period to enhance prevention and increase preparedness, thus reducing vulnerability. Recovery activities continue until all systems return to normal or better. Recovery measures, both short and long term, include returning vital life-support systems to minimum operating standards, temporary housing, public information, health and safety education, reconstruction, counseling programs, and economic impact studies. Information resources and services include data collection related to rebuilding, and documentation of lessons learned for supporting the mitigation of future disasters.

1.1.3. Conclusions

Natural disasters are a major threat to a sustainable development. Based on data gathered at the International Disaster Database in Brussels[19] [EMDAT] damages and frequency caused by natural disasters are high and growing; in the period from 1990-2012 alone the economic damage caused by natural disasters is estimated to over 4000 $US billions. Gathered data confirms following detailed trends in the number and impact of natural disasters in the last decades:

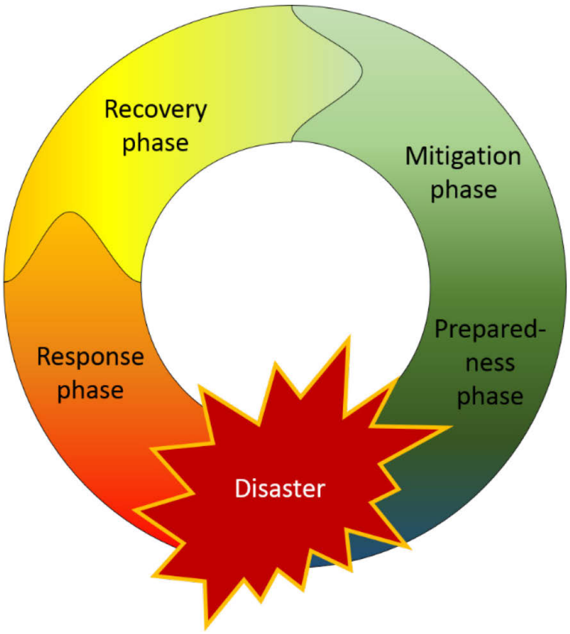

Fig. 2: Disaster Management Cycle.

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[19] In order for a natural hazard to be entered into the EMDAT Disaster Database in Brussels at least one of the following criteria has to be fulfilled: 1) 10 or more people reported killed, 2) 100 people reported affected, 3) A call for international assistance, or 4) Declaration of a state of emergency.

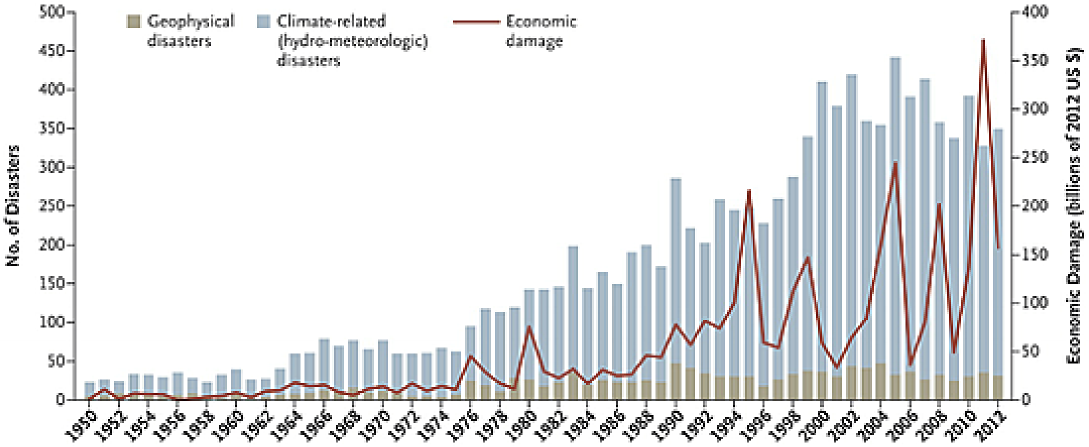


Fig. 3: Number of natural disasters and corresponding economic damage in years 1950–2012, based on [EMDAT], graph taken from [Lea13].

- Reported **economic damage** from natural disasters is **growing** (Fig. 3).
- The **number** of reported **climate-related disasters** is **growing** (Fig. 3).
- Most reported **economic damages** are due to **storms** (cyclones, hurricanes, and typhoons), **floods** and **earthquakes** (Fig. 4).
- Among all natural disasters **droughts**, **earthquakes**, **tropical cyclones** and **floods** are responsible for most **deaths**.
- Among all natural disasters **floods**, **droughts**, **tropical cyclones** and **earthquakes affected** biggest number of people (**homeless**, need **assistance**) in total.
- Most economic damages suffered Asia, followed by Americas and Europe (Fig. 4).

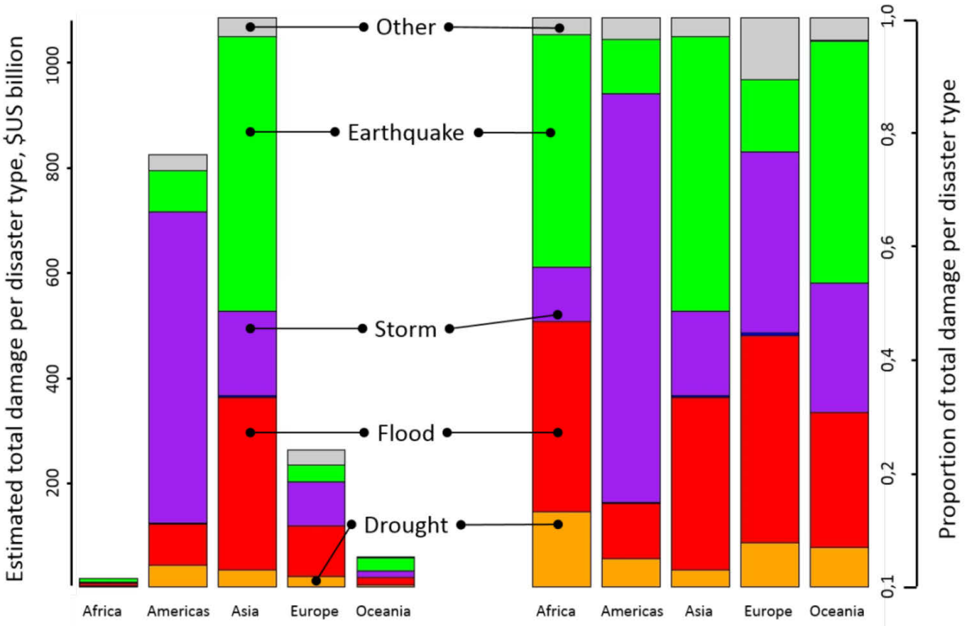


Fig. 4: Estimated total damage caused by reported natural disasters in 1990-2012. Type storm includes cyclones and hurricanes. [EMDAT].

Moreover, growing frequency of natural disasters can be accounted to the rising Earth's population analyzed in Section 1.1.1.1 and the ongoing climate change known as the global warming presented in Section 1.1.1.2. This forces us to assume that these trends will continue.

Disaster Management (DM) is an answer to this threat. DM aims to reduce disasters through integration of all possible means that allow international and local communities to withstand unavoidable disasters. The most important and promising disaster management tool is **disaster mitigation**, which focuses on adjusting to hazards, for example through appropriate building constructions that can withstand the impact of a disaster, intelligent early warning systems that prevent secondary disasters and obligatory education about disaster in disaster-prone areas, which results in focused and effective reactions to an alarm and or disasters and easies relief actions.

Earthquakes and wildfires are examples of disasters that can be reduced by dedicated disaster management systems, which we present in the next sections.

1.2. Earthquake and Wildfire Mitigation

Among other disaster types, **earthquakes** and **wildfires** have a highly damaging impact.

Earthquakes are one of the most destructive natural disasters. They carry huge energy caused by a sudden motion or trembling in the Earth's crust caused by the abrupt release of accumulated stress along a *fault* (a break in the Earth's crust). Earthquakes are responsible for about a quarter of both total economic damage and all deaths from reported natural disasters since 1900 [EMDAT]. Earthquakes are (after droughts) the second deadliest natural disaster and are able to kill many at once. Earthquakes threaten about 13% of Earth's surface [Fri13] and their occurrences are often spatially correlated with attractive urban coastal areas (Fig. 5).

Wildfires (e.g., forest fires, bush fire) also occur in all parts of the world. They are caused by strong winds combined with hot temperatures and dry air, mostly throughout the hotter months of summer and spring, by people's mistake or arson. Forest fires can be devastating for millions of different species living in and around the forests. When they spread into urban areas they can cause within in a short time massive destruction of infrastructure and property and endanger life, such as in 2009 when firestorms in Australia killed 173 people and destroyed more than 2,000 homes, even entire towns. Also many of the secondary effects of wildfires, including erosion, landslides, introduction of invasive species, and changes in water quality, are disastrous. Altogether, forest fires release enormous amounts of carbon dioxide and greatly increase global warming. By some estimates, forest fires contribute about 30% of total yearly carbon dioxide emission [Kas02]. In the United States alone, there are typically between 60,000 and 80,000 wildfires each year, burning 3 million to 10 million acres of land. Wildfire frequency is expected to grow because of the increase of the extreme temperatures due to a global warming (Section 1.1.1.2, *The Effect of Global Warming*).

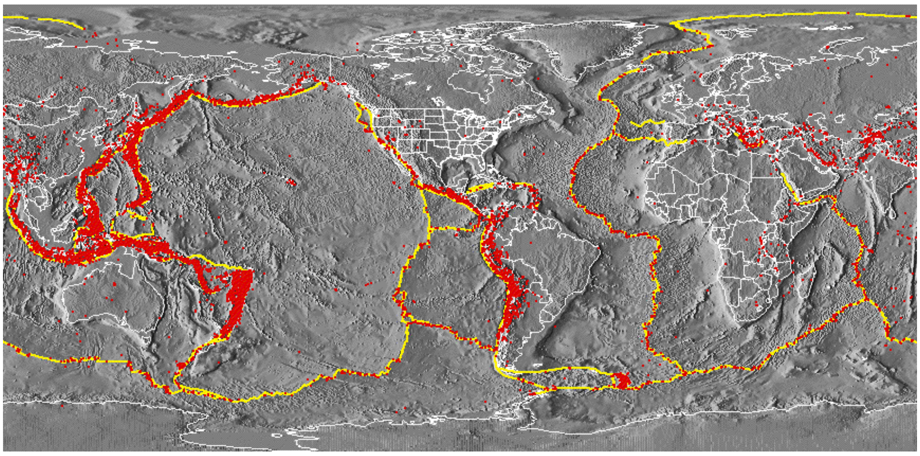


Fig. 5: Red dots are earthquakes of magnitude greater than 5 in period from 1980 to 1990; yellow lines are plate boundaries. From National Geophysical Data Center, Marine Geology & Geophysics, Globes and Global Relief Images, Slide 17.

In this section we describe the purpose and principles of operation of chosen earthquake and wildfire mitigation processes. The development of decentralized wireless networks to support these processes motivates this thesis.

1.2.1. Earthquake Modelling

Earthquake modeling is a highly complex problem that combines techniques from geodynamics, mineral physics, seismology and applied mathematics with the purpose to gain knowledge of the characteristic of seismic activities, with special attention to their impact on surface structures [Kan12]. Impact of seismic waves on surface structures depends on the Earth's crust formation in the area (e.g., existence and locations of faults), which makes the exploration and modeling of Earth's crust an integral part of the earthquake modeling.

Purpose

The knowledge of the characteristic of seismic activity in the area, i.e., possible strength and locations of earthquakes and resulting ability to simulate earthquakes is used in:

- **Earthquake engineering** to lessen earthquake effects on structures by finding for them a proper design that lets them withstand the seismic effects while sustaining an acceptable level of damage [Bir13].
- Creation of **building codes**, which specify the standards for constructed objects that provide minimum safety and structural and mechanical integrity [Hag08].
- **Measuring vulnerability** [Bir13] and **assessing disaster risk** [Rub12] (more about this in the following paragraph about shake maps).
- **Zoning** by the appropriate authorities that defines and controls the use of land by dividing areas into zones within which various uses are permitted with the goal to reduce vulnerable usage of land, such as the urbanization of disaster-prone areas [Bir13].

- Assessing the feasibility of the **placement of earthquake early warning systems** (EEWS), which depends on the relative location to the possible source of a quake and the local Earth's structure [Fri13].
- Other DM tasks, like in the **workflow optimization** during relief actions.

Shake Maps

A **shake map** is a representation of an **actual ground motion** produced by an earthquake. The information it presents is different from the earthquake magnitude and epicenter estimated during an earthquake detection. While an earthquake has one magnitude and one epicenter, shake map shows a range of ground shaking levels at sites throughout the region. These levels depend on earthquake parameters, distance from the earthquake, the kind and condition of rock and soil, and on variations in the Earth's crust, that together influence the propagation of seismic waves.

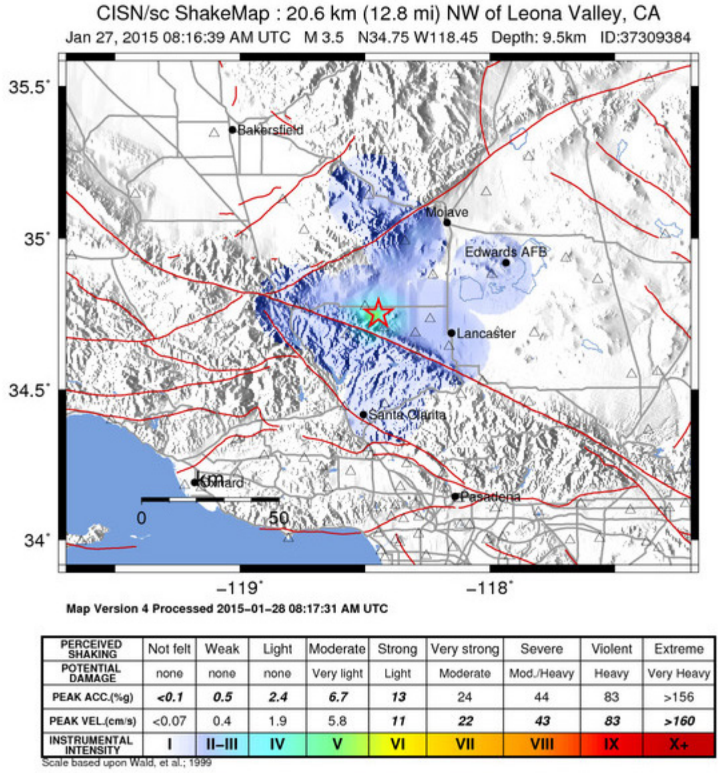
Shake maps are released relatively fast after the quake and are used by federal, state, and local organizations for assessing the risk connected with the event and improved decision making concerning immediate response and recovery activities, public and scientific information, as well as for preparedness exercises and disaster planning.

Data

To create a shake map **seismometer data of an earthquake is needed**, i.e., Earth's 3D velocity readings tagged with the geographical coordinates of sensor and the time the reading was taken. In the ideal scenario, earthquake data with a high granularity and from the whole area for which the shake map is to be produced is accessible. If in the existing real-life systems there are only few seismometers installed, possibly remote to the area of interest, then the data for the shake maps must be *interpolated* from existing measurements and *deduced* from the Earth's structure in the area, if known.

Example

In California, the California Integrated Seismic Network (CISN) uses different types of sensors (short-period, broadband, and strong-motion) in different environments (surface and/or free field, structures and boreholes) to model earthquakes and create shake maps. The CISN Real-Time shake maps are posted approximately 10 minutes after a Californian earthquake of magnitude 3.5 or larger [Hut10].



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Fig. 6: Shake Map of a minor earthquake in California, 27 January 2015, based on data from CISN (California Integrated Seismic Network).

1.2.2. Earth's Exploration

Data collected during earthquakes allows scientists to explore the Earth's structure, both its crust and interior.

Purpose

Information about the Earth's crust structure is widely used in disaster management[20] for:

- Modeling the probability of earthquake occurrences in the area.
- Modeling the earthquake's impact in the area.
- Computer simulations of seismic activities.
- In earthquake engineering.
- Deducing shake maps when small amounts of data are available.
- Zoning and building codes.

Principle

To understand how we explore the Earth using vibrations, we must study how waves interact with the rocks that make up Earth. The process is similar to the ultrasonography of the human body, with the difference that when assessing the Earth's interior we do not have the choice of where the sources are located - we have to rely on earthquakes. Just like any other wave, seismic waves undergo reflection and refraction when they encounter an interface between two materials with

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[20] Other applications of Earth's interior exploration are assessing groundwater and oil basins.

different wave velocities. The precise speed that a seismic wave travels through the ground depends on several factors, among which most importantly is the **composition of the rock**, other factors are **temperature** and **pressure**. We look at the travel time, or the travel times and the amplitudes of waves to deduce the existence of features within the plane [Ken82][Kan12].

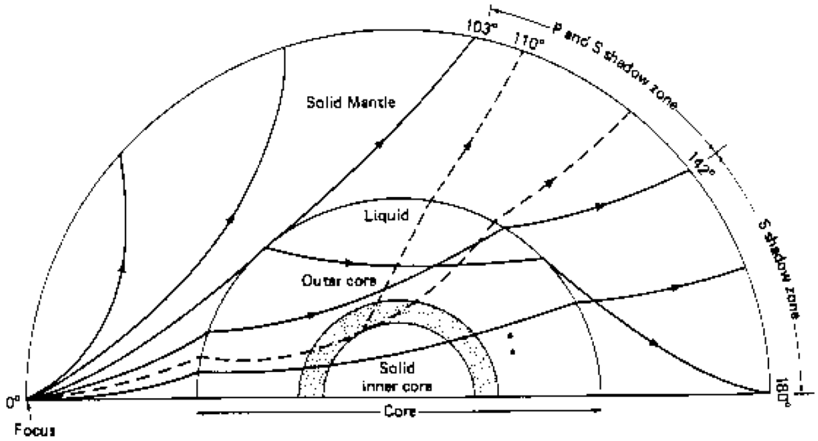

Fig. 7: Principle of exploring Earth's interior with seismic waves: selected ray paths for seismic waves passing through the Earth, from [Ken82].

1.2.3. Earthquake Early Warning Systems

At present, it is impossible to predict an earthquake. However, in many cases it is possible to *detect* an earthquake before its *devastating* impact arrives on the site.

Principle of Operation

Early earthquake detection is possible because of the physical nature of this phenomena. It is known, that earthquakes consists of fast, primary waves (P-waves) and slower, secondary waves (S-waves)[21]. P-waves travel with twice of the S-waves speed and always precede the latter[22] thus arriving early at the observed area (e.g., city). It is the slower S-wave that has the high energy and causes the significant ground shaking that brings actual damage to people, buildings and infrastructure.

The time measured between both waves depends on the distance to the earthquake's epicenter, and the medium and its structure that is being measured to detect the P-waves. Typical early warning advances are in the size of seconds to maximal 60-90 seconds for a deep, distant, large quake.

Detection of an event is the first of two main sub-tasks of any warning system, while the second is to execute the system's reaction to a discovered incident, i.e., *disseminate* the alarm or *trigger* the automatic reactions through actuators[23]. This thesis focuses on the **hazard detection problem**, although it is known that the

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[21] P and S waves are body waves, which travel into Earth's interior. Next to body waves there are also surface, Love- and Rayleigh- seismic waves, not used in EEWS, see [Kan12].

[22] Typical values for earthquakes P-wave velocity are in the range 5 to 8 km/s.

[23] An electrical, hydraulic, or pneumatic device that controls a mechanical device, e.g., turns it on or off, adjusts or moves.

usefulness of early warning systems lies in the fact that they communicate information about the threat. We will give examples of the usages of such information dissemination.

An Earthquake Early Warning System (EEWS) can be a useful tool for reducing earthquake hazards, if the spatial relation between cities and earthquake sources is favorable for such warning [Esp96][Gol97][Zsc03][Hut10].

Purpose

In case of detected earthquake an EEWS may disseminate an alarm, and/or activate automatic operations concerning infrastructure by connected actuators. Issuing a public alarm to inhabitants is done usually by using sirens, radio, web or television. It allows people to move away from dangerous machines or chemicals in work environments and to take cover under a desk or door frame. During this time flight control towers might stop taxiing planes and relief teams can initiate their procedures. Additionally, alarm may be used for activating automatic (using actuators) or manual operations concerning infrastructure like shutting down and isolating industrial systems, slowing down or stopping trains, preventing cars from entering bridges and tunnels and stopping lifts at the next floor and opening their doors. Taking all above actions before damaging S-Wave arrive can reduce damage and casualties during an earthquake. They can also prevent cascading failures of an event. For example, isolating utilities before S-wave shaking starts can reduce the number of fire ignitions.

Examples

Operating EEWSs exist in Mexico City [Esp96][Gol97], Taiwan [Hsi09] and Japan [Ash04]. In **Mexico City** the *Sistema de Alerta Sismica* (SAS) consists of 12 digital **strong motion** field stations located along a 300 km stretch of the Guerrero coast, arranged 25 kilometers apart from each other. Each field station includes a computer that continually processes local seismic activity. An algorithm programmed into each field station computer can detect the occurrence of an M>6 earthquake within 10 seconds of its initiation with an 89% accuracy level. At least two stations must confirm the occurrence of the earthquake before the public alert signal is automatically sent. SAS proved itself multipe times, for example during an M=7.2 earthquake in April 2014. Schools, institutions, and inhabitants were informed through the radio about the incoming damaging shock, and reaction to the warning was good because of past training and peoples' experience with the system. However, the systems covers only events coming from the Guerrero coast while earthquakes from other directions hit the city without warning. Unfortunately the system wasn't extended, because of the poor economic situation of the city and the high costs of the system: SIS took 1,2 million dollars for its development and installation and further 200 thousand dollars per annum for operation and maintenance [Esp96][Gol97].

Taiwan is one of the leading countries in EEWS development, which is motivated by the M=7.8 Hualien earthquake in 1986. The most severe damage occurred in metropolitan Taipei, 120 kilometers away from the epicenter, due to the basin amplification effect. A real-time **strong-motion** network provides a warning of impending ground motions with a few to tens of seconds of advanced alarm [Hsi09].

In **Japan** an effective EEWS system protects the high-speed Tokaido Shinkansen trains. TERRA-S detects the P-waves using h**igh precision device**s and makes real-time computation to identify the scale of the earthquake and distance to the epicenter. The system estimates the extent of possible damage, before issuing a warning. Detection of a large-scale earthquake leads to immediate termination of power transmission to safely bring all train operations to a halt. A total of 21 detection points have been set up to ensure full coverage of the railway (Fig. 8). TERRA-S proved its usefulness in 2004 during the M=6,8 Niigata-ken Earthquake that caused trains to derail while in service. Thanks to the automatically initiated emergency braking induced by an EEWS none of the 155 passengers were injured [Ash04].

Another approach has been successfully tested within a research project SAFER [SAFER][Fis11]. SAFER's SOSEWIN EEWS is based on wireless mesh network with up to 30 cheap wireless sensor nodes distributed at buildings in Istanbul. Nodes are equipped with GPS and a 3D-accelerometer, and they sense vibrations and assign them to a specific location. Through distributed algorithms, the nodes cooperatively detect the P-wave of an earthquake and immediately bring out the warning before the S-wave arrives. The warning messages reach a control center through sinks (i.e., nodes connected to the Internet). After a serious earthquake each node propagates data (like its own maximum acceleration) through the network, thus cooperatively producing a shake map. This data can be directly accessed by connecting to any node. Furthermore, one can make queries to the network in the field, which makes fast decision making far easier.

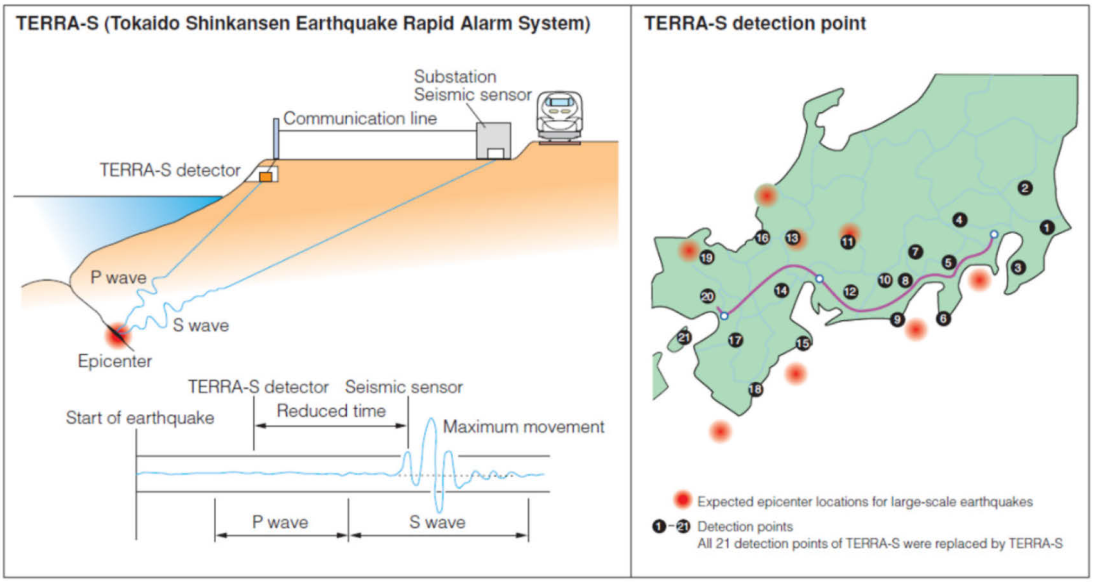

Fig. 8: Tokaido Shinkansen Earthquake Rapid Alarm System in Japan (TERRA-S), from the web site of the rails owner, the Central Japan Railway Company[24].

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[24] http://english.jr-central.co.jp/, accessed 4.02.2015.

In SAFER project and its SOSEWIN EEWS, the collaborative earthquake detection algorithm requires certain knowledge about network topology for creating clusters and defining leaders inside the clusters [Fle09]. To compare, proposed in this work LPS algorithm for event detection requires no group leader for earthquake detection and uses only local topology information. LPS is therefore better suited for larger networks, where costs of topology exploration and update might be too high.

1.2.4. Wildfire Early Warning Systems

Wildfire hazard is another case for early warning systems. Currently, manned lookout towers and the optical system are being used. The average fire detection time is five minutes in manned lookout towers and two to four minutes in systems with optical scanning. In manned lookout towers guards have to work 24 hours in remote locations under difficult circumstances. They may get tired or leave the lookout tower for various reasons, which reduces the detection time and increases the spread of fire. This problem exists also in the optical scanning systems, where forest's pictures are evaluated by humans in central offices.

Purpose

Accurate and early fire warning allows for an early reaction to fire and therefore reduces its spread within an area. Also, pre-suppression actions are possible before the fire problems begins, if dangerous temperatures that may lead to an outbreak of fire are detected early.

Example: optical system

An example of up-to-date early fire warning systems are tower-based, automatic forest fire early recognition systems utilized in Germany, Estonia, Mexico, Portugal, and the Czech Republic. The **optical scanning system** has automatic recognition of clouds by day and smoke at night. It incorporates local online data processing and utilizes a small band radio or cable transmission of alerts to a central office. It has an optimum coverage range detection of 15 kilometers. The time between detection and alert is approximately four minutes for a single tower setup and approximately two minutes for a multi-tower system. The system has a detection accuracy for smoke clouds of 10 x 10 meters at a 10 kilometer distance. During a 360° rotation, the camera takes three photos every 10°. For a better presentation of the smoke clouds, 36 photos are combined to form a panorama view in the central office. Reported smoke areas are marked on electronic maps and an operator evaluates all events by means of the data transferred to the central office. The systems installation, maintenance, and service are expensive and requires experienced personnel. The operator has to hire staff that is familiar with the local area to decide, in view of their knowledge of the area, if there really is a fire.

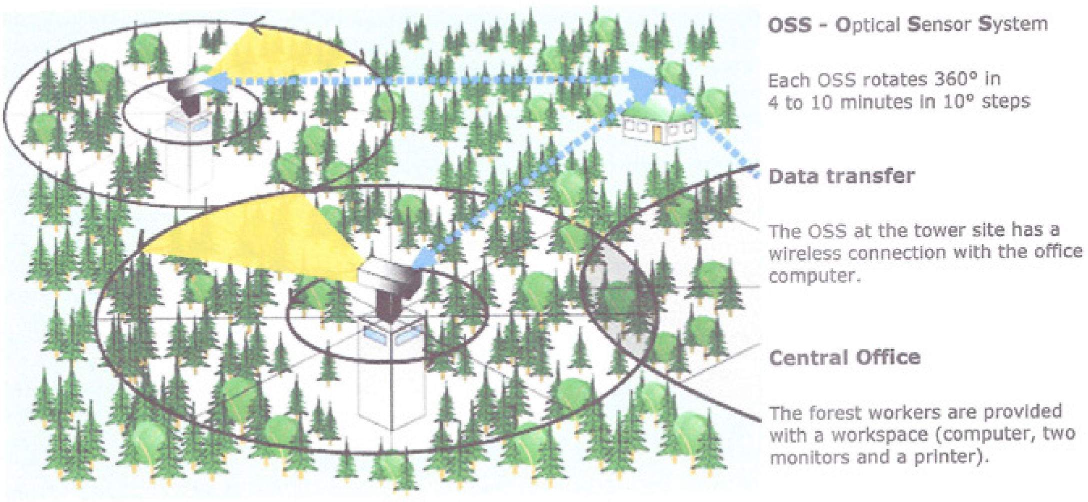

Fig. 9: Architecture of Early Fire Recognition Systems based on optical sensors, used in Germany, Estonia, Mexico, Portugal, and Czech Republic, from [Bri10].

1.3. Wireless Networks

Wireless networks (WNs) are telecommunication networks consisting of devices that are not connected by any physical cables with each other. Wireless devices (i.e., wireless nodes or simply nodes) use **radio waves** (RF)[25] transmitted over electromagnetic field in free space to communicate, instead of electrical and optical signals transmitted in copper wires and optical fibers in wired networks.

Cable-free communication combined with nodes miniaturization, built-in batteries and possible robust construction of wireless nodes makes wireless networks highly **flexible**. They are **easier** and **faster** to **deploy** in any terrain than wired networks, and require no electrical grid to supply power. They can be **portable** and nodes can **move** without disconnecting from the network. Networks **membership is dynamic**, so new nodes can be added at any time and other can leave seamlessly. Thanks to the omnipresent built-in wireless interfaces an **integration with wired** systems is easy, too. Flexibility of wireless networking and the fact, that wireless networks are often the most **cost-effective** solution empowers many applications impossible or unfeasible to be realized with wired networks. Examples of existing WN-based systems are wireless LANs at offices, universities and coffee shops, sharing the internet access in roof-networks, smart buildings applications, irrigation systems monitoring soil moisture, traffic and bridges monitoring, and water level and air quality monitoring.

Detailed properties and performance of **wireless nodes** vary. They have different **radios** (frequency, bandwidth, output power, MAC protocol, e.g., ZigBee, Bluetooth or 802.11g), number and type of **antennas** (omnidirectional, directional, isotropic), **energy source** (e.g., accumulator, solar battery, power cable, piezoelectric, thermal,

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[25] Alternative, there exists also wireless sonic, free-optic or induction communication. This technologies are not considered in this work.

photovoltaic, RF), **memory size**, **processor**, connected **sensors**, **operating conditions** (e.g., under water, allowed temperature ranges). Further, a node may know its **geographical location** (e.g., with GPS module) or not. It can also be **mobile** (with a certain mobility pattern) or **static**. Finally, in the same network nodes can be homogenous or heterogeneous, i.e., there are special nodes in network, e.g., relay nodes that do not generate traffic itself or super nodes with stronger computational capabilities. In general, wireless nodes are more **resource–limited** than computers connected by wired networks.

However, it is the **wireless medium** that creates the biggest challenge for the application designers. Wireless networks have a **spectral capacity disadvantage** in comparison to wired networks because of the significantly smaller frequency range that may be carried by wireless infrastructure. This disadvantage compounded with RF signal attenuation and multihop forwarding makes **communication** the network's scarcest resource. Therefore it is crucial to be aware of **shared wireless medium effects** that **limit bandwidth** and available to node **throughput**.

1.3.1. Wireless Medium

Radio waves propagate in free space, from their point sources (radio transceivers) in all directions of the three dimensional space[26]. With the following implications:

1. Signal can be concurrently received by multiple receives in sender's proximity, which results in **natural broadcasting** in wireless networks.
2. Signal's energy is spreading over area growing with the distance to source, so the signal attenuates with the distance to sender, which results in **short communication ranges of nodes**.
3. Signal changes when another medium is met (obstacles), which results in **irregular and changing communication ranges of nodes**.
4. Signals interfere with each other, which results in **reception errors**, **latencies** and **reduced throughput**.

1.3.1.1. Natural Broadcast

The first consequence of using space as signal carrier is that all devices close enough to sender can receive the signal **simultaneously**. Wireless is therefore a **natural broadcast** medium. We say that wireless devices **broadcast** their signal to its direct neighbors. (If a message should be forwarded to all network nodes, we call it a *network-wide* broadcast.)

Services that require delivery of the same information to multiple receivers can be made substantially more efficient if the inherent broadcasting nature of wireless is exploited properly. Any gossip-based protocols that use broadcast communication

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[26] For isotropic antennas. Signal spreads in all directions of a plane for omnidirectional antennas, which communication zone is modeled as a torus.

utilize bandwidth effectively in wireless networks. Protocols proposed in this dissertation are also gossip-based and intend to broadcast all messages to all node's direct neighbors.

In comparison, wired networks are inherently point-to-point and the cables carrying the communications signal focus the transmitted energy to specific devices at either end of the link. In wired networks, broadcasting can be realized by an addressing scheme[27] or at a higher level[28] in OSI model [Zim80], but is substantially less used.

1.3.1.2. Propagation Effects

In a static medium without any obstacles and interferences radio signals spread **uniformly** and we can calculate its energy for a given distance to the source. Because a signal's energy is spread over a bigger area, the further it is from the source, the more it will reduce with the distance. A signal's strength reduction with distance is rapid and proportional to the square of the distance to the sender (**free-space path loss attenuation**)[29].

At some point attenuation is so strong, that a signal's strength falls below the reception threshold and the signal cannot be received[30]. Therefore in a path loss propagation model (uniform signal dissemination, i.e., there are no obstacles or any other interferences) there are two zones around each node: a zone inside which signal is strong enough to be received (*communication zone*) and an area outside this zone, where the signal is too weak for reception and where communication with that node is not possible. The transmission (or communication) range (R) is the maximum distance of radio communication and it depends on used frequency, sending power (TX) and receiver sensitivity (RX). i.e., the minimum signal level the radio can demodulate. Two nodes are said to be (direct, one-hop) neighbors if they reside within each other's transmission range. If two nodes are neighbors they can send and receive each other signals and it is said that they are connected by a **wireless link** (see example in Fig. 10). Limited communication ranges means that nodes can create wireless links only with node in the vicinity and they will be never longer than the communication range of nodes and therefore they are **short**.

However, if the medium is not free and static, and there are obstacles in the signal's range and possibly other sources of radio waves (also other nodes in the same network) such obstacles will obstruct communication. In such non-uniform and dynamic environments the propagation of the signal is amended, its energy decreases inconsistently and there might be also transmission errors.

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[27] In IPv4, IPv6 doesn't have a broadcast address any more [RFC2460].

[28] E.g., Message Passing at Presentation Level.

[29] Signal's strength at any point is also proportional to its initial energy, medium and inversely proportional to the used frequency (for higher frequencies signal attenuates faster).

[30] Reception threshold depends on receive sensitivity and noise. If the Signal to Noise ratio (SNR) is more than reception threshold (specified in dB), signal can be received without error. Otherwise, the packet is dropped.

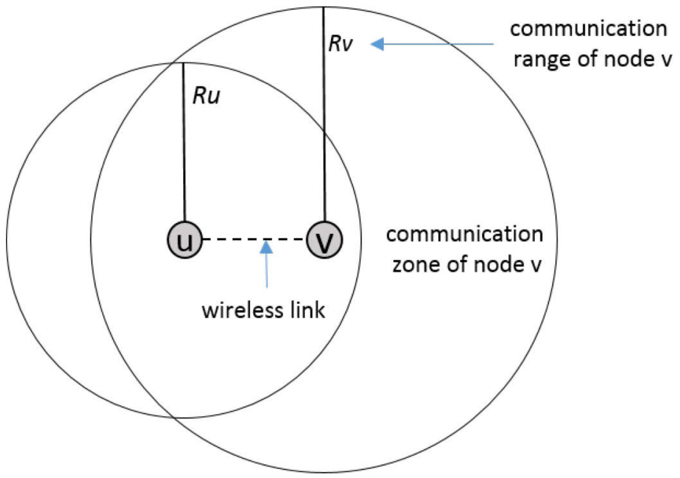

Fig. 10: Communication in a path loss model in free space for omnidirectional antenna.

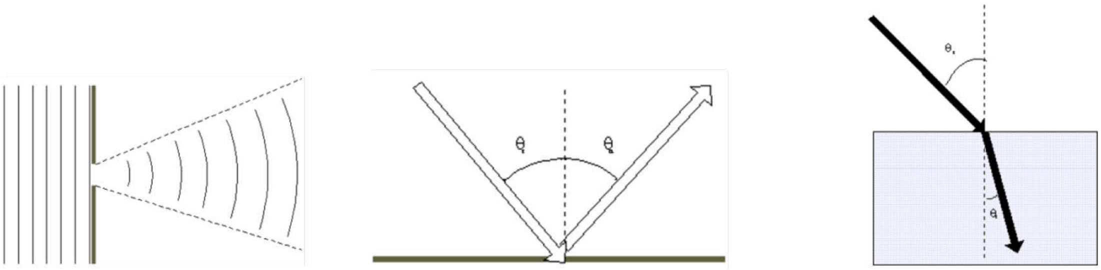

Fig. 11: Examples of propagation effects. From left to right: diffraction, reflection, refraction.

Signal is amended by **shadowing effects** connected with objects (e.g., concrete wall, trees or aluminum), like absorption, reflection, scattering, refraction and diffraction. They may change signal's strength, direction and speed (see examples in Fig. 11).

A signal might be a subject to a **multipath propagation**, which is the case when a scattered signal reaches receiver as multiplied signals with energy above reception threshold. Each signal arrives at the receiver at a slightly different moment in time, because each signal took a different path with a different length. Multipath propagation can cause signal's weakening or amplification (Fig. 12).

Another adversary effect is **interference** and its special case, interference with network's own transmission, i.e., **collisions**. Interferences with other radio sources always introduce transmission errors. The reason is that radio waves, as any electromagnetic wave, merge with other waves with the same or similar frequency and create a new, combined wave that does not carry the intended original information.

As a result of interferences and propagation effects and as measurements confirm [Ina09] the real communication zone is not regular.

Moreover, and very importantly, because the environment changes continuously (e.g., objects are moving, wind blows, air humidity changes, other radio waves appear and disappear) propagation effects like shadowing, interferences and multipath propagation are changing over time. This means that in any, even static, wireless network, **wireless links** are not only **short** but also **probabilistic**.

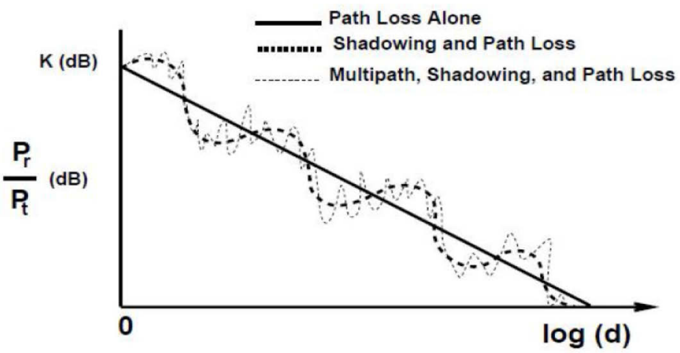

Fig. 12: Radio signal amendments and attenuation with the distance to the sender. P_t – transmitted power, P_r – received power, d – distance to sender.

1.3.1.3. Medium Access

Simultaneous transmissions utilizing the same channel in close spatial proximity (in so called contention zone[31]) may cause collisions that require retransmissions of the messages. Retransmissions increase latency, reduces throughput and waste bandwidth and should be avoided. Therefore a mechanism that provides collision-free and where possibly fair sharing of the wireless medium is desired.

The problem of accessing shared medium was successfully solved for early Ethernet by continuous collision detection (CSMA/CD[32]). However, in wireless networks this method cannot be used efficiently, because wireless transceivers can't send and receive on the same channel at the same time, due to the huge difference between sending power and receiver sensitivity (e.g., 100mw vs. 0.01mw). In other words, the sending a signal jams all foreign signals and if an error occurs, it is not detected immediately. For access to shared wireless medium explicit control messages can be used[33] and other techniques like carrier sensing, or frequency or time slot allocations. A comprehensive survey on Medium Access Control (MAC) protocols and operating principles that integrate various related issues and challenges is in [Kum06]. Still, simultaneous transmissions may occur due to e.g., wireless channel errors while sending control messages, or when new nodes appear in the network at an unfavorable time. For MAC protocols with carrier sensing the hidden node problem may also cause collisions.

The **hidden node** problem describes placement of nodes where two senders cannot sense (hear) each other, and if they transmit simultaneously, their common

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[31] A geographical area that belongs to the communication ranges of multiply nodes.

[32] Carrier Sense Multiple Access with Collision Detection access method.

[33] For example, often the Multiple Access with Collision Avoidance for Wireless (MACAW) protocol is used, specified in IEEE 802.11 RTS/CTS. It uses RTS-CTS-DS-DATA-ACK frame sequence (Request to Send, Clear to Send, Data-Sending with metadata about DATA frame, and Acknowledgment from the receiver).

receiver situated within the sender contention zone experiences interference of both signals and cannot receive any of them correctly.

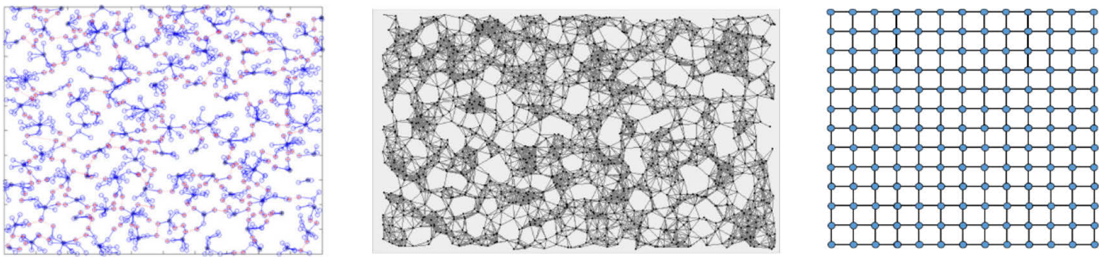

Fig. 13: Examples of (from left to right) random, uniform random and grid placement models.

Contrary to the hidden node, the **exposed node** problem describes the situation where two senders *are* in each other's contention zone, so they never send at the same time in order to avoid collisions. However, if their messages are intended for receivers that can respectively hear only one of the senders (they are not within the senders' contention zone) parallel transmissions can succeed.

1.3.2. Node Placement Model

The performance of wireless networks in terms of coverage, connectivity, resource usage, lifetime and robustness to node failures and changes in environment is greatly influenced by the physical placement of the nodes.

Because only nodes in close proximity can create links, the way the nodes are distributed over the area to a great extend determines average node degree (number of direct neighbors), network diameter, and number of partitions, bridges and articulation points in the graph modeling the network. This value defines many important characteristic of the network as the communication backbone, for instance the speed of information dissemination, which might be important in case of alarm dissemination, or the probability of network partitioning after failure of some nodes, which is likely to happen in a disaster.

On the other hand, if there are a high number of nodes in close proximity, resulting in a high nodes' density, this may cause congestions. Such hot-spots cause collisions and low throughput and thereby influence the performance of any distributed algorithms.

Often used placement models are **random** [Yun13], **uniform random** and **grid** (see Fig. 13). In these placement models the **deployment area is being determined first** and afterwards a given number of nodes is distributed in the area randomly, uniformly or at grid points, respectively. Such a placement process results in artificially **regular topologies**. Networks have **low diameter** and have an **average node degree with a small variance** for the given number of network nodes. They are often relatively **dense**, because researchers choose high numbers of nodes per area to receive **connected topologies**. For example, for a uniform-random placement model, the number of nodes versus communication radius and placement area is generally defined in a way that results in an average node degree of at least eight, in order to produce a connected topology *w.h.p*. Otherwise, produced topologies are not connected and the number of nodes in the connected partitions will vary.

There is a body of research on methods of determining positions of wireless nodes so desired optimization goals are satisfied, which is a NP-hard problem for multiply objectives [Hoj11]. For example [Tor12] seeks good coverage and connectivity while reaching desired resilience to changing environmental conditions. Also mobile sensor nodes or nodes with ability to move once to their final position [Zou03][Ahm13] are proposed. See [You08] for a survey.

However, such node distribution does not correspond to real-life ad-hoc networks placed by a **decentralized process**, as was shown in the example of existing multihop ad-hoc networks [Mil06][Mil07]. On the contrary, examined real-life networks have an irregular coverage and poor connectivity. They are characterized by high network diameter and long paths between a two arbitrarily chosen nodes. Examined real life networks have much more nodes with a **low degree** (2 and 3) and **articulation points** and **bridges**[34] than synthetic topologies (e.g., 20% vs. 5% [Mil06]). These network elements are important because they show how easy it is to partition the network and also they are potential points of **traffic congestion** which further reduces network throughput. Also, **information dissemination is slower** at nodes with lower degrees. Therefore techniques that rely on the certain regular distribution [CIT] and average high number of neighbors [CIT] may not function in irregular networks.

An alternative is to generate topologies reassembling topologies of existing ah-hoc networks. This is possible with usage of the probabilistic algorithm NPART [Milic09] that produces irregular topologies examined in [Mil06][Mil07].

Unlike other models, in NPART a **parameter is a non-uniform node degree distribution** and not the node placement area. As a result NPART produces probabilistic, connected, irregular topologies with desired number of nodes that follow the node degree distribution of existing ad-hoc networks, have many articulation points and bridges and a high network diameter. Also, NPART networks populate an irregular network area (Fig. 14), which is an important variable in real life ad-hoc networks. These topologies allow for more realistic testing of wireless algorithms and they ease the statistical assessment of the results, as produced connected topologies always have the desired number of nodes. They are also used to evaluate the algorithms proposed for this dissertation.

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[34] Articulation point is a node whose removal partitions the network. Bridge is a link whose removal partitions the network. Network partitions cannot communicate with each other.

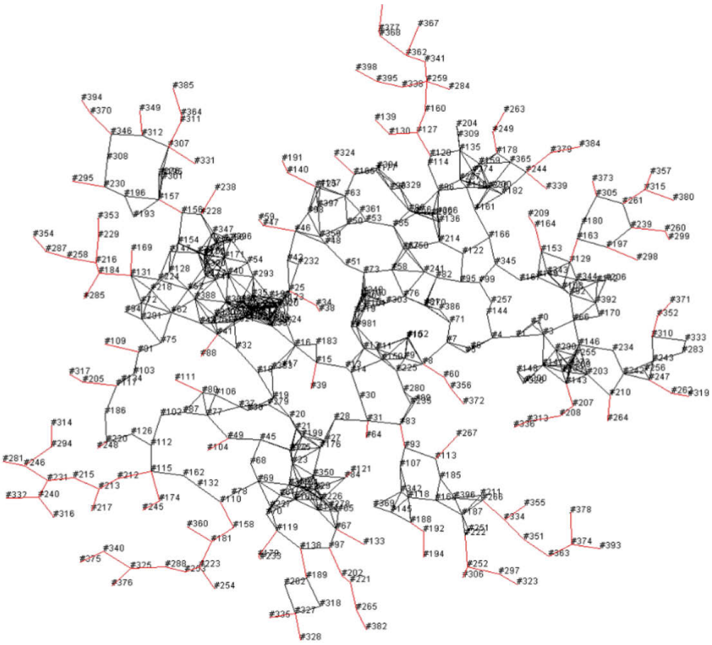

Fig. 14: Example of a network generated with NPART [Mil09]. Red links are bridges.

1.3.3. Types

Literature categorizes wireless networks (WNs) according to different aspects, but existing classifications are not exhaustive nor disjoint. Some network types imply certain network features, like used infrastructure, radio type or node density. Therefore it is practical to specify an assumed network model at every time.

According to networks' coverage area we distinguish:

- Wireless WANs (Wireless Wide Area Networks), infrastructure-based networks, with connections between cities and countries, using multiply antenna sites and/or satellites. Examples: cellular networks (e.g., GSM) and satellite networks.
- Wireless MANs (Wireless Metropolitan Area Networks), infrastructure-based networks for broadband connections between different locations like buildings of a campus, often serve as backup for wired networks, uses RF waves.
- Wireless LANs (Wireless Local Area Networks), infrastructure-based or ad-hoc networks, which provide flexible provisional data communication in offices and other spaces, usually enable connections within 100 meters inside buildings, includes 802.11 radio (Wi-Fi) and Hiperlan 2.
- Wireless PANs (Wireless Personal Area Networks), ad-hoc connections typically within up to 10 meters between devices as cellular phones and laptops, usually with Bluetooth or Infrared.

Typical usage scenarios and connected node models characterize:

- MANETs (Mobile Ad-Hoc Networks)
- VANETs (Vehicular Ad-Hoc Networks)

- WSNs (Wireless Sensor Networks)
- SNs (Spontaneous Networks).

MANETs and VANETs are mobile infrastructure-less (ad-hoc) networks corresponding mobility models, while WSNs refer to very dense networks of tiny devices with very limited resources, which harvest data and transport it to the static sinks. In WSNs duty cycle is a usually a topic, as energy constraint is dominant. The objective in spontaneous networks is an instantaneous service availability without any manual intervention. Spontaneous networks [Llo12] are hence self-organized networks with respect to addressing, naming, service discovery and security and they consists of usually mobile and heterogeneous nodes sharing a common location and interests.

Multihop routing characterizes Multi-Hop Wireless (MHWNs) and Wireless Mesh Network (WMN) Networks. MHWNs are characterized by routing in a multihop fashion, without deployment of wired backhaul links; this can be realized by relay antennas but also by connecting end devices with a mesh topology, where each node relays data for the network; such setting is referred to as Wireless Mesh Network (WMN). Wireless multihop and wireless mesh networks usually include hierarchy and existence of nodes with special features and can be implemented with various wireless technologies including 802.11, 802.15, 802.16, cellular technologies or combinations of more than one type.

Finally, depending on the architecture wireless networks are classified in two types: infrastructure-based and infrastructure-less (ad-hoc) networks. Infrastructure network consists of a network with fixed and wired gateways. An ad-hoc host communicates with a bridge in the network (called base station) within its communication radius. The mobile unit can move geographically while it is communicating. When it goes out of range of one base station, it connects with new base station and starts communicating through it.

In contrast to infrastructure-based networks, in **wireless ad-hoc networks** (WAHNs) all nodes connect dynamically in an arbitrary manner. WAHNs need no existing infrastructure, and all nodes of these networks behave as routers and take part in discovery and maintenance of routes to other nodes in the network.

In our understanding the distinctiveness of WAHNs is, connected with their independence from existing infrastructure, their **self-organization** with respect to **deployment** and **connectivity**. Such understood WAHNs are fundamentally Peer-to-Peer (P2P) networks: ad-hoc devices are equal peers that through locally made decisions fairly share resources for network's connectivity and packet forwarding. It is the subject of research, including this dissertation, to extend WAHN's self-organization to other network services.

MANETs, VANETs, WSNs and MHWNs, WMNs, SNs and wireless PANs can all be examples of ad-hoc networks, they operate independently from any existing infrastructure and are self-organized with respect to deployment and communication, i.e., nodes are able to automatically connect to each other and share their resources for data forwarding.

1.4. Thesis Structure

Chapter 1 gives the background information on natural disasters, chosen disaster management processes and on the characteristic of wireless networking.

Chapter 2 presents the dissertation’s motivation, challenges and goals, along with network and fault model.

Chapter 3 analyzes efficiency, scalability and fault-tolerance of existing Peer-to-Peer (P2P) algorithms in WAHNs. A special emphasis is on the scalable algorithms that use position information.

Chapter 4 and **Chapter 5** propose new algorithms: PANA (Polygon Approximation of the Network Area) Protocol and Grid Approach for WAHNs that deliver new, aggregated position information that can improve efficiency and scalability of the existing and new P2P algorithms.

Chapter 6 proposes protocol for localized data aggregation that uses Grid Approach for reaching scalability with respect to the system size.

Summary of the thesis’ contributions and possible direction of the further research are in **Chapter 7**.

Chapter

2. Motivation, Challenges and Goals

The goal of this dissertation is to improve reduction and prevention of natural disasters by supporting Disaster Management (DM) processes with use of wireless ad-hoc networks (WAHNs). In this chapter we present our motivation and deliver the dissertation specific goals, which are efficient, scalable and fault-tolerant, self-organized Peer-to-Peer (P2P) data storage and localized data aggregation services for WAHNs.

2.1. Disaster Management Processes

This research is motivated by support for DM processes for cases of earthquakes and wildfires, which may have a damaging impact on lives, the economy and the environment However, it is possible to lessen their negative impact with the following DM processes:

- Earthquake and fire early warning systems (Sections 1.2.3, 1.2.4).

For some hazards, like forest fires, sensors can detect the upcoming event early. Another detectable hazard are earthquakes. Early detection allows an earlier response to hazards (warning system) in order to lower or even to avoid its devastating impact, measured in casualties and environmental and economic damages.

- Disaster and environmental modeling (Sections 1.2.1, 1.2.2).

Disaster modeling is a part of disaster mitigation. For earthquake mitigation, models of earthquakes and the Earth's crust and interior are generated. Environmental data of a high resolution (from many geographically dispersed sensors) collected over big geographical areas during disasters improves creating of accurate disaster models.

- Disruption-tolerant emergency communication in the disaster area.

Disaster may occur where there is no cellular telephony coverage or land lines, or the disaster may damage all existing communication systems. However, a functioning communication system is the prerequisite for any effective relief actions.

Our motivation is to extend availability, improve quality and to lower the price of the above systems. For instance, for any early warning system, a good coverage and low price, compounded with high accuracy, in the event detection is wanted. Bigger coverage through warning systems increases the ability to prevent and reduce more disasters, and the requirement of high precision makes the warning system usable and economic, as missing to detect a disastrous event or issuing a false alarm causes obvious costs. However, these goals are not fulfilled by the existing early warning systems, which fulfill only the accuracy requirement. Existing EEWSs reach good accuracy in the detection of catastrophic events by using expensive, robust strong-motion seismometers with a high precision [Esp96][Gol97][Zsc03][Hut10]. Typical EEWS usually have a dozen of high-precision sensors installed outside of a city, usually deep under the surface and specialized in the detection of earthquakes originating from a certain location. In such systems both the initial and the ongoing costs are high[35]. Because the availability of warning systems limited by price and running costs, traditional EEWSs are not widely available.

Instead of using a single, high-precision, but costly system of seismometers for detecting an earthquake, many unreliable but cheap and arbitrarily located sensors could detect an earthquake collaboratively. A large network of cheap sensor (e.g., CO, humidity and temperature sensors) could be also a great improvement to the existing fire early warning systems (FEWS) [Sin13][Bri10] and could increase the observed areas, lower the installation and maintenance costs and eliminate the need for a human involvement in the fire detection process. Moreover, early alarm sensors networks can be additionally used to collect a high-resolution data for disaster modeling and even as an emergency communication system, too.

We propose to realize the DM processes presented above with use of wireless ad-hoc networks.

2.2. Wireless Ad-Hoc Networks for Disaster Management

Wireless Ad-Hoc Networks (WAHNs or simply ad-hoc networks) are flexible wireless networks that operate independently of existing infrastructures and can be deployed in any area. WAHNs are interesting for DM applications because of their self-organization with respect to connectivity and communication:

- Two wireless ad-hoc devices placed in each other’s proximity connect, and in that way mutually create (or extend) an ad-hoc network
- Ad-hoc routing finds a valid path between any two nodes, if such nodes exist, even if changes occur in the network and without overloading the network, what could cause interruptions in its functionality.

Therefore, WAHNs can be used as a backbone for other self-organized services.

2.2.1. WAHN Capabilities

Independence from existing infrastructures and self-organization in connectivity means that WAHNs can be deployed without human assistance on site. This offers the possibility of a rapid networks deployment through a decentralized process without any detailed planning, and in a possibly hard to access areas. For example, nodes can be dropped from an airplane over a disaster or disaster-prone area [Tan11].

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[35] A single strong-motion seismometer (accelerograph) can cost as much as 25.000€ or more. Initial cost of EEWS in Mexico City with a dozen of strong-motion seismometers was 1,2 million $ [Esp96].

Fig. 15: A commercial wireless sensor node with a 3D acceleration sensor, 802.11g radio, 138 meters communication range, size 40x40x82 mm3, weight 220 grams with accumulator and antenna[36] (*left*). A custom wireless sensor node with a temperature sensor, powered by a piezoelectric vibrational energy harvester and built from of-the-shelf components. The system is fully autonomous and generates sufficient power to measure and transmit the environmental temperature with an interval of fifteen seconds (*right*) [Loc13].

Because ad-hoc nodes can be small and inexpensive (see example in Fig. 15) WAHNs can serve geographical areas of a significant size. DM objectives of preventing and reducing disasters is significantly improved the larger the geographical coverage.

In addition to communicating abilities WAHNs can be equipped with sensors capable of measuring, storing and processing environmental readings. Therefore, they can support DM applications that are depending on environmental readings, like, among others, disaster modelling and disaster detection.

Finally, ad-hoc nodes can be designed to function in harsh environments (e.g., they can be water- or fire-proof). This allows WAHNs to observe areas where human and infrastructure presence is difficult or impossible (e.g., network placed close to a crater can observe volcanic eruptions) and to function despite a disaster (e.g., allow for communication and collecting data while in the fire/flood).

2.2.2. WAHN Challenges

Inherent characteristics and limitations of the wireless networking, irregularity of the real-life ad-hoc networks and the possibility of damages to network nodes during a disaster pose the following challenges for DM services in WAHNs:

- Efficiency with respect to communication, i.e., amount of sent data.

Because bandwidth is the scarcest resource in wireless network, wireless applications need to limit the amount of data sent over wireless channels. Nodes with a finite energy source must also limit the volume of data sent, as this is the most power-consuming operation of a wireless node, in comparison to receiving, processing and sensing of data.

- Broadcast whenever possible.

Wireless is inherently a broadcast technology in the sense that transmitted energy is spread over a geographic area and several receivers in that area can receive

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[36] Node Tediasens SN-I by Elovis, http://www.tediasens.de/

the signal simultaneously. Services can be made substantially more efficient if the inherent broadcast nature of wireless is exploited properly.

- Incorporate low reliability at application level

Both nodes and links are much less reliable than in wired environments. Wireless links unreliability can be an effect of temporary fading, various propagation effects and changes in the environment[37], interferences and collisions with other transmissions. Methods of compensating unreliability of wireless links consume additional capacity. Delegating the reliability compensation mechanisms to the application service can reduce overheads and therefore significantly increase overall system capacity.

- Adjust to changing topology

Because of the changing quality of links and a low reliability of unattended nodes and a possibility of dynamic, decentralized changes in the network's membership (nodes arrive and leave, e.g., because of battery exhaustion), topology of a static wireless ad-hoc network must be seen as dynamic, where paths between pair of nodes and nodes may appear and disappear. This implicit dynamicity is increased in the event of a disaster.

- Deal with irregularity of real-life ad-hoc networks

Wireless nodes need no cables and they can be placed anywhere, and therefore they may have an unknown and irregular size and topology that on the other hand influence network's performance. Dense areas may experience congestions, when packets are lost what may lead to serious performance degradation. Sparse provision of nodes on the other hand will hinder information dissemination.

- Deal with possible spatially correlated nodes' crash.

In a disaster a group of nearby placed nodes may crash (be destroyed) simultaneously, e.g., by an outbreak of fire. This poses a special requirement for data replication to ensure survivability [Gei09].

- Security

Security in wireless networks is a difficult issue, too. Wireless communication can be overheard and physically unattended nodes can be compromised. For example a false alarm could be issued through a disaster warning system. This dissertation does not address the topic of security.

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[37] Temporary link failures for a fixed distance to sender can be prevented by increased transmit power. However other factors such as the need to minimize interference and to minimize mobile device battery weight push for system designs with low transmit powers.

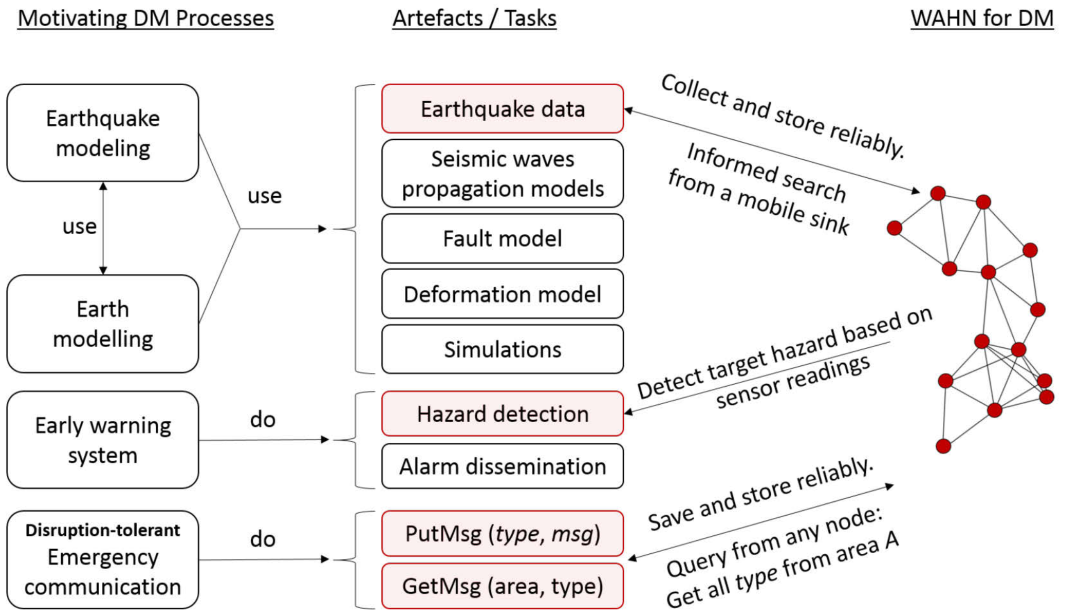

Fig. 16: Motivating DM processes and tasks and possibility of WAHN support.

2.3. Motivating Scenarios

The disaster management processes presented in Section 2.1 that we want to improve with use of WAHNs are highly complex and may have many steps and tasks, which may also depend on a given methodology, specific application and disaster type, as pictured in the example in Fig. 16 .

In this section we propose WAHNs support for chosen tasks connected with a distributed data management. We present four DM scenarios that use wireless ad-hoc networks and for each scenario we identify the specific service that WAHN shall deliver to the higher-level DM application along with DM challenges for the addressed services.

2.3.1. Scenario 1: Collecting Disaster Data

Earthquake and Earth modeling necessitate disaster data. Seismologists and geologists wish to have earthquake data from ever bigger areas, with a high resolution and from many events. However, existing systems usually only deliver few data points, and the required data for models (e.g., shake maps, see Section 1.2.1) must be interpolated.

We propose to use WAHNs equipped with cheap sensors (e.g., like sensor in Fig. 15) for collecting the necessary disaster data. This functionality can be connected with the EEWS functionality (2.3.3) and even with the emergency system communication functionality (2.3.2), so the overall cost to efficiency ratio will improve.

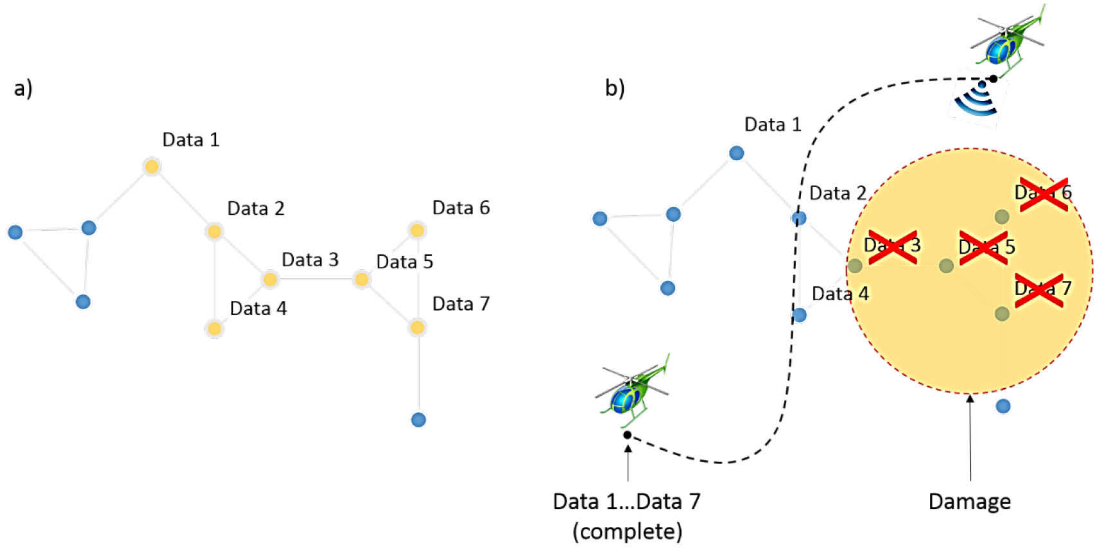

Fig. 17: Example of Scenario 1: a) WAHN collects disaster data (yellow sensor nodes nodes). Disaster destroys a part of the network. b) A helicopter flying over area contacts some healthy nodes and retrieves all disaster data, also these recorded by destroyed nodes.

Scenario 1 (Disaster Data):

Let's consider an earthquake-prone area or the area where the Earth's acceleration during an earthquake is of an interest. Assume that wireless ad-hoc nodes with accelerometers and an energy source are distributed in the area in a decentralized way. (For instance they are equipped with solar-batteries and dropped form an airplane over the area.) Nodes connect to each other and create one or more wireless ad-hoc networks that constantly observe ground accelerations. Nodes know their geographical location and time. In case sensors observe ground motions above the defined threshold they store their readings along with the current time and location.

After an earthquake, data is collected from the network by a mobile sink. For instance, a helicopter flies over the area and retrieves the disaster data by connecting to one or more ad-hoc nodes. See example of Scenario 1 in Fig. 17.

The goal of Scenario 1 is that a mobile sink can collect as fully as possible the stored data. The challenges are:

- Possibility that earthquake destroys some nodes along with their local storage (as nodes 3, 5, 6, and 7 in Fig. 17),
- Danger that disaster partitions the network,
- Possibility, that a mobile sink during data harvesting does not connect all nodes but only their subset.

2.3.2. Scenario 2: Disruption Tolerant Emergency Communication

In many disasters people that are harmed and need assistance have no possibility of informing the relief teams about their position. It might be due to the damages to the existing communication systems (GSM towers) caused by a disaster or by a situation when disaster finds people without their cellular phone in a hardly visible or inaccessible place. We propose to prepare for such a situation and to install in inhabited disaster prone areas dedicated emergency communication systems, which allow disaster participants to report on their status, e.g., issue a distress call. The envisioned systems function independently from any existing infrastructure (communication, power grid) and keep their functionality even in spite of partial damages cause by a disaster.

Scenario 2 (Emergency Communication):

Let's consider an earthquake-prone area. Each inhabitant of the area wears a battery-driven mobile sensor node that knows its own location and has a simple interface to issue a distress call 'I need assistance' (red button) or to send a message 'I am fine' (green button). Mobile sensor nodes are off when there is no disaster. Additionally, each house possess a wireless static ad-hoc node in the electrical socket, which ensures that the static nodes battery, can operate at least 72 hours after it has been cut off from the power supply (i.e., socket in the given example). In case of a disaster, ad-hoc static nodes switch on automatically and then connect to each other and mutually create an ad-hoc network. The mobile wearable devices of the inhabitants can be now turned on and automatically connect to the ad-hoc network. Now, each person with a mobile device can issue a distress call (push a red button) which will be immediately stored in the network together with the position of the mobile device and time. Alternatively, a person can issue the message 'I am fine', which is also stored in the network along with mobile node position and time.

As the relief teams arrive at the disaster site and reach the first ad-hoc node of the local network they can issue a search in the network for the distress calls issued nearby or in some given area. Alternatively, messages of 'I am fine' can be requested.

The task of WAHNs in this scenario and the challenges are the same is as in the Scenario 1, with the difference that relief teams can call upon data regarding the event collected in a defined vicinity.

The goal of Scenario 2 is that relief teams retrieve all messages that answer their (localized) queries.

The challenges are:

- The likelihood that the earthquake has destroyed some of the nodes along with their local data storage (and the recorded local distress calls),
- The danger that the disaster partitioned the network,
- That relief teams may use an arbitrary node for querying the network.

2.3.3. Scenario 3: Earthquake Early Warning System

Existing EEWSs use expensive seismometers with a high precision. Typical EEWS with single high-precision sensors are installed outside of a city, which necessitates that the eventual alarm has to be transmitted to the inhabited area which might require dedicated technical solutions and additional time. Such traditional EEWSs have high initial and running costs and are not widely available.

Instead of using a single, high-precision, but costly system of seismometers for detecting an earthquake, many unreliable but cheap and arbitrarily located sensors could detect an earthquake collaboratively.

Scenario 3 (EEWS):

Let's consider an earthquake prone urbanized area. Wireless ad-hoc nodes with accelerometers and energy sources are distributed in the area in a decentralized way. (For instance nodes which have batteries and can be connected to electrical cabling are handed over to inhabitants, which plug the devices into the electrical sockets of their houses, so that when a quake starts and the electrical grid is destroyed, the batteries are fully charged.) The individual devices connect with each other to create one or more wireless ad-hoc networks that constantly observe ground accelerations and if increased readings above a defined threshold are observed they report an earthquake.

After detecting an earthquake an alarm is issued (by sound, radio or another way) automatically be the network, and if also connected to other actuators[38], which is easy because the system is placed within an inhabited area, the latter can be initiated to undertake predefined safety actions (e.g., for closing gas pipes, stopping trams, turning traffic light to red etc.). Alarm dissemination is a separate problem, not addressed in this work.

The goal in Scenario 3 is to accurately detect an earthquake, i.e., to avoid false alarms and to detect all earthquakes of a defined strength. The challenges are:

- Low sensor precision, and
- Environmental noise (seismometers can be influenced by some other event causing ground shaking).

2.3.4. Scenario 4: Fire Early Warning System

Scenario 4 (FEWS):

Let's consider a forest area prone to wildfires. Wireless ad-hoc nodes with temperature sensors and stand-alone energy sources are distributed in the area in a decentralized way. (For instance nodes are air-dropped). Devices connect to each other and create one or more wireless ad-hoc networks that constantly observe environmental temperature, humidity and CO concentration and in case of a predefined pattern of environmental readings detected a fire is detected.

After detecting fire (or a danger of fire) an alarm is issued, e.g., by a satellite or radio connection accessible from some nodes. Alarm dissemination is a separate problem not addressed in this dissertation.

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[38] An electrical, hydraulic, or pneumatic device that controls a mechanical device, e.g., turn it on or off, adjust or move.

The goal of this scenario is to detect a fire outbreak or a danger of fire outbreak (depends on a setting and used sensors), with a high accuracy, and with information about geographical location of a fire/intensity of a fire.

The DM challenges are:

- Low sensor precision, and
- Environmental noise (other sources of changed sensor readings than the fire)

2.4. Requirements for the Addressed Services

We address following services in the presented scenarios:

- **Storage of disaster data**, both environmental readings for disaster/Earth modeling as messages used in emergency communication system, and
- **Hazard detection** based on sensor readings in an early warning systems.

Any algorithm executed in WAHN should be **efficient**, i.e., they should respect very limited storage, energy and computational capabilities, load balance resource usage and limit the number of send operations (optimize communication overhead and use local broadcast). Additionally, addressed services should have a **Peer-to-Peer** (P2P) design because of the unknown network size, unknown location of a disaster and the need for sharing resources and load balancing resource usage in resource-limited, unattended WAHNs. Also, WAHNs in DM work without any coordination and be able to respect dynamisms of the network topology and adjust to changes in the network, which results in the need of **self-organization** of the algorithms. As the size of the WAHNs is not a priori know, and there are visions of large DM systems, they should also **scale** with the network size.

Summary of requirements for any DM services in WAHNs are in Table 3. Other requirements are tasks-specific.

In the following subsections we analyze them with respect to the addressed services in more detail. The summary of this analysis is shown in Table 4.

2.4.1. Data Storage

The role of storage system in Scenarios 1&2 is to **reliably** store the data. Even if in course of a disaster some nodes are destroyed, the data produced by those nodes, shall still be present in the system so it can be retrieved by the querying nodes (Fig. 17). This implicates that some **replication** mechanism must be used. Our goal is to supply data survivability in case of a given damage, i.e., our goal is that data item (or its replica) is still present in the system after damage that destroys system within given radius (see Section 2.5 for the exact goal definition).

Because the sink nodes are not present at the time of data production, an **in-network** data storage is required. Because disaster location, victims' locations, locations of the mobile sinks or relief teams are unknown, the storage service must

Table 3: Requirements of algorithms in WAHN networks.

	Characteristic/Scenario	Algorithms' Requirement
Wireless Ad-Hoc Network	Strong resource-limitation	Efficiency in communication
		Efficiency in memory footprint
		Easy computations
		Share resources
		Avoid flooding
	Large networks	Load balance
		Scalability
	Disaster/Unattended operation	Self-organization, robust to disaster, adjust to changes in network membership P2P design
	Cheap, unreliable nodes	
	Nodes addition	
	Wireless Communication	Tolerate message losses
		Broadcast communication preferable

allow any network node to insert and request data from the network, which implicates its **Peer-to-Peer** design.

2.4.2. Disaster Detection

In Scenarios 3&4 the challenge is **high accuracy** of event (disaster) detection. High accuracy means high recall, i.e., system's ability to detect all target events (e.g., earthquakes and fires) and high precision, i.e., the ability to avoid any false alarms.

It is also a necessary requirement in large early warning systems, in addition to the information that the hazard has occurred, to provide information on its **location**. Only then can an appropriate response to the alarm be undertaken. For instance, in case of a detected fire, actuator-based watering systems can initialize watering in the given area or fire brigades can be sent to the given location.

System's recall in event detection depends on hardware factors like number, quality and types of sensors (w.r.t. target event), size of the network, its coverage and relative position to the target events. Assuming useful network equipment, position and coverage, the performance of the detection algorithm defines the rate of success, where success is measured by a ratio of correctly recognized events and the time needed for event detection.

In order to avoid false alarms, an event detection scheme in a network consisting of unattended and unreliable sensors should be based on a collaborative decision of a group of nodes rather than on a reading of a single node only. A single node might be malfunctioning or compromised or can record abnormal sensor readings caused by other, than targeted, events. For example, the increased ground shaking can be caused by a passing truck and not by an earthquake. There are approaches to filter the input stream from abnormal data with statistical means [Der07], but in our target scenarios with resource-limited nodes and for events that need to be detect fast there might be not enough time to assess the sensor readings first. Therefore, disaster detection in presented scenarios should be based on readings of several sensors. Taking a distributed decision about occurrence of a phenomena is known in the literature as the *distributed event detection problem*.

Distributed event detection is a vast field of research [Bah10][Sin13][Cer14] [Par14]. Some events can be detected only with spatial or spatiotemporal observations, like detecting an illness or a person climbing a fence [Wit10], while other can be recognized when sensor readings exceed some threshold value, like an event 'garden needs watering'. To detect events from the first category different techniques from the fields of probabilistic and Artificial Intelligence (AI) are used, like fuzzy logic, neural networks [Par14], machine learning [Wit10][Bah10], Markovian Agent Models [Cer14] or Bayesian Algorithms [Kri04].

We assume that our target events (disasters) belong to the second category and can be simply recognized by comparing environmental measurements to defined threshold values. Because different sensors might have different environmental readings (or local assessments of readings), disaster detection is a *distributed consensus problem*, one of the most fundamental problem in a distributed systems.

There are different approaches to the distributed consensus problem. On one spectrum there are voting techniques, that explore network topology in order to establish some hierarchy for the voting scheme (e.g., decision trees [Bah10]), which must be renewed after changes in the network, what uses time and network resources. Voting schemes are feasible for small and stable wireless networks like sensor networks for detecting a residential fires [Bah10], but are not a good solution for intrinsically dynamic and big wireless ad-hoc networks.

An alternative to voting for reaching a consensus is *aggregation of sensor readings* [Mak09][Mak14]. Aggregation is a process that combines several numerical values into a single representative value. This value can be a *count* of input values, their *sum*, *average*, *minimum* or *maximum* or total over set of values. We chose this scheme for event detection algorithm, because of its usefulness for threshold-detectable events, like fires and earthquakes and clarity with communicating with domain specialists. Computer scientists and specialists of a given domain can use aggregate values (e.g., 'number of sensors', 'average CO concentration', 'minimum humidity') and well understood inequalities ('Less than', 'Greater than', 'At least' etc.) to clearly define the environmental conditions that characterize given disaster. For instance, a danger of grass combustion could be defined, and directly implemented in FEWS that is able to calculate needed aggregates, as an event, when the average temperature is at least 60 degrees, while the average humidity is below 10%. However, in large WAHNs, we need to additionally specify an extent of the observed phenomena, i.e., a **localized** data aggregation scheme is needed.

Table 4: Partial requirements for data storage and hazard detection services delivered by WAHN, based on the DM scenarios analysis.

Service	DM Goal	Scenario	Result	WAHN Service Requirement
Data Storage	Reliability	Unattended network	Unreliable nodes	**Replicated** data storage
		Disaster	Network partitioning	
			Spatially correlated nodes crash	To assure survivability, possibility to support minimum **distance between replicas**, bigger than damages cause by disaster
	Successful collection of all required data	Mobile sink collects data	Sink is not present at time of data production	**In-network data storage**
			An arbitrary node is used for data collection	**Peer-to-Peer** design
		Disaster appears at unknown location	An arbitrary node must be allowed to store and replicate data	
Disaster Detection	High accuracy of event detection	Unattended network	Unreliable nodes	**Distributed** event detection
		Environment	Other sources of sensor readings	
	Identify event location	Nodes know their location		**Location-aware** event detection

2.5. Network Model

In this dissertation we consider stationary wireless ad-hoc networks consisting of homogenous nodes with omnidirectional antennas, limited proprietorial energy source and sensors depending on the specific scenario. Nodes create links only within their common transmission range R according to Unit Disk Graph (UDG) model i.e., two nodes are connected by link *if and only if* the Euclidean distance between them does not exceeds the communication range R [Cla90]. Nodes know their geographical location based on GPS or other positioning system.

This model is equivalent to the path loss propagation model. However, in order to express the irregularity and intrinsic dynamicity of communication range of nodes and unreliability of the wireless communication, we assume each wireless message can be lost with a probability P_{LOSS}. Also, we assume that nodes are placed in the area by a probabilistic and/or decentralized process so the resulting networks may occupy an irregular area and have an irregular density.

2.6. Data Model

Nodes generate data items $m_j \in M$, $j=1,..,L$. Data item m_j has the size $s(m_j)$. Data items are small, $s(m_j) << c_{avg}$, where c_{avg} is the average node storage capacity. Data items consist of *location*, *timestamp, type* and *value*. The *value* represents a sensor reading of a given *type*, e.g., acceleration or temperature, or a message exchanged in immediate response actions, like status of a disaster victim. The *location* is the geographical position of the node generating the data and *timestamp* represents the time the data item was generated. Once written, data items do not change.

2.7. Fault Model

Disaster may damage a group of spatially correlated network nodes. We model network failures caused by a disaster as a *damage D* [Gei09]:

Damage D(*a*) simultaneously removes all nodes located in a defined geographic area *a* from the network. *D* removes nodes without warning, permanently, and they work correctly until they stop (*stop crash fault model*). The damage area is defined through its *size* and *shape* and *location* (e.g., center), which is unknown a priori. Damages of the same shape represent a damage class (Fig. 1). For example, class *fire* models the damage caused by a fire outbreak. In this dissertation we consider damages of type "fire". $D_F(c, r)$ crashes all nodes that are located in the *circle* with a maximum radius *r* and unknown center *c (x, y)*. Data items stored at crashed nodes is permanently lost.

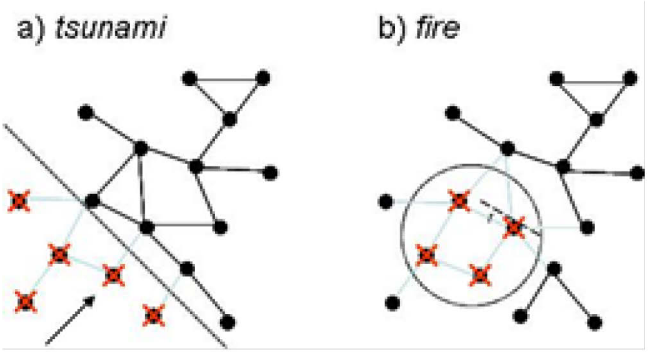

Fig. 18: Example of damage classes.

We define the *survivability* of stored data for a given set of *damages* as a fraction of data items that survive that set of damages. The survivability of data in our model is a ratio of all data items stored on not crashed nodes to the number of all data items stored in the system before a set of damages appears. Data survivability after a single damage *D, S(D)* equals:

$$S(D) = \frac{M_V - M_K}{M_V} = 1 - \frac{M_K}{M_V}$$

where M_V is the number of data items stored in the system before *D* and M_k is the number of items deleted by *D*. In a replicated system, data item *m* survives the damage, if any replica of *m* survives the damage.

We say that a system is *one-damage-tolerant* with respect to the sub-area *a*:

$$1 - DT(\ a, A)$$

if it tolerates any *damage* of sub-area *a* on a given plane of area *A*.

We say, that a *data storage* is *one-damage-tolerant* with respect to a damage $D_F(c, r)$ in a network place in the area NA:

$$\text{DS: 1-DT}(D_F(c, r), NA)$$

if $S\big(D_F(c, r)\big) = 1$, i.e., all data stored on nodes before damage D_F is still present in the system after the D_F.

2.8. Dissertation Goals

The goal of this dissertation is to find, for the fault and network models presented in Sections 2.4-2.6, *efficient*, *scalable*, *self-organized* and *fault tolerant*:

- In-network data storage system that can supply data *survivability* in presence of *damage* $D_F(c, r)$, i.e., a *one-damage-tolerant storage system*

DS: $(1 - DT(\ D_F(c, r), NA))$, and

- *Location-aware data aggregation algorithm* that is able to *count* nodes and/or values and calculate their *averages*,

where:

Efficiency means economic usage of bandwidth, energy, memory and computational effort.

Scalability means that as the number of nodes in the system grows its capacity grows, too, while communication overhead does not grow excessively.

Self-organization is understood as an algorithm's ability to function in a decentralized way and to adapt to changes to its environment, e.g, changes to the network topology, the number of active nodes and partitions, the location of the disaster (damage D) and the amount of traffic.

Chapter

3. P2P Algorithms in Wireless Networks

The networks envisioned in this dissertation consist of wireless nodes with sensing, computational, storage and communication capabilities. They operate in an unattended mode and record information about their surrounding (e.g., temperature or Earth's acceleration). As networks grow in size and the number of sensors become large, so the volume of data produced by the sensors grows. The question is, how this data shall be stored. We need a data storage system that organizes how data is allocated in the system and how it can be retrieved. Another requirement in our scenario is data replication.

The challenge for efficient and scalable algorithms in the target wireless ad-hoc networks is a strong limitation of resources, most of all bandwidth, energy, and storage. Because of inherit limited throughput and finite nodes' energy source in some scenarios, most important efficiency metric is the amount of send data. Sending occupies bandwidth and additionally drains nodes energy most of all operations (send, receive, sense, write to memory and compute).

An inseparable issue from the wireless algorithms' efficiency is their scalability with the system size. The number of wireless channels and therefore simultaneous transmissions is strongly limited. Wireless signal attenuation with distance implies that the path's length, expressed with number of hops, between a random pair of nodes grows with the network size. Therefore bandwidth and energy consumption needed for the transmission grow proportionally to the distance between nodes. Moreover, growing number of transmissions results in transmission errors and packet drops, which further reduces the available throughput. It was proven that the theoretical upper limit of the per node throughput in random static wireless ad-hoc network is

$$O\left(\frac{1}{\sqrt{n \log n}}\right) \text{ bits/sec},$$

and even in case of optimal node placement and ideal global scheduling and routing per node throughput is still asymptotically limited by

$$O\left(\frac{\mathbf{1}}{\sqrt{\boldsymbol{n}}}\right) \text{bits/sec},$$

where *n* is the number of network nodes [Gup00]. This means practically zero throughput available to every node in a WAHN, where each node transmits to a randomly chosen destination and network size is large.

This result means that either ad-hoc networks must be small enough to avoid long paths in the multihop communication, or that networks may be large, but the majority of the transmission should be localized, i.e., connect nearby localized nodes.

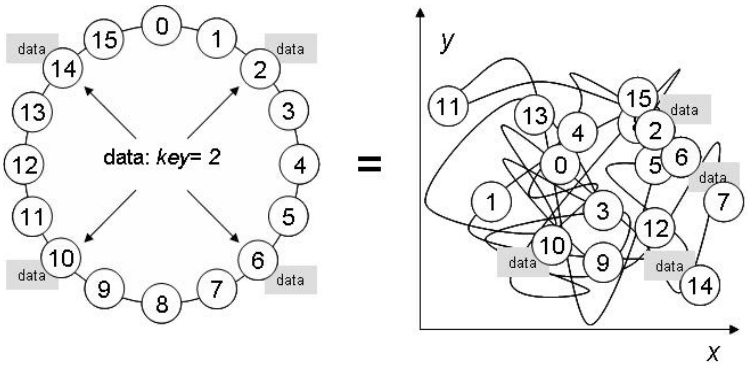

Fig. 19: Symmetric replicas of an object presented on the overlay's identifier ring (*left*) and in Cartesian coordinates (*right*) for an overlay implemented over spatially distributed nodes.

3.1. Approaches from Wired Networks

There exists a large variety of algorithms available which address issues of scalability, self-organization and fault tolerance in wired networks. However, it has been shown, that P2P algorithms designed for the wired systems are significantly less efficient w.r.t communication overhead when implemented in the wireless environment [Cra06][Ahn08][She10] what leads to problems with scalability. Also existing solutions for WAHNs do not fulfil goals of this dissertation presented in Section 2.6.

Structured P2P overlays (SONs) [Stoi01][Row01][Sch06][Roy08] solve the problems of efficient data allocation and search combined with self-organization in the presence of network dynamism (churn). SONs distribute the keys over the network nodes evenly (for instance, with usage of Distributed Hash Table, DHT) and enable logarithmic routing in the logical address space (so called 'overlay'), what results in efficient search for the data in the network [Stoi01][Row01][Sch06][Roy08]. However, in the wireless networks with short links and modeled with sparse graphs, structured algorithms suffer from so called 'underlay stretch' [Cra06][She10] which means that a single hop in the logical structure might involve a long, multihop route in the physical network. Moreover, to find a rout in the physical network, additional overhead is usually induced in dynamic ad-hoc networks. This renders the efficiency of structured algorithms, measured with the number of hops in the overlay invalid in WAHNs.

Unstructured P2P systems [Vou05][Vou07][Fah13] resign from a structured assignment of nodes responsibilities and offer instead flexibility of search (e.g., range queries) combined with robustness (measured with connectivity of an overlay) to a massive nodes failures. However, they are inefficient in wireless networks mainly because of their search mechanisms that involve network flooding, which may cause message storm problem in the wireless environment [Ahn08][She10]. Another issue is storage inefficiency as unstructured algorithms create a large number of copies (replicas) of data that may be prohibitive in resource-restricted WAHNs.

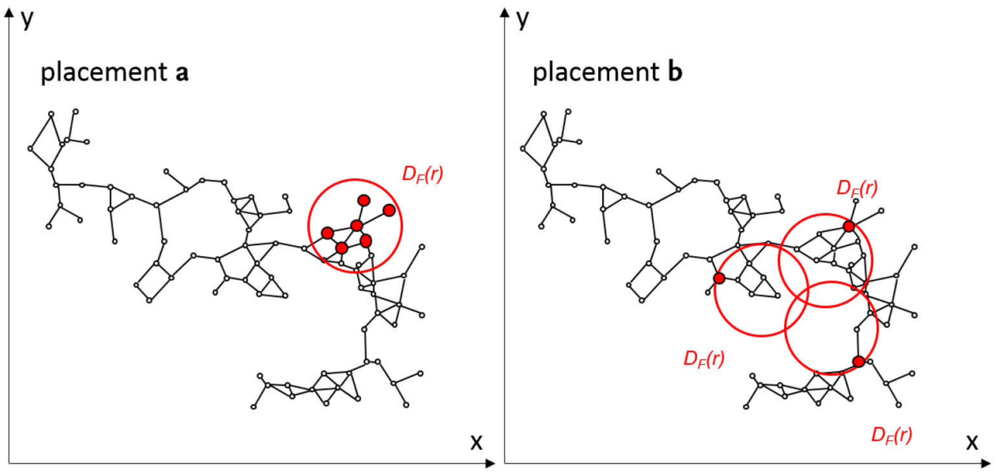

Fig. 20: An example of replica placements. Only placement ***b*** can tolerate damage of class $D_F(r)$. In this placement single damage $D_F(r)$ can destroy at most one replica.

There are approaches that exploit the location information in order to adapt existing structured P2P algorithms for the wireless environment [Zah05][Lem06]. Their goal is to place the nodes that are close in the overlay close to each other in the physical network, too. They use a cross-layer routing and combine DHT routing with physical forwarding and so effectively reduce the underlay stretch. However, these solutions divide the network in a predefined number of clusters only.

Besides efficient search for data, our target storage system is to supply data survivability in case of disaster. A known method to increase data survivability is data replication. A number of proposed systems tackle the replica placement challenge but according to our knowledge no system considers bandwidth and capacity constraints for a peer-to-peer system with a simultaneous stop-failure of a group of *spatially correlated* nodes.

Web caching [Kat04] and content delivery networks (CDN) [Dill02] replicate immutable data in distributed networks with limited storage capacity. Their focus, however, lays on minimizing the average access latency while minimizing storage costs in a client-server model. TopSen [Bro06] maintains the desired replication factor (policy) in face of nodes joins and leaves, but assumes a connected network with a good performance. Tempo [Sit06] keeps a constant replication factor at the given bandwidth budget. Structured overlay networks [Stoi01][Row01][Sch06][Roy08] deal with arrival and failure rate and incorporate different types of replication, but they are not able to guarantee the geographical distance between replicas [Gei09]. As such, they can be close to each other physically even if they are uniformly distributed in the overlay ring (Fig. 19). Also solutions that create cluster for reducing overlay stretch in SONs over WAHNs [Zah05][Lem06][Awa08] do not guarantee a physical distance between replicas, as the clusters relative positions are not controlled. Therefore, even a large number of replicas can be destroyed by single damage (see placement *a* in Fig. 20).

Our goal is however to deal with the spatially correlated node crashes and to find a replication scheme that provisions data survivability for the damage of a given radius, according to the definitions from Section 2.5. An example of replica placement that is fault-tolerant to a single damage $D_F(c,r)$, 1-DT($D_F(c,r), NA$) is in Fig. 20 (*b*). This DT is reached in this example thanks to distance between replicas, which is bigger than damage diameter.

We conclude, that in order to supply a one-damage tolerance to damage $D_F(c,r)$ with a given radius *r* and unknown location *c*(x, y), replication system must be able to explicitly define relative distance between replicas.

3.2. Data Storage

There are for the wireless networks following basic approaches for storing and retrieving data:

- Local Storage (LS). Each node stores locally its own data (e.g., environmental readings). If the user requires data, query is executed in the network and must reach all the nodes that hold it.
- External Storage (ES). All data is immediately transported to the known sink or sinks. Queries involve only external storage.
- Data-Centric Storage (DCS). Data is saved in the network, but it is spread across the network nodes using *known* rule of data allocation that depends on the data's name (type or key). Allocation rule can be chosen in such way that data keys (names) are distributed evenly across nodes, like it is in structured overlays (SONs) that use for the node assignment a uniform hashing function. Store and get operations consider given key and do not involve network flooding, but use unicast routing to designated nodes.
- Location-Centric Storage (LCS) refers to the storage of spatial data in a wireless multihop network, where each spatial data item is stored on the network node that is located closest to the geographic position specified by the spatial data item.
- Query-Centric Storage (QCS) is a dynamic on-demand storage protocol that stores data closer to the user (node) that initiated a specific query so that subsequent queries instigated by users (node) are processed with a smaller latency.

Local Storage (LS) has no cost of data dissemination, as data is simply kept locally. The querying cost are on the other hand high and use network flooding or require other kind of traversing the whole topology. Because of that, Local storage approach lacks the scalability. Finally, LS makes no copies of data and disaster (modeled as *damage*) or even a single node crash/battery exhaustion removes locally stored data from the system. **External Storage** (ES) transports all the data forehand out of the network despite if data will be needed in the future or not. Queries over external storage are then cost free. ES exhaust the sink nodes and network parts close to them when the number of events in the network is big. In that case it might exploit limited system resources faster than other approaches and for example shorten the network lifetime because of the rapid usage of the energy in the battery driven nodes. Moreover, in some use cases the predefined sink might not be present at all, but instead any node in the network might be used for injecting the queries (e.g., in disaster rescue actions recuse teams will use the first met node for injecting the queries for distress calls). ES is however not an option for target DM scenarios, because they record many events and the sink connected to the network can be missing at the data production time at all. **Data-Centric Storage** (DCS) systems allow to load balance the limited resources (storage and bandwidth) across network nodes and because data location is known (based on its name or key) the dissemination and querying for data is efficient and does not use flooding, prolonging by this the network life time. DSC systems can be disconnect from the sink – it does not have to be defined a priori, and every node can be used as a temporary sink and be use to query the network. Moreover, DCSs take care of a data persistence through data replication. In the **Location-Centric Storage** (LCS) scheme spatially tagged data is stored in the network multiply times in a predefined geographical hierarchy and at locations related to the location of the event. For example, event records are stored in a concentric circles with gradually larger radii, around the sensor where the event was originated [Xing05]. The intensity value of data (σ), determines the geographical propagation of the event record. This approach is a good choice for the mobile ad-hoc networks [Dud09], however in the static ad-hoc networks may cause a poor load balance; some locations will be never used for storing data or as replica nodes, because of the characteristic of data production by nodes and used geographical hierarchy. For comparison, DCS spreads each kind of data equally across the network with the quality of the hashing function. **Query-Centric Storage** (QCS) optimizes the storage of data so it's positioned closer to the requesting user so it depends on the information coming from the request stream [Papadi09]. Obviously, this approach cannot be profitable in the sensor networks before queries are issued. Approach depends also on the assumption that once a node was used for the injecting a specific query into the network, the same node will be used for a similar query again, what can but must not be the rule in a P2P system. On the contrary, different users may issue similar queries although they are spatially dispersed. Also, usage of this scheme in a wireless peer-to-peer application, when the time between data gathering and harvesting may be distant, is questionable.

We conclude that the scalable approach for target DM scenarios is **data-centric storage** (DSC) [Rat03], because it load–balances resource usage, is efficient with respect to communication (no flooding), makes no assumptions about the data patterns/sink location. Moreover, the existing DSC systems for WAHNs use a motion of geographical location and store data at geographical locations instead of concrete nodes. Therefore replication scheme of such system could be implemented in such way that it supports target fault-tolerance to a disaster 1-DT($D_F(c,r), NA$).

3.3. Communication

Communication is the basic functionality of any telecommunication network. It is also necessary in any data storage system whose efficiency and scalability in WAHN depends on the communication performance. Depending on data destination, traditionally broadcast (one-to-many), multicast (one-to-many) and unicast (one-to-one) logical communication types are distinguished.

In wireless networks we distinguish two kinds of a broadcast: a network-wide broadcast, called *flooding*, that disseminates data to all network nodes, and a local broadcast (shortly *broadcast*) which sends data to all sender's direct neighbors[39]. Realization of the network-wide broadcast in the wireless networks is a well-known optimization problem. Broadcast protocols instruct nodes how to rely messages to choose and good tradeoff between reliability of message delivery and the induced message overhead (redundant messages). Network-wide broadcast should be avoided by any efficient and scalable application, as it may result with so called *message storm problem* leading to message reliability deterioration that can block the proper functioning of the whole network or its part. However, some applications may still need it. For instance, an alarm in early warning systems could be disseminated with an appropriately designed network-wide broadcast, what is a separate topic not addressed in this work. In this dissertation we do not focus on the efficient network-wide broadcast.

Local broadcast on the other hand should be exploited by wireless applications, as it uses the bandwidth and nodes energy most efficiently. The group of protocols that are broadcast based are gossiping protocols. Wireless protocols developed for this dissertation are use local broadcast only.

Multicast is also one to many communication and can be realized as a broadcast in the wireless medium, with the difference that only designated nodes process the message. Protocols proposed in this work do not require multicast.

A unicast message must reach a specified receiver. Unicast is solved efficiently in the wired TCP/IP networks, where route of a packet follows the hierarchical structure of the IP address. Practical absence of packet congestion, significant throughput of the links and stability of the network topology allows the use of stable routing tables that make unicast communication in wired networks fast.

In the wireless networks however the packet forwarding for the unicast communication is not trivial. Protocols must deal with the typical limitations of the wireless networks, which include high power consumption during the radio communication, low bandwidth, and high error rates. Consequently, routing protocols should on one hand use as little messages as possible, i.e., choose shorter paths between sender and receiver, avoid packets to unreachable destinations and avoid network flooding, but also tolerate the packet losses. There are two main levels where the optimization can take place: 1) at the physical level including the radio scheduling responsible for effective communication between the nodes in the contention zone and 2) at the logical level or finding a communication path between source and receiver of data packet which is the task executed by a routing protocol.

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[39] Nodes that are connected with sender with a single link.

Last possibility is a crossed-layer solution that connects issues from above categories for the improved results[40].

There are two types of unicast routing protocols in wireless networks: topology based and position based (geographical). As we explain below, only the position based (geographical) approaches scale with the system size.

3.3.1. Topology-based Routing

Topology based protocols [Per94][Per99][Cla01][Joh01] make the decisions on the next hop of the data packet based on the node's position in the network topology. Among topology based approaches there are two groups of protocols: *proactive* (table-based), that build the paths in advance and *reactive* (source-initiated), that find the paths ad-hoc, at the time of data request.

Proactive routing protocols attempt to maintain a consistent, up-to-date routing information from each node to every other node in the network. These protocols require each node to maintain one or more tables to store routing information, and they respond to changes in network topology by propagating route updates throughout the network to maintain a consistent network view. The areas where protocols differ are the number of necessary routing-related tables and the methods by which changes in network structure are broadcast. Examples are Destination Sequenced Distance Vector (DSDV) protocol [Per94], based on the classical distributed Bellman-Ford routing algorithm, Wireless Routing Protocol (WRP), Cluster Switch Gateway Routing (CSGR) and Optimized Link State Routing (OLSR) [Cla01] which gained most attention and today is used in the roof nets all over the word.

Reactive routing protocols create routes only when desired by the source node, what avoids topology discovery to the nodes that never receive messages, but creates a significant delay during the route initialization. When a node requires a route to a destination, it initiates a *route discovery process* within the network. This process is completed once a route is found or all possible route permutations have been examined. Once a route has been discovered and established, it is maintained by some form of route maintenance procedure until either the destination becomes inaccessible or the route is no longer desired. Among established reactive protocols Dynamic Source Routing (DSR) [Joh01] and Ad-hoc On-Demand Distance Vector (AODV) [Per99] are best known.

The problem with the topology based routing is the number of messages they use for scouting the network topology and refreshing it. Topological protocols gain information by the network-wide broadcast. They flood the network with the discovery messages in order to build nodes' view on the network (e.g., reactive protocols use flooding for the route discovery, proactive for updating link changes or building the shortest path). In a consequence, topology routing does not scale with the network size.

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[40] An example of a crossed-layer solution is also described later Greedy Perimeter Stateless Routing (GPSR) Protocol [Kar00].

3.3.2. Position-based Routing

An alternative to the topology based protocols are geographical routing protocols (position-based, georouting). Geographical routing is scalable, i.e., it indices communication overhead that is proportional to the distance between nodes only and not to the network size.

Geographical routing protocols can be used only in the location-aware networks, i.e., where each node knows its own geographical position. This requirement is reasonable in many, including presented, disaster management scenarios, because environmental data collected by sensors usually is useful only when accompanied by the geographical position of the recording node.

Geographic routing is a routing scheme that determines the path from the source to the **geographic location** of the destination instead of destination's **network address**. Geographic routing exploits the fact, that in the wireless networks with short links the number of hops between two nodes is generally roughly proportional to the distance between them. It means that the closer a pair of nodes geographically is the less hops has a shortest path between them, and if the distance between them is small enough (smaller or equal transmission range), there is a single, direct link between them (with a high probability). Based on this insight geographic routing aims to constantly reduce the Cartesian distance between transported messages to their destinations at every hop. Messages are forwarded without any prior route discovery and routing tables, whose acquisition and maintenance in inherently dynamic ad-hoc networks involves additional message transmissions that consume limited energy and bandwidth.

Geographic routing can be on the other hand implemented only in a location-aware network. GPS and other satellite based navigation systems and location estimation techniques advanced rapidly and position information can be made available to even small devices. An alternative to geolocation is that nodes know their position in a virtual coordination system [Car05] that describes their relative locations. However, calculation of coordinates in such virtual system incurs additional communication overhead.

Georouting is a **scalable protocol**. It is the only type of routing that fully evades network flooding used at some point by all other routing mechanisms. Instead, the next hop is always chosen locally at every node on the message's way from the source to the destination. Georouting requires only local position information: nodes own location and locations of its direct neighbors[41].

However, because the position-based routing works without the global knowledge, the protocol is not hop-count optimal and produces routes longer than the shortest paths. In spite of it, protocol's efficiency combined with the easiness of implementing locality awareness nowadays in the wireless networks makes

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[41] This set can change. It is normal in wireless networks, that a node, if it is not sending packets within a specified time period, must send a HELLO message to ensure proper connectivity information in the network.

georouting attention-grabbing and most importantly – scalable alternative to the topological routing mechanisms.

3.4. Geographic Routing

For the first time the method of choosing forwarding neighbor locally based on nodes locations were made in late eighties in the working groups of the legendary Leonard Kleinrock. In these first works location based routing was used nearby to the main goal of their research which was to find an optimal radio transmission range of nodes and resulting network density that allowed for an efficient communication (tradeoff between connectivity and congestion) [Nel83][Tak84]. The first explicit position-based routing algorithm was proposed in 1987 [Fin87]. The algorithm was thought for the wired Internetworks, and its goal was to *"eliminate (*routing*) algorithms which rely upon large routing tables or substantial amounts of computation per packet."* As the history shows, the geographical routing idea did not become a standard in the wired networks, but was further developed for the wireless multihop networks, especially ad-hoc, MANET and sensor networks.

At the beginning the geographic routing protocols were simple *greedy forwarding* schemes that did not guarantee packet delivery in a connected network: in graphs with the average density of four delivery rates were as low as 50% [Fin87][Lin98]. In some cases, although the nodes were connected, greedy scheme does not progress.

In 1999 greedy routing was complemented by the *recovery routing* mechanism able to overcome voids[42], i.e., network parts that prevented the progress of a greedy routing. Proposed solutions include a local planarization methods of the underlying communication graph executed with local neighborhood information only) [Kra99][43][Bos99][44] [Kar00][45]. Since then, a number other void handling methods that do not require graph planarization was proposed [Che07][Kul13]. Resulting up-to-date georouting protocols are able to rout to any connected destination (e.g., GPSR [Kar00]).

A group of other works regard optimization of choosing a next hop in a greedy forwarding. Further metrics were proposed instead of the original hop-count: used power, available throughput, latency or a combination of above [Stoj01][Yeh01] [Hua04][Ham09]. Most recent works concern special topics like quality of service of the geographical routing for the media transmissions in WSN [Li12], robustness of the protocol in the presence of high nodes mobility [Xia12][Gha15], beaconless georouting in energy harvested sensor networks with duty cycles [Jum13] or georouting in the delay-tolerant networks [Sid13]. An exhaustive survey about state-of-the-art georouting protocols for ad-hoc networks is in [Pop12].

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[42] We explain voids in detail later in that section.

[43] Compass Routing II.

[44] Greedy-Face Greedy Routing, GFG.

[45] Greedy Perimeter Stateless Routing, GPSR.

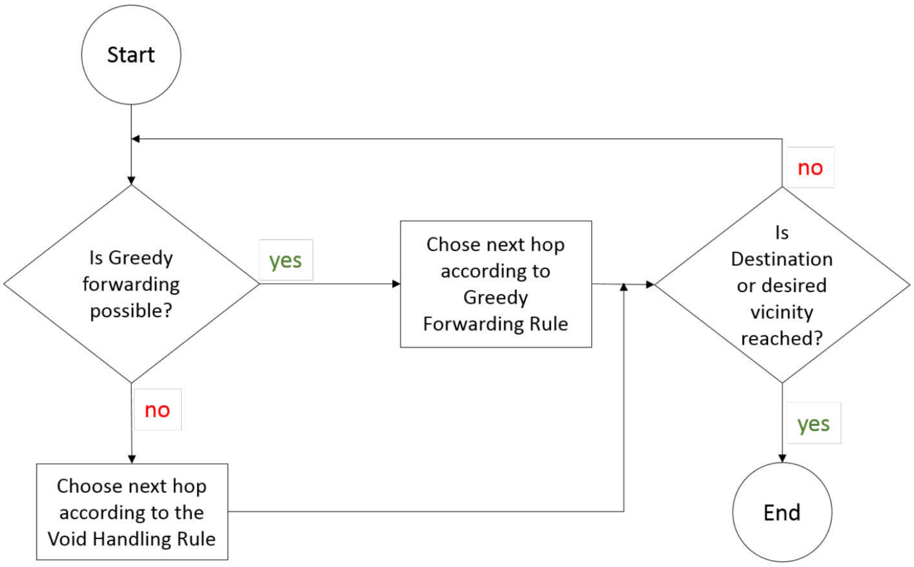

Fig. 21: Generic algorithm of a geographic routing protocol with void handling.

Each current geographic routing protocol with a guaranteed delivery (like GPSR [Kar00]) functions in two modes: when it is possible, the *greedy routing* for choosing the next hop is used. In the situation when a void is met (or so called local minimum) and the greedy routing cannot proceed, the recovery strategy is used (see Fig. 21).

3.4.1. Greedy Routing Algorithm

The idea of the greedy routing is that each nodes that currently holds the data packet forwards the packet to its direct neighbor that is geographically closer to the destination then the node itself. Therefore, under the general assumptions, that:

Assumptions of a Geographic Routing Protocol:

- All nodes know their location, and
- Each node knows locations of its direct neighbors, and
- That the location of the destination D is known

a node choses the next hop in the greedy mode by:

Forwarding Rule of a Greedy Routing is:

- Forwarding a packet to a neighbor B that is closer to D than the node itself.

The choice of the forwarding neighbor may vary, depending on the optimization goal [Che09]. Metrics like link quality46 (for throughput optimization), maximum geographic progress towards destination (for hop count optimization) or a length of

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[46] Information about link quality come from the physical layer and resulting protocols are a crossed layer approaches, like for example GPSR [Kar00].

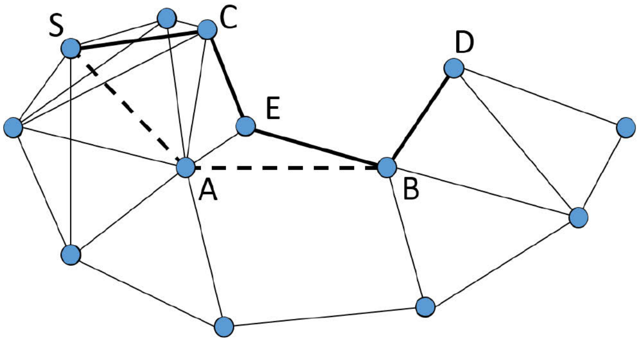

Fig. 22: Greedy routing. Source S forwards to C, node C to E, E to B and B to the destination D (thick line). For comparison, shortest path is SABD (dotted line).

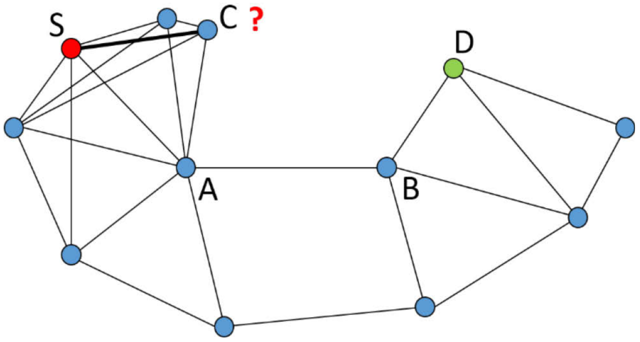

Fig. 23: Network from Fig. 1 with removed node E. Greedy routing from S to D fails at node C that is a local minimum with respect to D.

a whole path (for energy optimization) might be taken into account [Stoj01][Yeh01][Hua04][Ham09]. In any case the next hop in the greedy forwarding must reduce the geographical distance to the destination.

The forwarding is started by the source node *S* and repeated by every forwarding node until the destination *D* is reached, or a distance to the destination is below some application threshold. The later termination rule is typical for sensor networks and is also reasonable because of the imprecision of the used positioning systems.

Possible Termination Rules of a Greedy Routing Protocol:

- (greedy success) Destination *D* is reached (or distance to *D* is ≤ *threshold*)
- (greedy failure) Void (local minimum) is reached.

Although in some cases greedy routing successfully finds the connected destination (see Fig. 22), it may end up in a deadlock and fail to route to a connected destination when a local minimum is reached. *Local minima* (or voids) exist at the border of void regions and are regarded with respect to the given destination. These are nodes that have no neighbor closer to the destination than itself. For example, node *C* in Fig. 23 is a local minimum with respect to the node *D*. When message arrives to node *C*, the greedy routing cannot progress any more, as *C* has no neighbor that is closer to the destination then *C* itself.

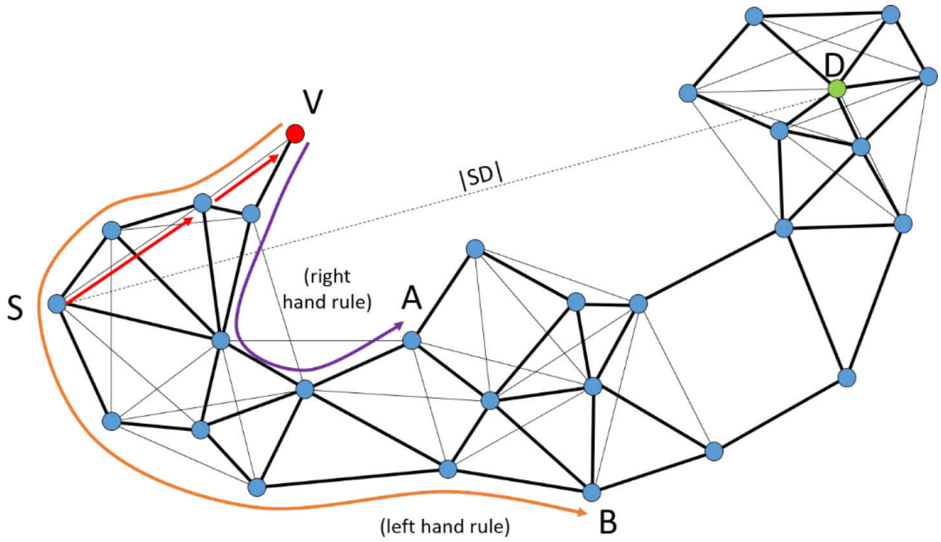

Fig. 24: Void handling based on planar graph traversal. On the route from S to D node V is met by the greedy forwarding. V is a void with respect to destination D and it initiates face routing towards D. In face routing only planar graph is taken into account (bold links). Left- or right-hand rule is possible. Face routing is executed till a node closer to D then node V is met (node A for right-hand or node B for the left-hand rule).

3.4.2. Void handling

When the greedy forwarding mode fails to forward a packet due to the presence of a void the *void forwarding* is initiated. The goal of the void forwarding is to overcome a local minimum and bring the messages to the destination or to the point, where greedy routing is possible again.

There are several void handling methods: planar graph traversal-based, topology based[47], link-reverse-based, geometric, heuristic, and hybrid. They may guarantee a delivery or not, produce an optimal path during the void handling or traverse loops, they also vary with the size of the introduced message overhead and state needed at the void handling nodes [Che07].

The most representative and fully localized void handling methods used in the established geographic routing protocols like GPRS [Kar00] and GFG [Bos99] are based on planar graph traversing and are known under simple term *face routing*. *Face routing* is based on well-known solution for finding a way out of a simple-connected maze[48]: the rule is, that if in a simply-connected maze we will keep a right hand in touch of the wall while walking we will finally find the exit[49]. Applying the right-hand (or left-hand) rule to network communication graph means to find a successor node in clockwise (or counterclockwise) order after the predecessor.

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[47] If a topological void handling is used, resulting protocol is not pure geographic routing protocol any more.

[48] A simply-connected maze is a maze with all walls connected together or to the maze's outer boundary. In other words, in simple-connected maze there are no detached walls.

[49] Alternatively, we can do the same with a left hand what results with traversing the maze in the counter-clock wise instead of clock wise direction.

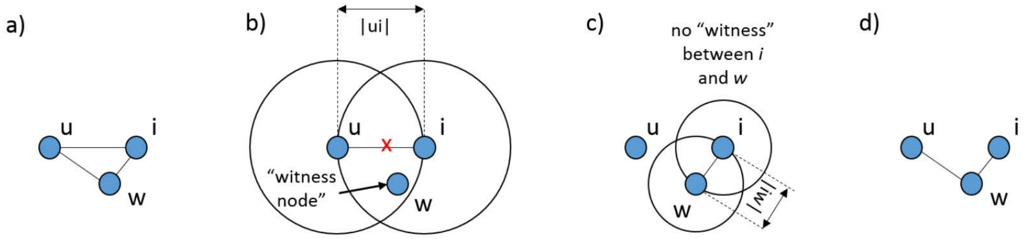

Fig. 25(a) The input communication graph. (b) Node i has to remove link to node u from its RNG graph because of the witness node w that is placed in the intersection of the discs (u, |ui|) and (i, |ui|). (c) Node w belongs to i's RNG. In (d) we see resulting RNG graph of (a).

In the face routing method packets are forwarded by the *left*- or the *right-hand rule* along a sequence of faces of the planar network communication graph till they reach a non-convex node that is closer to the destination that the initiator of the face routing and where a greedy forwarding can be resumed (see Fig. 24). Faces are regions of a plain bounded by edges of a planar graph, including the outer, infinitely large region, that are not crossed by any other edge. Routing along a face means that the nodes of a face (lying on its boundary, nodes that have defined given face) pass the packet along the incident edges by locally applying the left-hand or right-hand rule.

Face routing void handling defines which faces shall be traversed. For this, a line connecting a location *S* of a source with the location *D* of a destination is computed. Traversing will start from this face adjacent to the starting local minimum, which is crossed by the *SD* line and has an edge closest to *D* and continue on other faces crossed by |*SD*| in the direction of source. Additionally, in Face Routing II in Greedy-Face-Greedy protocol and in the Perimeter Routing in GPRS protocol, not the whole faces, but only their parts lying under (or above) an |*SD*| line must be traversed in order to progress (in the first face routing algorithms the whole faces were traversed).

For a successful application of this graph traversal rule the underlying graph has to be planar. Required planarization of the graphs, usually to the Relative Neighborhood Graph (RNG) [Tou80] or to the Gabriel Graph (GG) [Gab69] is easily done locally, without additional message exchange and relies on the UDG model [Fre06][Leo06]. Planarization of the graph results with disregarding by nodes some of their links, and considering in the process of finding and traversing faces only this links that belong to the locally computed planar sub graphs of the original network graph. An example of a local planarization can be seen in Fig. 25. A node *i* removes its link to node *u*, because in the intersection of the circles with diameter |*iu*| centered by connected nodes *i* and *u* there is another node (*w*). The same operation results in leaving the link to node *w* in the set of links in the RNG graph of the node *i*.

A proper overview of greedy and void-handling techniques, along with characterization of resulting geographic protocols for wireless ad-hoc networks is available in [Che09].

Regardless to the chosen greedy forwarding scheme and a void handling rule, a geographic routing protocol can be described as follows:

Geographic Routing Protocol

- All nodes know their location and location of their direct neighbors
- Source located at S has message to the destination located at D
- If the greedy forwarding is possible, the current node choses the next hop according to the Greedy Forwarding Rule
- Forwarding is continued till destination (or its defined vicinity) is met
- If the void is met, next hop is chosen according to the void handling method, till destination is met or the till the greedy forwarding is possible again.
- Algorithm terminates, when the destination (or its desired vicinity) is reached or when it can no longer make progress, i.e., it visits the same face twice.

In GPSR [Kar00], the void handling method is based on the efficient planar graph traversal (only parts of faces are traversed) and is called *perimeter routing*. Additionally, GPSR routs all packets addressed for an arbitrary location (unoccupied by a node) consistently to the same node, located closest to that location (this feature is exploited by the data –centric storage systems like GHT [Rat02] and based thereon, see Section 3.5).

3.4.3. Conclusions and Open Issue

We conclude, that georouting protocol GPSR [Kar00] scales with respect to the network size in WAHNs, requires no memory about past traffic nor network topology and guarantees packet delivery to the connected location.

We notice that GPSR (and other geographical routing protocols) rely fully on the accuracy of the information subsystem and assume that the source knows the correct geographical position of the destination. However, in the real word applications, the given location might be not present in the network, due to the changes in the network membership (e.g., node removals or crashes due to a disaster, network partitioning). Also, the destination coordinates might be received incorrectly due to transmission errors or node’s malfunctioning or changed by purpose due to a security attacks. In such case the message designated for the given address will traverse potentially the whole (possibly large) network before packet will be recognized as unreachable and finally dropped. This results in an unnecessary consumption of the limited wireless resources.

With the knowledge about the geographical span of the network (“*network area*”) georouting protocol could locally drop packets designated to inaccessible destinations and thus would increase efficiency, i.e., save resources, especially bandwidth and nodes energy. Issue of gaining and disseminating the knowledge about network area is addressed by the PANA protocol in Chapter 4.

3.5. Geographic Hash Table

The key concept in the data centric approaches is that the data of interest is not the data coming from the concrete node with a concrete ID or network address (comparable to the file name in a file system), but it is the data connected with a system-wide known label: e.g., temperature or humidity in forest surveillance applications, or ‘seen elephants’ or ‘white tigers’ in an animal tracking system. These labels are then used as the keys for both inserting and searching data. In DSC for WNs it is also recommended and efficient to let the nodes to process the raw data forehand and prepare the network to be ready for retrieval of the relevant information. Such proactive aggregation shortens subsequent queries and spreads the communication load over time, increasing overall throughput. For example, occurrence of seeing withe tigers can be counted and only the result of such aggregation would be stored. For example, if counting of white tiger population is an application’s goal, the key-value pair (‘seen white tigers’, 6) for a six detected white tigers would be stored. There is a number of research on the in-network data aggregation [Dim06][Mak09][Gei12], and they can be usually composed with DCS system.

DCS systems designed for the wireless networks, unlike their wired counterparts, assume networks’ locality awareness, i.e., they assume that each network node know its geographical position. To achieve this, all nodes have their own Global Positioning System modules or only a proportion of them, while others have to calculate their positions based on the position of the so-called 'anchor points', the nodes knowing their position with some minimum accuracy, with some triangulation technique [Liu10][Zek11]. Locality awareness allows to use in wireless DCS systems scalable georouting protocols for the data dissemination and acquisition. Second idea is to spread the data equally among the network nodes, when the hashing function spreads the data tuples uniformly over the geographical area covered by the network.

This two concepts, data labeling and locality awareness of nodes, let the researchers to design the native DCS systems for wireless networks [Rat02][Ara05]. Thanks to the locality awareness they avoid the problems with porting the existing P2P wired solutions to wireless networks [Zah05][Lem06][Wir12]. It has been shown in [Rat02][Rat03][Gho03][Zha03] that location-based DCS can reduce network traffic and lower energy consumption for sensor nodes.

3.5.1. Data Allocation

The earliest data-centric storage system for the wireless networks and the groundwork for the following GHT-DCSs (e.g., CHT [Ara05] or Dynamic GHT [Tha06]) is the Geographic Hash Table [Rat02]. GHT is a Hash Table designed for the locality aware wireless networks and for the data dissemination and retrieval GHT uses the

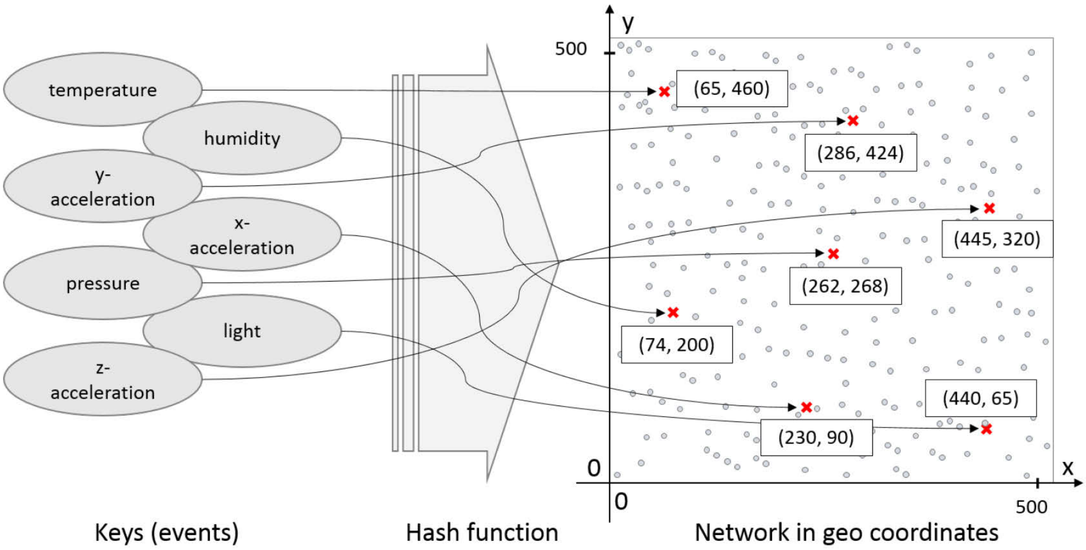

Fig. 26: GHT uses a hash function to map a keys (data names) to a geographic positions attempting to distribute data uniformly across the network.

GPSR protocol [Kar00]. GHT is a structured overlay systems and it offers all nodes the following well-known interface:

- **put** (*key*, *value*) for storing a key-value pair and
- **get** (*key*) for retrieving it.

In GHT events are assigned and stored on the specific nodes in the network, and this assignment is a result of a computation based on event name and can be done by each node in the network. Similarly like in wired overlays, this computation is done with usage of a hashing function. But, instead of hashing keys into a number or string (like in Chord [Stoi01] or Pastry [Row01]) that is put in some predefined hierarchy (e.g., ring for Chord) the GHT hashes keys into *geographic coordinates*, and stores a key-value pairs at the sensor node *geographically nearest* the hash of its key (see Fig. 26). For this transformation, GHT assumes that a *coarse network shape* is given in order to pick locations populated by nodes. Hash function spreads then the different key names evenly across the geographic region where the network is deployed.

GHT uses a uniform hashing function independently of the real distribution of sensors. This can lead to unbalanced networks. In [Alb09] an approach for hashing according to the given density function is proposed. In this approach, during hashing procedure before hashing the keys are extended with the consecutive natural numbers as long as the hashed value falls in the area with the required density (strategy similar to the *rejection method* [Neu51]). However, also this approach assumes that the geographical range where the keys are being hashed into is known.

Hashing function, as can be seen in Fig. 26, returns a location that belongs to the populated area but does not represent a concrete node. A tuple with a given key is stored at the *home node* of that key which is the node closest to the geographical location indicated by the hash function of a *key*. Home node for given key is unambiguously found by GPRS routing to the location hash(*key*). For example, when storing the tuple (“temperature”, 68) GHT will calculate the hash function of the label “temperature” and route the data packet to the calculated coordinates. Because a GHT packet is not addressed to a specific node, but only to a specific geographical location, it is treated by GPSR as a packet bound for a disconnected destination: no receiver ever sees the packet addressed to its own identifier. In such case, according to the specification of GPSR, packet enters the perimeter routing mode at the node geographically closest to this destination. During the void handling the packet traverses the entire perimeter that encloses the destination, and when it comes back to the node where the perimeter routing started[50] it is discarded. At this point the closest node to the desired destination is found: it is the node where the last perimeter routing was initiated and the packet was discarded. The home node of a given key stores in its memory all key-value pairs with a given key (see Fig. 27).

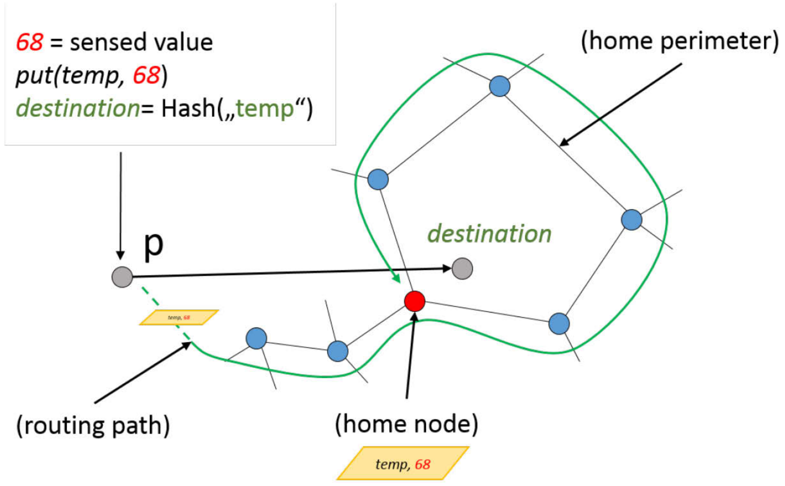

Fig. 27: Routing in GHT. A key-value pair is stored on node closest to the location computed by hashing the key.

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[50] This condition is detectable because GPSR writes the identity of the first edge a packet takes on a perimeter routing into the packet.

3.5.2. Replication

GHT uses local and structured replication (SR). Local replication is used as a persistent measure for increasing data survivability, while SR is used for reaching scalability.

3.5.2.1. Local Replication

Perimeter replication stores copies locally and ensures persistence when nodes fail. Copies of the key-value pairs are created on all perimeter nodes of the home node of a given key (creating the home perimeter, see Fig. 27). Request for the given key is served then by the home node or any replica, if it is met first on the request route (see Fig. 28). GHT uses an efficient consistency protocol for creating this replicas and to ensure that key-value pairs are stored at the appropriate nodes after topological changes - the perimeter refresh protocol (PRP).

PRP distinguishes between the home node and other nodes on the home perimeter, the *replica nodes*. PRP generates refresh packets periodically using a simple timer scheme. Every T_h seconds, the home node for a key generates a refresh packet addressed to the hashed location of that key. The refresh contains the data stored for that key, and is routed just like *get*() and *put*() packets in GHT are. As a result, the refresh packet will take a tour of the current home perimeter for that key, regardless of changes in the network topology since that key's insertion. When a refresh packet arrives at a node, there are two possibilities: either the receiver is closer to the destination than the originator, in which case the receiver consumes the refresh packet and initiates its own; or the receiver is not, in which case it forwards the refresh packet in perimeter mode. In both cases, the receiver appends any additional key-value pairs it has stored for that key to the refresh packet. When a refresh packet returns to its originator, and that node was not previously the home node for that key, it consumes the refresh packet, and becomes the home node for that key. That is, the new home node sets its own refresh timer, and subsequently originates refreshes for that key. This mechanism provides the consistency: it ensures that the node closest to a key's hash location will become the home node for that key and store that key's data after topological changes. On the other hand, when a node that store replicas for a key receives no refresh packets within a given death threshold *(*T_d*)*, also not the ones it initiates, it realizes it does not belong to the perimeter of a given key any longer and it may evict the data from its memory. The PRP includes also a join procedure, which improves performance on dynamic topologies. When a node senses a new neighbor, it sends this neighbor all event entries from its local database for which the new neighbor is closer than the node itself. In general, PRP typically generates very local network traffic. On dense networks, perimeters are quite short (most perimeters in a dense network are three hops in length). When a home or perimeter node moves or fails, the refresh communication it generates won't have far to travel before reaching the new home node / detecting the new home perimeter.

Local replication increases the survivability (presence in the system after fault) and availability of data (understood as data instance reachability), but does not solve the problem of the spatially correlated node failures. Also, because GHT stores all events with the same key in the same place, hot spots may appear in case when data volume stored under the same key becomes big.

3.5.2.2. Structured Replication

GHT employs structured replication (SR) to address this scaling problem. SR distributes data throughout the network using a geographic hierarchy: locations of keys are supplemented with a hierarchy depth and they decompose the key space into quasi-equal areas[51], what recalls the partitioning approach of GLS [Li00].

For a given root *r*, which is the original location of a key (*r=hash(key)*), and a given hierarchy depth *d*, one can compute 4^d-1 mirror images of *r* over the key space by modifying the values of *r*'s coordinates as showed in Fig. 29. In total 4^d places for storing tuples with a given key are in the system. The depth of the hierarchy *d* can be different for different event types.

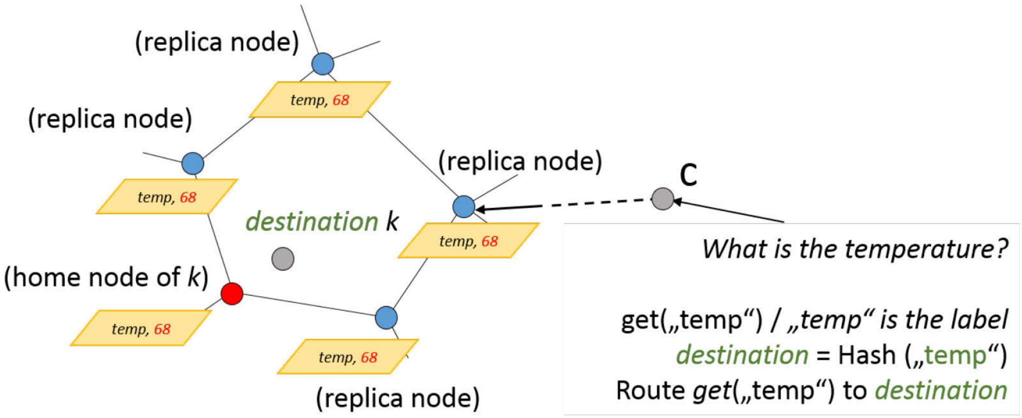

Fig. 28 Example of retrieving the data in GHT. Node C will become the data tuple from the first-met replica node. Replicas are stored on all perimeter nodes of the home node for the given key.

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[51] Equal *iif* the key space represents exactly the geographical area covered by the network and this area is symmetric and can be divided into sections of same size with the given space dividing approach.

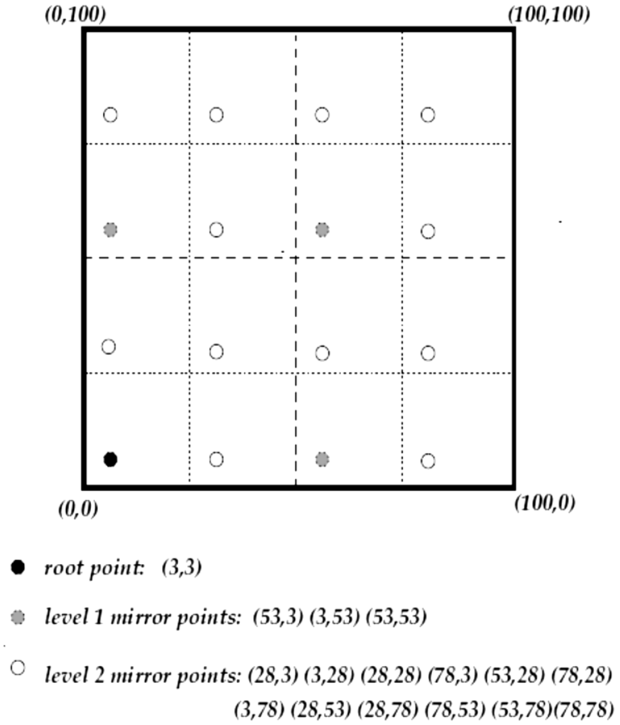

Fig. 29: Example of structured replication (SR) in GHT with a 2- level decomposition (Fig. taken from [Ratna02]).

With structured replication a node that detects an event stores it at the site (called *mirror*) closest to its location, which is easily computable. SR reduces the storage cost at one node for one key by the factor 2^d and by the same factor lowers the communication overhead connected with routing to the storing node. The disadvantage is the query processing: GHT must route queries to all nodes responsible for the key. It does so recursively. First it routes a query to the root node, then from the root node to the three level-one mirror points, and each of these forwards the query to the three level-two mirror points associated with them, and so on depending on *d*. This recursive process continues until all mirrors are reached. The total cost of queries increases then by factor 2^d, when comparing to GHT without structured replication. Responses traverse the same path as queries but in the reverse direction—up the hierarchy toward the root. As we see, SR reduces the cost of storage (both in the mean of memory and communication connected with putting data into system), but does not solve the problem of communicational hot-spot during data retrieval. SR offers an intermediate solution between the local storage canonical method, where storage is free but queries expensive, and GHT without SR, where both are of moderate cost and is well suited to the systems with more detected events and less frequent data retrieval.

3.5.3. Follow-Up Systems

Based on the GHT [Rat03], another DCS systems for ad-hoc networks were proposed. For example, the Resilient-DCS (R-DCS) proposes a distributed zone replication scheme [Gho03]. Network is partitioned in defined number of zones, and keys are replicated and synchronized between different zones what provides resilience to both clustered and isolated node failures. Since queries need to be routed to the closets replica node for an event type, overall query traffic is reduced. R-DCS improves energy efficiency in the larger networks with big number of detected events and it suits very well to the target scenarios of this dissertation.

In [Tam04] the usage of multiply hash functions in GHT is proposed. Keys are stored at multiply locations, indicated by different hashing functions, what increases data availability in case of nodes failures.

Another approach that increases resilience is the Cell Hash Routing proposed in [Ara05] designed for dense networks. Network is divided in small cells, up to $R/\sqrt{8}$ in size. The scalability relies on the assumption that in each of these small cells are at least several nodes. GPSR routing is done over those logical cells, without the need for the graph planarization in the perimeter routing. However, the high density assumption makes this approach little usable in some ad-hoc networks.

For the improvement of the load balance and overall system efficiency, the Dynamic Geographic Hash Table, D-GHT [Tha06] was proposed. While traditional DCS systems use a static hash function for mapping the data names into geographic coordinates, D-GHT uses a well-known temporal function. Static hashing results in a static set of nodes serving the network throughout its lifetime. It may cause 1) unbalanced resource utilization connected with uneven spreading of data across the network and with the unfair resource usage (some nodes are drained faster) and 2) the problems connected with network dynamics such as new sensor deployments or runtime sensor failures. D-GHT deals with these issues by using 1) a temporal-based geographic hash table for achieving overall load balancing among nodes over time (different nodes are chosen as host for the same data name over time) and 2) by fine tuning of the home node for the data, based on so called node contribution potential, connected with its resources. This local selection process results in slightly extended paths lengths but also with the extending the network life time. In order to use the time interval hashing, the interface of this DCS is extended by the time interval ΔT.

3.5.4. Conclusions and Open Issue

A geographic based data-centric storage for the wireless networks (GHT-DCS), like GHT or CHT uses data typing, and maps data according to its type to the geographic locations. Also, GHT-DCS use a geographic routing (in the presented algorithms GPSR [Kar00]) for data dissemination and retrieval. Because the location of data is known, and the routing protocol is position based, GHTs avoid network flooding at all times, what reduces network traffic and lower energy consumption in many scenarios. With respect to communication overhead these data stores scale in WAHNs.

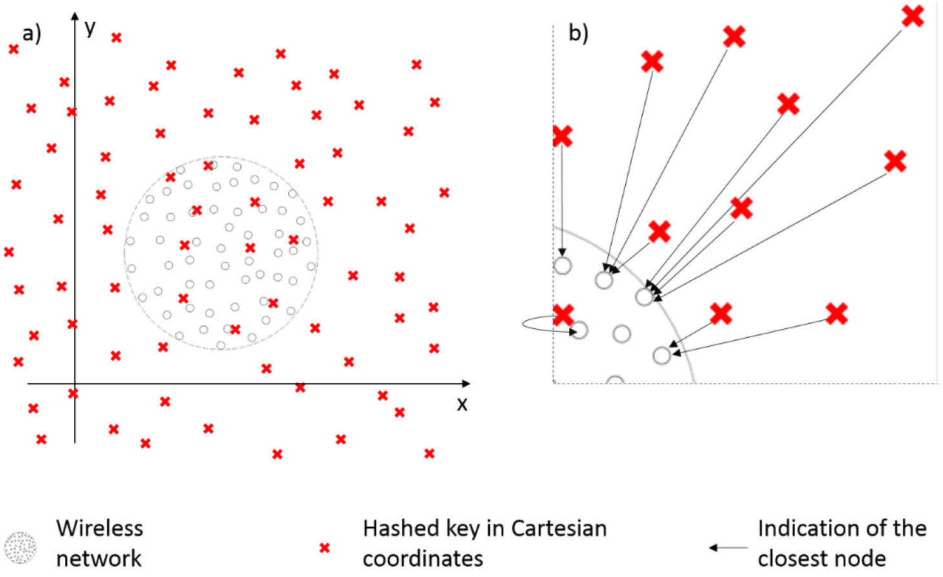

Fig. 30: Example of geographic hashing without information about network boundary (a). In (b) examples of the home node assignment.

All referenced GHT systems assume that an *approximate geographic boundaries* of the network is known to the network operators. This knowledge is used for the mapping of the keys into the geographical space where the nodes are deployed. However, as stated by the authors of GHT [Rat02] it is possible to use GHT without this information. In such case, keys are hashed in coordinates that may lie outside of the network (Fig. 30-a). These locations from outside of the network find as their home nodes (using the GPSR protocol) the nodes geographically closest to them (see Fig. 30-b).

This procedure leads to the strong load unbalance in case of the unknown network shape - all keys (i.e. all events of a given types) that lie outside of the network are stored only on the network boundary nodes[52] (see Fig. 31). Thus, without the information about approximate network boundaries (i.e., network area), the goals undertaken by the GHT design are not fulfilled.

Although it is easy to set the network area in the simulator, in the real-life wireless ad-hoc networks this information is usually unknown, and must be gained in the system during its runtime. Lack of the information on the coarse network shape prohibits the efficient usage of the introduced systems in the real wireless ad-hoc networks. PANA (Polygon Approximation of the Network Area) protocol [Geibig13], designed for this dissertation answers this shortage by constructing and delivering the information about network shape to all network nodes (see Chapter 4).

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[52] Most loaded will be subset of boundary nodes belonging to the convex hull of the set of all network nodes.

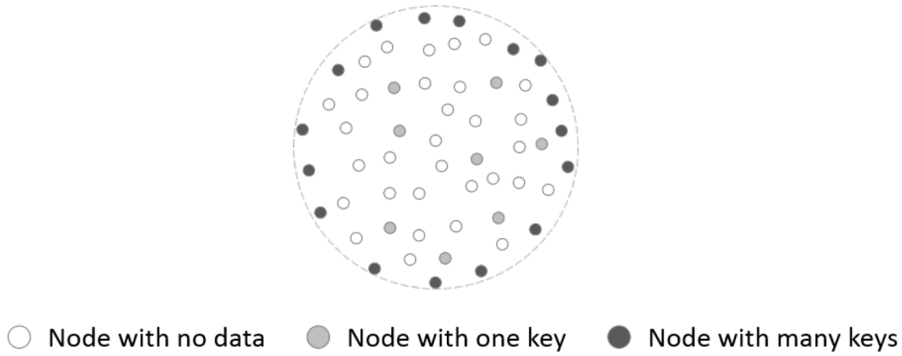

Fig. 31: Unbalanced key distribution among network nodes in the network from Fig. 30.

Chapter

4. PANA Protocol for Network Area Estimation and Dissemination

While the majority of the existing scientific works on wireless networks assume a priori knowledge of a network's geographical area, as a circle or square of a known size [Kya06][Bur08], the network area of the real networks may be arbitrary and unknown. This is the case in wireless ad-hoc networks, where decentralized process of adding new nodes results in networks occupying geographical areas of unknown shape and size [Mil06][Mil07]. Examples of such ad-hoc networks are wireless mesh networks used for provisioning of internet access (mesh networks, WMNs), wireless sensor networks (WSNs), and mobile ad-hoc networks (MANETs).

Unknown geographical area populated by nodes makes it necessary for the application to assume that the network nodes may be placed anywhere, what may cause unnecessary usage of network's resources. The knowledge about the network area on the other hand, can in various ways reduce communication costs and increase the efficiency of a wireless application.

For example, let's look at the geographical routing protocol GPSR [Kar00], which realizes efficient routing without any network flooding. In GPSR packets are forwarded based on the *geographical location* of the destination. GPSR makes a locally optimal, greedy selection in choosing a packet's next hop: it picks up the neighbor geographically closest to the packet's destination. When a void is met (no neighbor reduces the distance to the destination), a perimeter routing is executed, which can be seen as going along a border of a void till GPSR may go back to the greedy mode[53].

The problem with GPSR (and any geographical routing) is, that routing process is initiated for *any* destination. At the initiation time the source node cannot verify if there is a valid route to the given destination at all. However, destination can be unreachable, for example because of the network partitioning or malicious destination coordinates. In such case the packet will be retransmitted for potentially many hops, before it loops and is recognized as undeliverable, wasting during the process network resources, in particular, nodes energy and bandwidth.

The authors of GPSR recognized this problem and suggested to hand the decision of unreachability of a given location over to the sending end-system, but no example is given. Proposed in this work estimation of the geographical *network area* allows GPSR to filter a big part of unreachable locations. Knowing network area GPSR could check forehand if given location can be reached at all by calculating if it lies within network borders. Routing to unreachable destination would be dropped what would conserve the network resources and prolong network and service life time.

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[53] For details on GPSR see Chapter 3, Section 3.5.

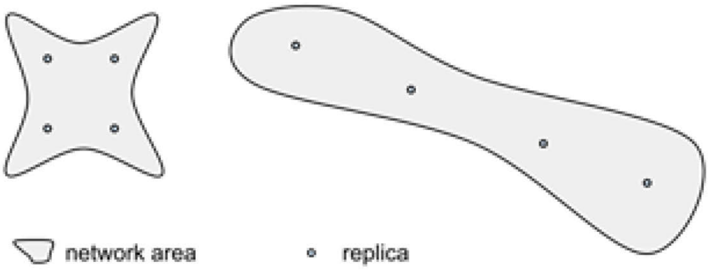

Fig. 32: Uniform distribution of four replicas in structured replication in GHT over two wireless networks with different network areas.

Moreover, information on the network area enables the use of existing protocols in real use cases. For instance, the Geographical Hash Table [Ratna02] assumes knowledge about a coarse geographical network shape to determine the locations of replicas in a structured replication. Structured replication in the GHT distributes data to the defined number of nodes in such a way that the maximum geographical distance to the closest replica from an arbitrary node is minimized (see Fig. 32). However, the prerequisite for this operation is knowledge of the *coarse network geographic area*. In evaluating the GHT in a simulator it is easy to provide the network area to the algorithm, but in a real network, this information is unknown and must somehow be determined. An alternative optimal solution for this placement problem is graph-based, and requires a full system knowledge (including positions of all nodes).

With the information on network area replication schemes can be proposed that support one-damage-tolerance with respect to a damage of a given type and size. For instance, replication scheme can calculate where to palace replicas in a way that minimum distance between they is guaranteed so assumed damage of given type and size can never destroy all replicas at once (Fig. 33, a, b). However, not all such calculated location must be covered by the network. In order to accomplish efficient dissemination and search, nodes can calculate with the help of network area information if a given replica location is within the network (Fig. 33, c).

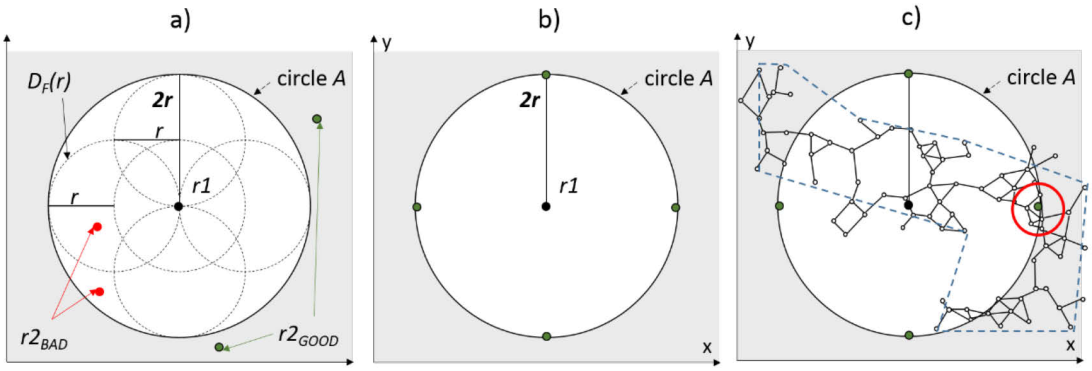

Fig. 33: a) A replica of data item *m* is stored on node r1. For every node within the circle A with radius 2*r there exists a damage of class D_{FIRE} with radius r which destroys both replicas. Storing another replica on a node outside the circle A guarantees that at least one of two replicas survives a damage of the given class. b) Possible replication scheme for $D_{FIRE}(r)$ c) Determination with the help of the information on the network area (blue dotted line) if replicas locations are within the network (red circle).

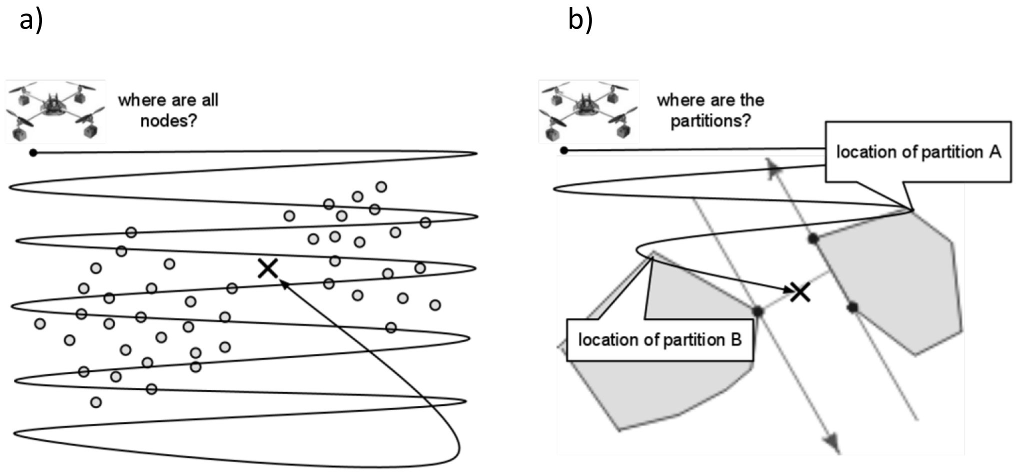

Fig. 34: Reconnecting network partitions by a UAV

The knowledge about network location could improve the efficiency of other disaster management applications, too. In a scenario when a disaster (e.g., fire) destroys a group of nodes, the network may split in two partitions. To restore the connectivity, UAVs (Unmanned Aerial Vehicle) can fly in to create a link between partitions [Fre10] [Sim12] or they may deploy new nodes between the partitions in order to connect them [Cor04][Oll07]. If the network area is unknown (Fig. 34-a), the UAV has to scout a large area in order to discover where the nodes are deployed, and only then it can determine where to position itself so that the partitions are connected. During scouting, UAV would communicate with each met node, what uses the local nodes power. Nodes awareness of their partitions' geographical areas reduces the flying overhead of the mobile node and the communication overhead of the stationary nodes. If network area partitions are known by all nodes, the UAV needs only to communicate with one node from each partition to requests partition's geographical area (Fig. 34-b), instead of communicating with all *n* network nodes. After receiving information on location of both partitions UAV can determine its location so that the partitions are connected (red arrows in Fig. 34-b illustrate one of possible ways to calculate the final UAV position as the point on the plane that minimizes the distance to both partitions). Thus, information about partitions' network areas provide considerable reduction of reaction time, energy spent on flying (UAV) and communication (UAV and stationary nodes).

The awareness of the geographical network area can also ease the network capacity estimation by combining network area with the average node density. It may help to estimate the 'health' of a sensor field and give the guarantee that newly added nodes are deployed in the expected area. Generally, it would allow for the great reduction of network costs in real-world, location aware, wireless applications.

The network location-awareness is useful, but providing the locations of all nodes to all nodes in a network has very high bandwidth and energy costs [Yao99][Lia07][Lip09], which limits the applicability of such an approach in real networks. In addition, every node should retain the positions of all other nodes in its memory, which can be an issue in some wireless ad-hoc networks. For instance, the

TMoteSky[54] nodes used in the Motelab wireless sensor network have only 10KB of operating memory.

Instead of using the exact positions of individual nodes, a wireless application may lower the communication overhead and its memory footprint with the help of another form of the location information: the information about the geographical area occupied by the network, i.e., the *network area*.

In this Chapter we:

- Formally define the network area, i.e. the geographical extent of the network,
- Discuss representation forms of network area (exact and approximated),
- Propose a *closed-curve approximation* of the real network area
- We define two estimators for the above approximation of different size and computational complexity,
- Propose PANA protocol, which simultaneously calculates and disseminates proposed network area approximations to all network nodes [Gei13], and
- We evaluate our approach by simulation on highly irregular and sparse networks consisting of 50 to 500 connected nodes.

Proposed protocol is simple and efficient, as it uses local broadcast for communication, relies on local neighborhood information and uses only small messages that can be piggy-backed to other communication or be used as hello messages.

4.1. Formal Definition of the Network Area

We address a connected, stationary wireless ad hoc network with bidirectional and unreliable links (packets may not be delivered). We assume the common communication range and model the network with the Unit Disk Graph [Cla90] Nodes have information on their location, provided by GPS or similar positioning technology.

Definition 1 (Network area): For the wireless network modeled as a graph $G=(V, E)$, the Network Area (NA) is the union of disks d(v, R) defined by the locations of all nodes $v \in V$ in Cartesian coordinate space and their common communication range R:

$$NA = \cup_{v \in V} \bar{d}(v, R) \tag{1}$$

The network area defined in this way provides the coverage of a network, meaning that if a wireless node is placed in the network area, it will be able to connect to the network with a high probability. An example of network area is given in Fig. 35.

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[54] http://www.eecs.harvard.edu/~konrad/projects/shimmer/references/tmote-sky-datasheet.pdf

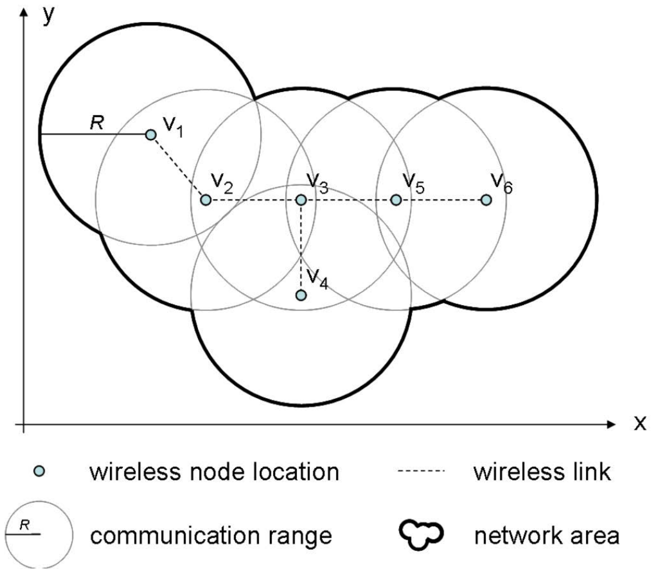

Fig. 35: An example of the network area (NA) of a small wireless network.

Definition 2 (*Perimeter nodes*): In the wireless network modeled as a graph *G*=(*V*, *E*) with the network area *NA* the perimeter nodes are the network nodes, whose communication disks have a nonempty intersection with a geometrical boundary of the network area *NA*.

Perimeter nodes according to this definition are illustrated in Fig. 36. Such defined perimeter nodes explicitly express the network area contour. In the next section we analyze the usage of perimeter nodes as a descriptor of the network area.

4.2. Exact Network Area Descriptor

Perimeter nodes describe the network area exactly. In this section, we analyze the feasibility of using them as a network area descriptor. We assess the communication overhead introduced by disseminating the positions of all perimeter nodes as well as the methods of their determination.

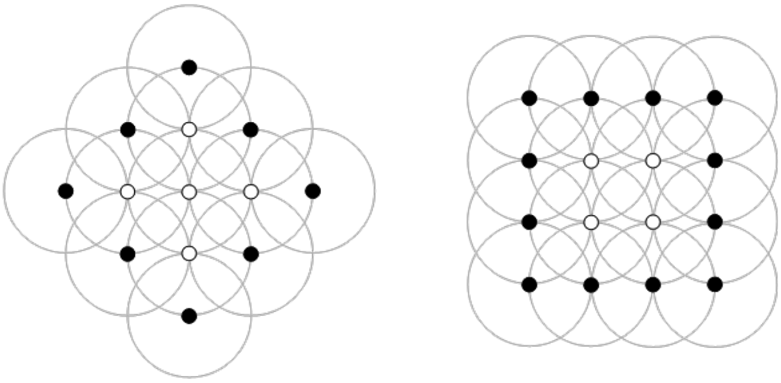

Fig. 36: Perimeter nodes (in black) of a wireless network.

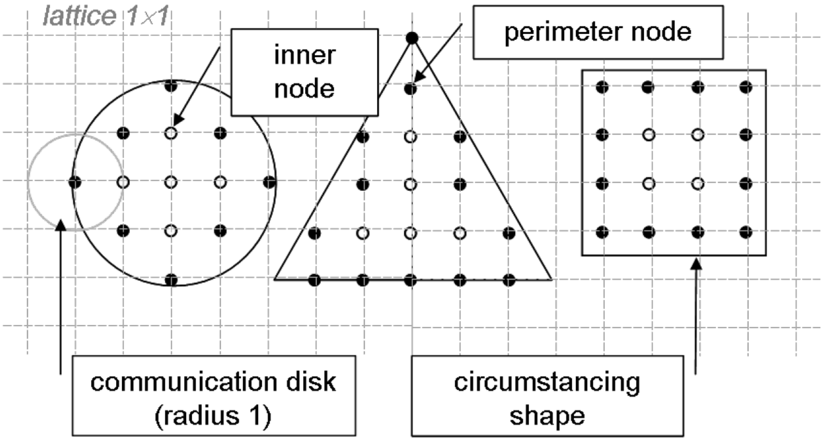

Fig. 37: Sparse regular networks with the node placement area selected by geometrical figures. All geometrical figures have the same area A. Number of perimeter nodes (black nodes) changes for different circumstancing shapes.

4.2.1. Size (Number of Perimeter Nodes)

The communication overhead introduced by disseminating the positions of all perimeter nodes depends on the number of perimeter nodes, which determines the amount of data to be transmitted. In order to analyze the number of perimeter nodes in an arbitrary wireless network let us observe wireless networks with the following regular topology: nodes are placed on an underlying lattice with a unit granularity and nodes have a common communication range of a unit. Such placement results in the smallest possible density for a grid network to stay connected in the UDG model (one node per square unit). To assess the size of a perimeter, we observe four different shapes of networks: a square, a rectangle with sides' ratio 1:4, an equilateral triangle, and a circle (Fig. 37).

We determine the number of perimeter nodes *p* for the assumed topology. It can be noticed that networks with the same area *A* have different perimeter size depending on the shape of the circumstancing figure *S*. Based on the geometrical analysis we acquire following expressions:

$$p = 5\sqrt{A} - 4 \qquad \text{if } S \text{ is a rectangle 1:4} \qquad (2)$$

$$p = 4\sqrt{A} - 4 \qquad \text{if } S \text{ is a square} \qquad (3)$$

$$p = \frac{6}{\sqrt[4]{3}}\sqrt{A} - 3 \cong 4{,}6\sqrt{A} - 3 \qquad \text{if } S \text{ is an equilateral triangle} \qquad (4)$$

$$p = 4\left(\frac{2\sqrt{A}}{\sqrt{2\pi}} - 1\right) \cong 3{,}2\sqrt{A} - 4 \qquad \text{if S is a circle}^{55} \qquad (5)$$

where *A* is the area of a circumstancing shape *S*.

---

[55] In this estimation of the number of perimeter nodes for a circle p_c, we have used the number of perimeter nodes in the *inscribed* square p_{s_in}, which is clearly always smaller then p_c. Because we will use p_c, as a *lower* bound of the number of perimeter nodes *p* for any shape with the given area, this simplification does not introduce a mistake in our conclusion.

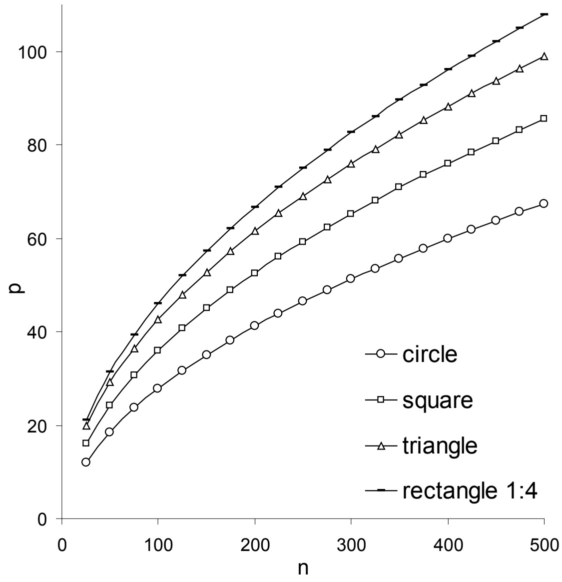

Fig. 38: Number of perimeter nodes *p* as a function of total number of nodes *n* for networks of different shapes.

We see that the number of perimeter nodes *p* grows proportionally to the square root of network size *A:* $p \sim (c * \sqrt{A})$ with different c for different shapes. The number of perimeter nodes for networks of different size (total number of nodes) and evaluated shapes determining node positions is shown in Fig. 38. We can see, that the circle has the lowest number of perimeter nodes *p* for given network size measured with number of nodes.

As a consequence of the isoperimetric quotient[56] inequality [Oss86] it is known that the circle has the smallest possible perimeter length *P* for the given area *A*. Thus, the network determined by a circle provides the lower bound with respect to the number of perimeter nodes *p*. This lower bound for the presented lattice topology with density 1 is a valid lower bound for an arbitrary network since irregular networks may contain denser, but not sparser parts. At least one node per square unit in the network area (where one unit reflects the communication range) provides the network to be connected.

We can thus conclude that the expected number of perimeter nodes grows at least proportionally to the square root of the total number of network nodes, regardless the shape of the network. In practical applications, additional issue is the constant *c.* It is rather big, so for examined networks of 400 nodes we need to transmit information on 70-100 perimeter nodes, depending on the network shape. For irregular networks, the number of detected perimeter nodes will be even higher than in analyzed regularly-shaped networks.

---

[56] Defined as the ratio of the curve area to the area of a circle with the same perimeter as the curve.

4.2.2. Dissemination Overhead

The number of perimeter nodes allows us to calculate the total overhead connected with using the perimeter nodes as a *NA* descriptor.

Let us consider two cases. First, all the *p* perimeter nodes disseminate their positions directly. The second approach is to disseminate the complete perimeter information packed in one message, so we have two components of the overhead: a) all perimeter nodes send their coordinates to a central node, b) the central node sends perimeter information to every node.

The complexity of the first approach is $p*n$, equivalently $O(\sqrt{n} * n)$ messages sent in a network. In the approach with a central node we have *p* messages for component a) and $O(m * n)$ messages for component b), where *m* is:

$$m = O(p) * \frac{8bytes}{\max\_packet\_size} = O(\sqrt{n}) * \frac{8bytes}{\max\_packet\_size},$$

which results in a total of $O(\sqrt{n}) + O(\sqrt{n} * n)$ messages. Additionally we also have to consider the issues of fragmentation and the reassembling of fragments. If a message fragment is not received, the receiving node may discard the whole message, or it will have incomplete information on the network perimeter. For example, for a regular network of 400 nodes, we need to transmit information on 70-100 perimeter nodes (depending on the shape). Assuming 8 bytes per perimeter node[57], the total amount of data for transmission of such a perimeter is between 560 and 800 bytes, which is considerably larger than a packet in a typical WSN (the maximum payload in 802.15.4 is 81 bytes [RFC4944]). The high number of messages in both cases leads to packet collisions [Yao99], and eventually the degradation of the network area information obtained.

In addition to these straightforward dissemination approaches, there are low-cost flooding techniques that considerably reduce the number of messages sent. For example, the minimum spanning trees (RMST [Lip04], LMST [Li04]), connected dominating sets [Stoj02] or the active and passive connectors [Lia07] can be used for the message dissemination (a good overview is accessible in [Lip09]). However, such optimized dissemination techniques introduce an additional overhead because they require network topology information for choosing the optimal dissemination paths. Changes in the network topology render such paths invalid and require their reconstruction, which causes additional network traffic. Other issue is that some well-performing low-cost flooding techniques assume known nodes duty cycles, high density of nodes or possibility to adjust radio power. Finally, when using low-cost broadcast techniques in a network with lossy links, the reliability of broadcast is low, and the potential inconsistency must be considered.

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[57] We assumed that a coordinate is represented by a real number in single precision, according to IEEE 754 which has 4 bytes, and a node has coordinates *x* and *y*.

Another problem connected with using the perimeter nodes as the network area descriptor is the need for *detecting them* first. A node cannot easily determine if it belongs to network's parameter. As we show in the next subsection, there exist yet no appropriate approach for detecting perimeter nodes in sparse, irregular ad-hoc networks.

4.2.3. Detection of Perimeter Nodes

There are approaches to the perimeter discovery in a WSN [Fek05][Wan06] [Khe09], also known as the problem of identification of the *border nodes*.

[Fek05] proposes a decentralized solution that requires second-order neighborhood information. The nodes locally compute their 'restricted stress centrality' (a graph-based metric), and assume they are the perimeter nodes if the value of this metric is higher than a given threshold. However, there is no guarantee that a node does indeed belong to the boundary. The threshold value is network-specific, *a priori* unknown and it must be found experimentally for each network, which makes it applicable only in networks of known characteristics and seriously limits applicability of the approach. Additionally, the solution is applicable only to very dense networks with a uniform node distribution. A similar approach requiring second-order neighborhood information is proposed in [Khe09]. Each node tests locally whether it lies in the convex hull of any subset of its neighbors. The test is applied up to m^3 times for each node, where m is the node degree[58] causing a significant computational overhead. This method is also applicable to dense networks only. A centralized solution for perimeter discovery proposed in [Wan06] allows sparser networks but still assumes a node degree of at least 10. This method has eight execution steps, and in the course of a single execution, the network is flooded several times, where the number of floods grows with the network size. The main drawback of the method is the high communication cost. Its advantage however is the ability to find all perimeter nodes, including those around the holes in the network.

The applicability of the presented perimeter discovery algorithms to real networks is limited. They assume a very high node degree, of up to 200 or more [Khe09][Fek05], or a uniform node distribution [Fek05]. Such assumptions are in strong contrast with real-world networks, which are both sparse and irregularly distributed. Moreover, these methods to do not evaluate the influence of packet loss on the performance of the presented perimeter discovery algorithms.

Unlike these listed approaches, which provide either partial or unfeasible solutions, our goal is to provide a network area detection algorithm that does not depend on any assumptions about network density and node distribution, and works without global topological knowledge. The algorithm should tolerate packet loss, discover the network area, and disseminate this information simultaneously in order to produce low communication overhead.

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[58] The number of the direct neighbors.

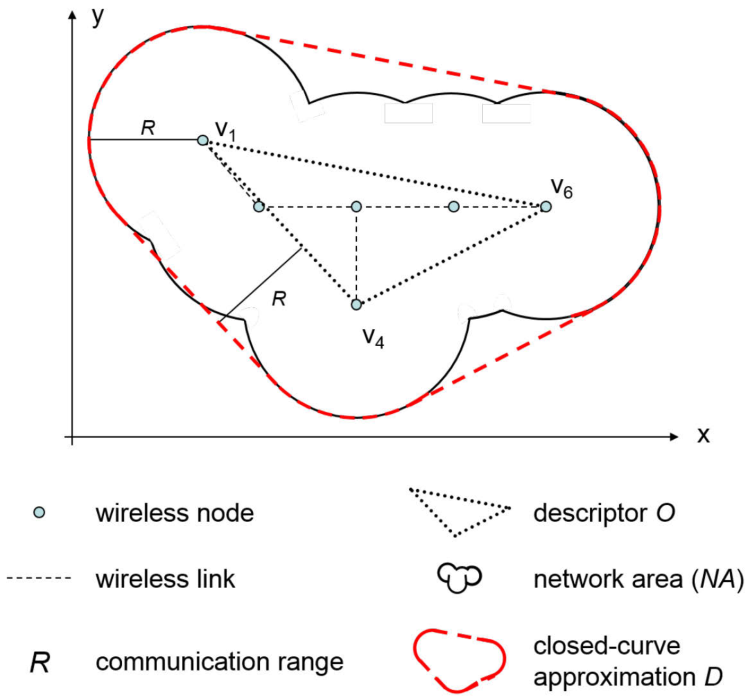

Fig. 39: Example of a closed-curve approximation of a network area. In this example approximation uses a triangle as a descriptor.

4.3. Approximation of the Network Area

Exact descriptors that contain the locations of all perimeter nodes offer an ideal network description, but as we demonstrated in the previous section, the problem of detecting border nodes is not solved for sparse and irregular ad-hoc networks yet. Besides, even if an appropriate approach for detecting perimeter nodes exists, the size of the exact descriptor may be prohibitively large.

In order to avoid the problem of border nodes detection and cost of its dissemination we propose to use an approximation of the network area.

4.3.1. Closed-Curve Approximation

To eliminate the problem of border nodes detection and large size of network descriptor we propose to use an approximation of a fixed, network-independent size. Proposed closed-curve approximation lets to choose a desired tradeoff between small data usage and high accuracy of the approximation.

Closed-curved approximation describes the network area by a simple geometrical shape *O* (called *descriptor*) and an *R*-thick stripe, adjacent to *O* (where *R* is nodes' common communication range).

Definition 3 (Closed-curve approximation): A closed-curve approximation *D* of the network area *NA* is defined by the shape *O* (called descriptor) and the nodes' common communication range *R* as all points in space belonging to the descriptor *O* or located at most *R*-away from *O*: $D=\{(x, y) \in R^2 \mid (x, y) \in \Omega_O \vee |(x, y), O| \leq R\}$, where Ω_O is the region bounded by *O* and $|\cdot|$ denominates the Cartesian distance.

Fig. 39 depicts a triangular descriptor *O*. According to the *Definition 3* the closed-curve *NA* approximation in this example consists of two areas: the surface of the triangle *O* with vertices $V_1V_4V_6$ and the surface of the *R*-thick stripe surrounding *O.*

Our goal is to transmit only the simple descriptor *O* throughout the network, thus reducing the communication overhead. Simplicity of the descriptor results in small computational effort during local calculation on the approximation of the network area at their nodes, and eases the process of determination whether a point in space belongs to the network area. Such decision would be made by applications that use this form of location information (as GPSR [Karp00]), based on a simple shape *O* and *R*. Communication range R must not be additionally transmitted because it is known at all nodes.

4.3.2. Descriptor for the Closed-Curve Approximation

We use a polygon as the descriptor *O* in a closed-curved approximation *D* (Fig. 39). We set the number of polygon's vertices to have a network area approximation size which is independent of the total network size. The polygon can be also simply manipulated even by nodes with low computational capabilities. Of course, its points have to be suitably calculated in order to reflect the network area adequately, what we describe in the following sections of this chapter.

In this work we propose two types of polygons as a descriptor *O* for approximation *D*. One is an envelope, defined as an axis-aligned bounding box that includes all nodes in the network. The envelope has four points on 2D plane. The second shape is an eight-sided polygon (octagon or 8-gon [Gei13]). In most wireless technologies, both: the envelope and 8-gon will fit in a single wireless packet, which makes a dissemination process less resource-intensive, easier to implement (no message fragmentation–defragmentation), and more reliable (long packets are more prone to losses). In section 4.4.3 we describe how to build an envelope and an 8-gon so that they represent the shape of the network area well.

As we will show, these simple descriptors build network area approximations of surprisingly good accuracy, considering their size. However, usage of descriptor with a bigger size is possible. For descriptors with number of vertices equal a power of two, the delivered by us joining algorithm (4.4.3.2) can be used, with only slight changes (extending a number of anchor points so they suit the number of vertices in used descriptor). However, in case of bigger descriptors, the amount of data transferred in the network would grow.

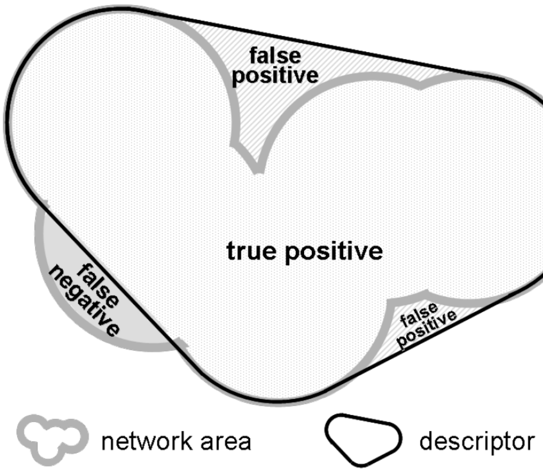

Fig. 40: Quantifying the accuracy of a network area descriptor.

4.3.3. Measuring Accuracy of Approximation

Use of an approximation introduces an inaccuracy into the network area identification. The inaccuracy of an approximation can be quantified by comparing the network area approximation with the accurate network area *NA* (known to the omnipotent observer). The following cases exist (see Fig. 40):

- t_p (true positive) is the area correctly classified by *D* as belonging to the *NA*,
- f_p (false positive) is the area incorrectly classified by *D* as belonging to the *NA*,
- f_n (false negative) is the area incorrectly classified by *D* as not belonging to the *NA*.

In order to measure the accuracy of a descriptor *D*, we use the established relevance metrics well-known from statistics: precision, recall and F-measure. Precision is the probability of the correct marking of the network area; recall captures the ratio of successfully identified network area and F-measure is a harmonic mean of the precision and recall. The metrics belong to the interval [0, 1], and in the ideal case they equal one. They are calculated as follows:

$$\text{precision} = \frac{t_p}{t_p + f_p} \tag{6}$$

$$\text{recall} = \frac{t_p}{t_p + f_n} \tag{7}$$

$$\text{F} - \text{measure} = 2 * \frac{\text{precision * recall}}{\text{precision + recall}} \tag{8}$$

4.4. Polygon Approximation of Network Area (PANA) Algorithm

In this section, we propose a Polygon Approximation of a Network Area (PANA) algorithm. PANA uses either an envelope or the eight-point polygon as the network area descriptor. In PANA, each node locally determines the vertices of polygon *O* (also referred to as its *current view* or shortly *view*) and shares it periodically with its neighbors by a local broadcast. The nodes update their local view based on the received information. Since functions used for calculating the descriptors are idempotent[59], the PANA algorithm is self-similar [Cha07], and an order of its execution by distributed system agents does not influence the result. Local descriptors of nodes are in that way gradually extended and eventually, they convert to a descriptor of the whole network area. Since this approach utilizes the locality of information and gossiping, PANA is efficient and tolerates message losses.

4.4.1. Initialization of PANA

At the initialization time, a node defines its own position as the descriptor *O*. It is sufficient, but not required that a single node initializes PANA. In fact, the more nodes initialize PANA simultaneously (or independently within its stabilization time) the faster it converges to the final approximation of the network area[60].

Which nodes do initialize the protocol and with which frequency (or else under which conditions) depends on the concrete scenario and applications that use PANA and network area approximation. For example, each node that joins the network can initialize PANA or it can be done by every node that notices a change in its direct neighborhoods set. Approaches that only nodes with a certain number of neighbors initialize the protocol are possible. In a dynamic ad-hoc network with unreliable nodes (e.g., in DM scenarios) determining a network area approximation should be scheduled periodically or when a global changes in the network are detected; here, a decision can be handled by an appropriate distributed failure detector [Tai04][Pit13][Sau13].

When a global change in the network is determined, the old network view (approximation) is not valid any more. The issue of reduction of descriptors is not supported in the current PANA implementation. In its current form, PANA is able only to extend the network view. When a node receives a PANA message (containing neighbor's view), it initializes (if needed) and joins its current view with the incoming one.

---

[59] An operation (or function) is idempotent if, whenever it is applied twice to any value, it gives the same result as if it were applied once. For example, the absolute value function is idempotent as a *abs*(*abs* (x)) = *abs*(x). Another examples are the minimum and maximum of a set.

[60] In our simulations, we were choosing the single node initialization scheme, which is the worst case with respect to needed algorithm rounds before the view of most of nodes represents the network area well.

4.4.2. Dissemination of Descriptors

At initialization time, the polygon *O* contains the position of a node itself. After initialization active nodes exchange their views by the periodical local broadcast (the frequency of broadcasts is a parameter of the algorithm). In order to avoid the synchronization of nodes and collisions on the wireless channel, a node randomly chooses a time instant to send its view (in the form of a current descriptor *O*) within the dissemination period. A node recalculates (joins) its current view with the neighbors' views as they arrive, thus increasing the knowledge on the network area. The calculation of views based on new information is crucial for the efficient and accurate description of the network area, and its implementation depends on the descriptor shape. We present it for envelope and 8-gon in the next section (4.4.3). Algorithm 1 shows this dissemination approach in PANA:

Algorithm 1: PANA algorithm for a node *i*

```
initialization() {
        descriptor:=position(i)   //once at start
}

dissemination() {
        do {
                sendTime:=U(0, disseminationPeriod)
                wait(sendTime)
                send(descriptor)
                wait(disseminationPeriod-sendTime)
        } while(TRUE)
}

receiveDescriptor(newDescriptor) {
        descriptor= joinDescriptors (descriptor, newDescriptor)
}
```

This sending scheme is simple, and therefore many messages are redundant. A node periodically broadcasts its descriptor even if it is the same as its neighbors' descriptors (i.e., there is no useful information in the descriptors for the neighbors who receive it). The communication overhead may be reduced by piggy-backing PANA messages to normal communication. However, if network traffic is low, this may not be sufficient for efficient dissemination, and dedicated broadcasts will have to be used.

In order to reduce the number of sent messages, we can use the smart (informed) broadcast. This scheme avoids sending redundant messages: a node *i* temporarily stops sending its descriptor if it observes that all its neighbors have a descriptor identical to its own. If the node observes such a situation, this node is in a *stabilized* state. If the node *i* receives a new descriptor from a neighbor that is

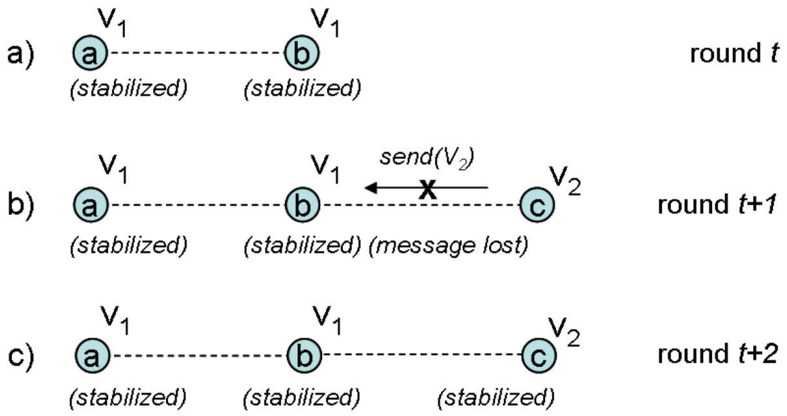

Fig. 41: Smart broadcast in a network with lossy links. Algorithm stabilizes and although views on the network are partitioned because of one lost message in round *t*+1.

different from its own, it recalculates its descriptor and schedules a (local) broadcast of the descriptor in the next algorithm's round.

A smart broadcast works perfectly for a network with no packet losses. Its convergence speed is the same as for the standard broadcast, and it cannot end in a deadlock. However, in a network with unreliable links, a smart broadcast may lead to a deadlock in the data-exchange and to the partitioning of descriptors, or it may considerably increase the algorithm's convergence time. The exact effects of message losses on the algorithm depend on the pattern of packet losses and network topology. Consequently, the accuracy of the network area description downgrades.

A simple example of such an invalid algorithm execution can be seen in Fig. 41. Let us assume that we have a stabilized network of two nodes *a*, and *b*. A new node *c* joins the network, and a message from *c* towards *b* is lost. The right part of the network stabilizes without receiving updates from node *b* which was oblivious to the existence of node *c*, and the algorithm enters deadlock prior to its successful stabilization (the network views are partitioned).

To mitigate this issue, we introduce an intermediate approach, a Probabilistic Smart Broadcast (PSB). A node uses the presented stabilization scheme, but once it is in the stabilized state, it sends its descriptor with a probability p_{gossip}. A PSB in the stabilized state recalls the smart gossip [Kyasa06], but in our scheme, the message forwarding is continuous, which ensures that the views are disseminated reliably. Algorithm 2 shows the final PANA dissemination with PSB scheme:

Algorithm 2: PANA with the Probabilistic Smart Broadcast for a node *i*

```
initialization() {
        descriptor:=position(i)    //once at start
}

dissemination() {
        stabilized:=FALSE
        lastSentDescriptor:=descriptor
        do {
                sendTime:=U(0, disseminationPeriod)
                wait(sendTime)
                if (stabilized)
                        send(descriptor) with probability $p_{gossip}$
                else {
                        send(descriptor)
                        lastSentDescriptor=descriptor
                        stabilized= TRUE}
                        }
        wait(disseminationPeriod-sendTime);
} while(TRUE)

receiveDescriptor(newDescriptor) {
        if newDescriptor<>lastSentDescriptor
                stabilized=FALSE
        if newDescriptor<>descriptor
                descriptor=joinDescriptors(descriptor, newDescriptor)
}
```

4.4.3. Algorithms for Joining Descriptors

As a node receives a descriptor during the exchange of PANA messages, it has to merge the incoming information with its current view on the network (function *joinDescriptors* in the PANA algorithm). In this section, we will explain how to join two descriptors, for envelope- and 8-gon-based descriptors, so they reflect the network area well.

Since the descriptor sizes in PANA are constant, the key problem of the joint operation is how to decide on a fixed-size subset of points from the two descriptors, so that the new descriptor provides a good approximation of the union of areas indicated by the two input descriptors.

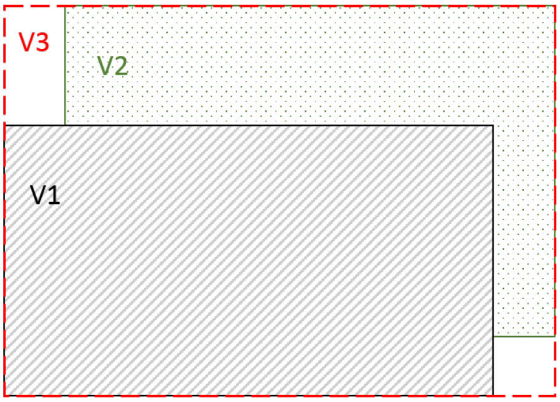

Fig. 42: Example of joining envelopes. V3 = join(V1, V2).

4.4.3.1. Joining Envelopes

The envelope descriptor is very simple, and it contains just two coordinates by its definition: one that contains the minimal values of node coordinates, and one that contains the maximum values of node coordinates, where the min/max operation is applied to all known nodes in network. Bearing that in mind, the join of the two descriptors is straightforward. If we have two descriptors *envelopeA* and *envelopeB*, together they have four coordinates that define them: four *x* and four *y*. We can put these coordinates in two sets: the coordinates *x* to set *X* and the coordinates *y* to set *Y*. The new descriptor $envelopeC = envelopeA \cup envelopeB$ is defined with two coordinates *low* and *up*, where *low*=(min{*X*}, min{*Y*}) and *up*=(max{*X*}, max{*Y*}). Such constructed descriptor is defined by points in plane that usually do not correspond to locations of any network nodes.

4.4.3.2. Joining 8-gons

An 8-gon descriptor is an ordered set having a maximum of eight points on a plane. Unlike the envelope, each 8-gon point corresponds to the location of an existing network node. The problem that a node needs to solve is the following: having two different polygon descriptions of a network area, each having up to eight vertices, create a new polygon with up to eight vertices that adequately approximates the union of the two input polygons. An example of such approximation is in Fig. 43.

The first step is to create a union *P* of all vertices of the two initial polygons *P1* (containing points *p1* to *p8*) and *P2* (containing points *p9* to *p16*). Then *P* is surrounded by an axis-aligned envelope (calculated as in section 4.4.3.1). The envelope's four corner points and four middle side points become the eight anchor points *E=E0..E7* (Fig. 44).

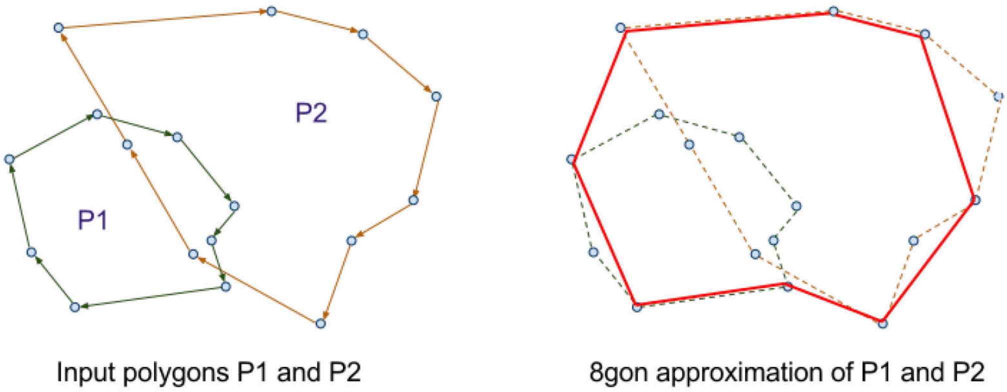

Fig. 43: Goal of joining 8-gon: find the new 8-gon that best describes the union of input 8-gons.

The joined polygon comprises of the points from *P* that are greedily closest to the anchor points. An anchor point may have only one assigned point from *P*. For that, we look for the smallest distance between any point from *P* and any anchor point from *E*. Once such a pair is found, they are assigned to each other and removed from sets *P* and *E* respectively. The process is repeated until all anchor points have an assigned point from *P*, or until all points from *P* are assigned. Situation where not all anchor points get their assignment may occur when there are fewer than eight points in *P*, what may happen in sparse parts of a network and during initial stages of the algorithm execution.

The resulting polygon is formed from the assigned points from *P*. The order of polygon points is the same as the order of anchor points to which they are attached. In Fig. 45 we can see an example of this approach. Minimum distance between any anchor point and any vertex of two input polygons is between node *p16* and anchor *E7*; so point *p16* is the first determined point of the join polygon. The points *p16* and *E7* are removed from the search space. The next smallest distance is between *E3* and *p5*, etc. At the end, we obtain the resulting polygon *(p1, p2, p3, p5, p7, p13, p14, p16)* that will be sent in the next round of the algorithm by the node that calculated it.

The presented algorithm has a linear complexity, which makes it suitable for use in low-resource networks.

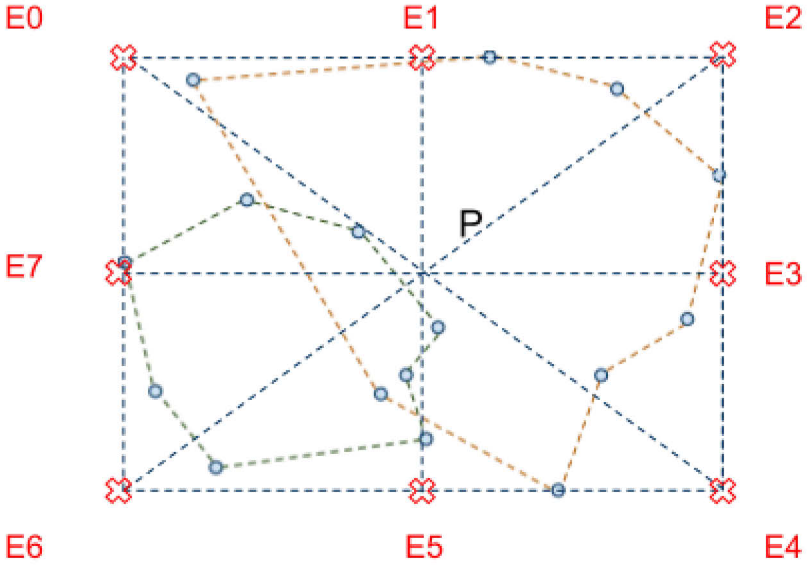

Fig. 44: Anchor points (E0 to E7, red crosses) used in joining two 8-gons. Anchor points are defined by the axis-aligned envelope circumstancing union of the input polygons.

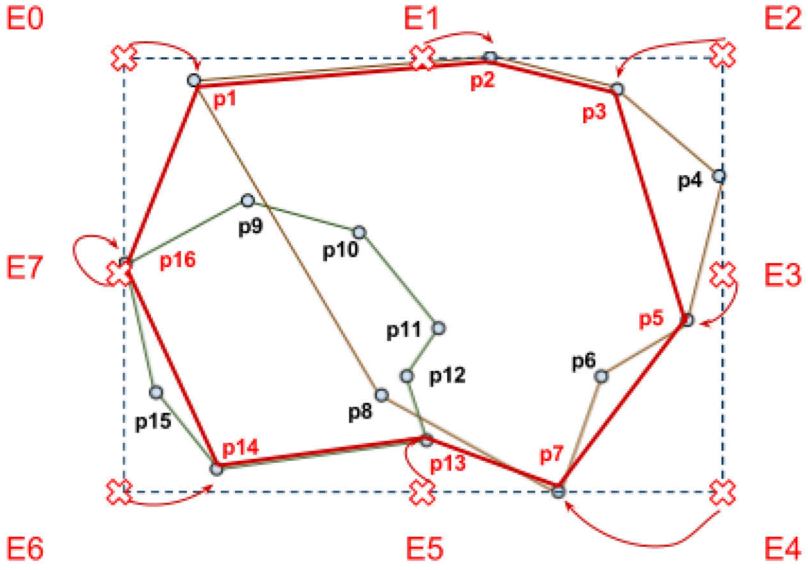

Fig. 45: Selecting points during 8-gon join operation. The arrows show the greedily chosen closest points to the anchors *E0..E7* from the input set *p1..p16*. Thick red line shows the resulting, joined polygon.

4.5. Evaluation

We evaluate the PANA algorithm by simulation with and without probabilistic smart broadcast (PSB), and with two proposed descriptors. We use a custom-built Java simulator that models wireless ad-hoc networks with the UDG model [Clark90]. Additionally, we can set the probability of message loss p_{LOSS} to reflect unreliability of the wireless communication. We simulate PANA without message loss ($p_{LOSS} = 0$) and with $p_{LOSS} = 0.3$.

To evaluate the PANA, we execute it in realistic topologies generated by the NPART algorithm [Mil09]. In [Mil07] it was observed that the real networks are highly irregular in their shape, and that their topological properties differ considerably from the models widely used in literature. The NPART algorithm produces topologies with node degree distribution similar to node degree distribution of existing, large-scale wireless networks. Resulting topologies are also highly irregular in their shape and size, what allows us to test PANA on irregularly shaped networks. Using the popular uniform node placement models requires the node placement area as a parameter. Thus, the accuracy results would be fully dependent on our decision of which area to place the nodes in. For instance, a common approach of using rectangular placement area for uniform node distribution would lead to a wrong conclusion that envelope descriptor has almost perfect accuracy. An example of a small topology generated by NPART, along with the produced 8-gon descriptor is in Fig. 46. Example of a 400-node network used is in Fig.14 in Chapter 1.

The evaluation is performed in order to investigate:

- Whether the algorithm stabilizes, and to evaluate the stabilization time counted in algorithm rounds.
- The accuracy of the proposed network area description after the algorithm has stabilized.
- The communication cost of the algorithm measured in number of transmissions.

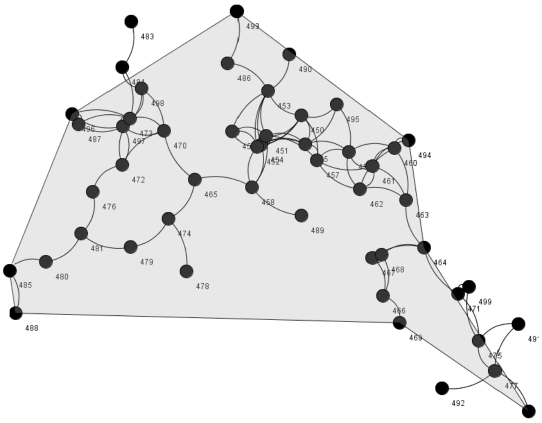

Fig. 46: An example of an irregular topology used in the evaluation and the resulting 8-gon descriptor.

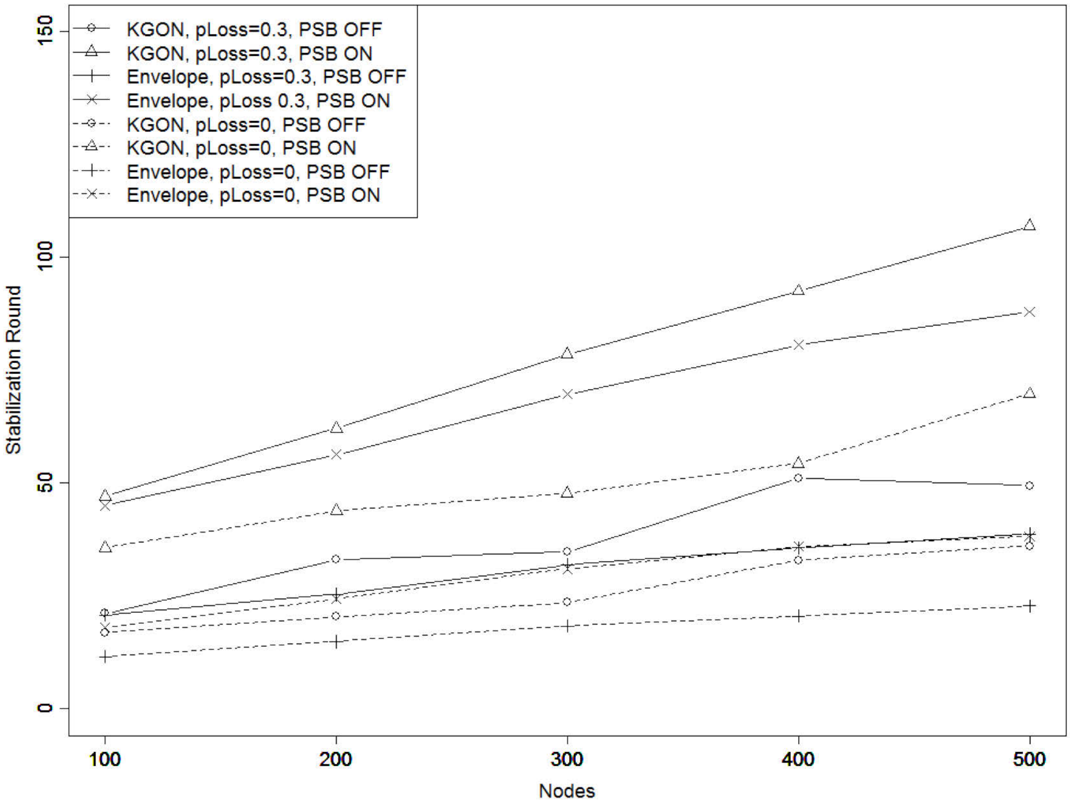

Fig. 47: Stabilization round of the PANA algorithm.

We evaluated networks of varying size, containing 50 to 500 nodes. The probability of packet loss was set either to zero or 0.3. For the probabilistic smart gossip, the probability of rebroadcast in the stabilized state is p_{gossip}=0.3. The presented results represent averages of 200 simulation runs for each scenario.

4.5.1. Stabilization round

Our evaluation shows that PANA algorithm converges to a stable state with both descriptor types. The stabilization time, measured with number of algorithm execution rounds, depends on the network size, the packet loss probability and the descriptor type. As expected, the stabilization time increases for larger networks, since more rounds are needed to transfer information through the network. It can also be seen that packet losses cause slower stabilization. The envelope-based descriptors converge more quickly than 8-gons, since they contain less information.

The number of rounds needed to achieve algorithm stabilization (Fig. 47) may seem prohibitive (close to 50 rounds for a realistic, lossy network consisting of 100 nodes), but if we observe the descriptors' accuracy growth rate in the consecutive rounds of the algorithm execution, we can see that most of the important information is disseminated quickly and that later rounds perform only fine-tuning of the descriptors. Consider for example simulation results of the 100-node network (Fig. 48), where each point represents the average of the F-measure for all the nodes in a network. The network area descriptor accuracy promptly (after 10 rounds) approaches its plateau and F-measure of 0.7 to 0.8, which is already a usable network area information for those applications and protocols that need it. This property makes the algorithm applicable even in highly dynamic networks. Additionally, in the applications where more nodes initialize the protocol simultaneously, high accuracy will be reached even sooner. In our experiments a single node initialized PANA, what is the worst case with respect to needed algorithm rounds before the majority of nodes approaches the global network approximation.

4.5.1. Accuracy of the Network Area Approximation

The simulator calculates true positives, false positives and false negatives of descriptors that are present at each node in the network in accordance with the definitions from Section 4.3.3. We use them to determine the accuracy of the algorithms in the form of F-measure, which is a harmonic mean of precision and recall defined as in equations (6)-(8) in Section 4.3.3.

Approximations' accuracy measured with F-measure calculated after the algorithm stabilizes is shown for different PANA and simulation configuration is in Fig. 14. Configuration considers descriptor type (8-gon or envelope-based), dissemination algorithm (PANA with and without Probabilistic Smart Broadcast PSB) and message loss probability ($p_{LOSS} = 0$ or $p_{LOSS} = 0.3$).

In Fig. 49 we show the development of accuracy measured with *precision* and *recall* separately for an example simulation configuration, we give an example of their average values at nodes for one simulation configuration, which shows accuracy results for 8-gon descriptor for the 100-node network, with message losses and without PSB, which is the fastest converging configuration.

We see that while approximation has a good precision from the beginning its recall is improving in successive algorithms rounds. It is due to the fact, that as network descriptor grows it embraces positions of more network nodes. On the other hand, at the initialization time, the smallest network descriptor has a perfect precision as it includes the position of a node itself.

The accuracy results are very good considering how small the used descriptors are. It can be seen that even the envelope-based network area description is highly useful: its F-measure is around 0.75 for all tested network sizes. The accuracy of the 8-gon description of the network area is considerably better than that of the envelope description, with an F-measure of approximately 0.9.

Although the proposed descriptors remain constant in size, they are able to capture the shape of the network area adequately, even for large networks. There is a drop in their accuracy as the network size increases, but the reduction is small and practically irrelevant. For instance, in a lossy network of 100 nodes, the 8-gon description has an F-measure of 0.91. This is reduced to 0.89 in a network of 500 nodes.

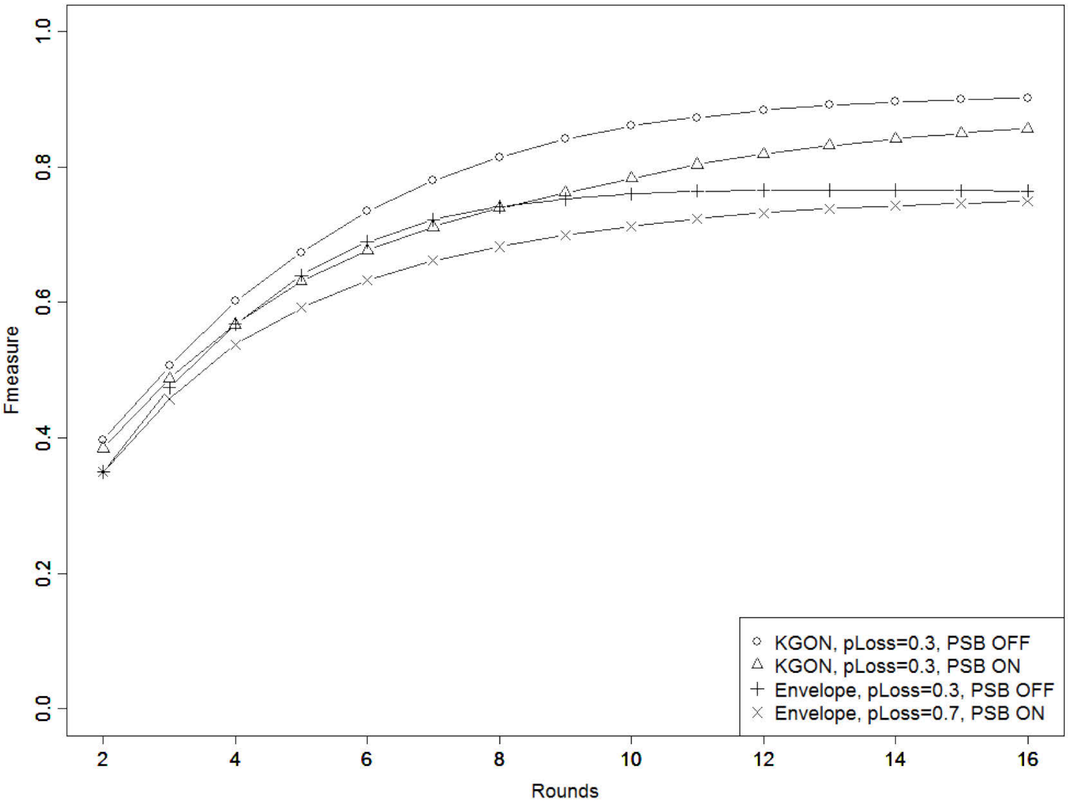

Fig. 48: Accuracy of PANA network area approximation (F-measure) in consecutive algorithm rounds, for envelope and 8-gon descriptors, *n*=100.

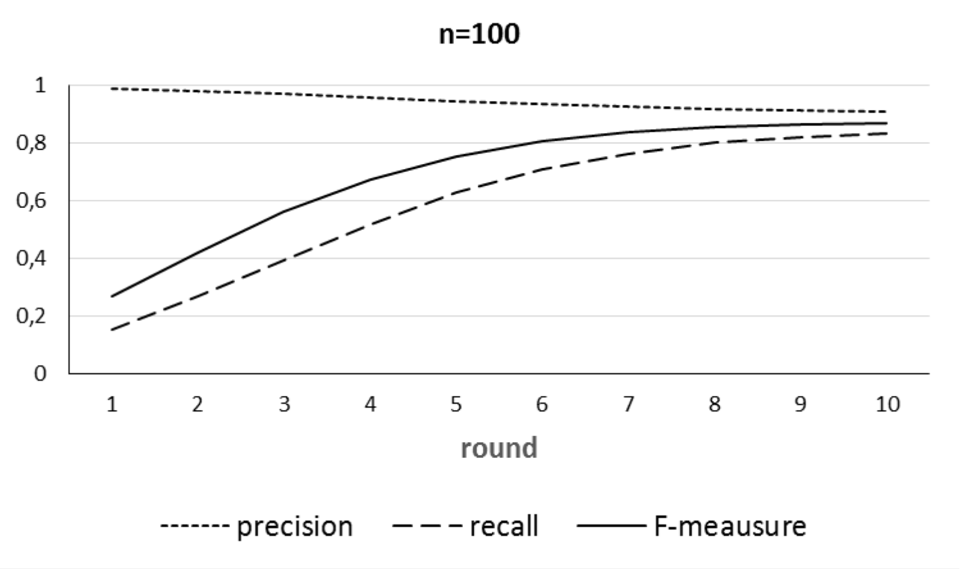

Fig. 49: Development of precision, recall and F-measure of PANA network area approximation for 8-gon descriptor in first algorithm rounds, *n*=100, with message losses and without smart broadcast (p_{LOSS}=0.3 and PSB=*OFF*)

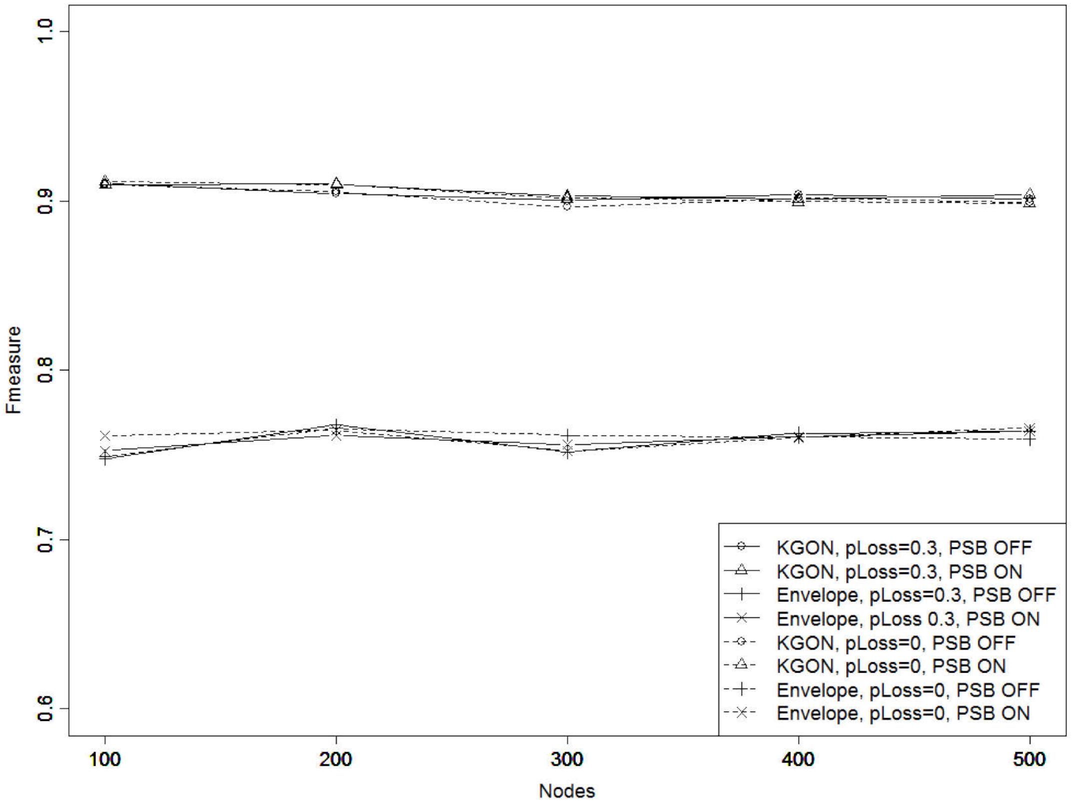

Fig. 50: PANA stabilization accuracy measured with F-measure.

4.5.2. Message overhead

In PANA without a probabilistic smart broadcast (PSB), each node sends one message in every round of the algorithm execution. In the dissemination with the PSB, the message overhead is reduced significantly. On average, from initialization to the stabilization time, a node sends a PANA message with at least a halved probability (Fig. 51). The communication overhead is considerably reduced, and the gains provided by PSB are even greater once the algorithm stabilizes. The number of messages sent per node per round will be further reduced to the p_{gossip} and yet keeping the algorithm ready to detect and react to network topology and area changes.

An interesting property of our approach is that presence of packet losses causes that fewer messages are sent. The loss of some packets causes that some nodes perform more information aggregation (create more accurate descriptors) prior to sending a new descriptor, which speeds up the convergence and stabilization of PANA.

When assessing the induced communication overhead, it also has to be taken into account that our descriptors are much smaller than the accurate perimeter node set used by related approaches [Khe09][Fek05][Wan06]. Assuming that coordinates are represented in IEEE 754 float format, the envelope based descriptor requires only 16 Bytes, 8-gon requires 64 Bytes. Assuming the same coordinate format, the total amount of data for transmission of the complete network perimeter in 400 node network is between 480 and 800 bytes (taken from example in Section 4.2.2). Hence, even if the perimeter could have been somehow known by a node in a network, the mere overhead of its dissemination would have allowed execution of 8 to 50 complete rounds of PANA. Additionally, the perimeter nodes would have to be discovered first, introducing non-negligible overhead, as explained in 4.2.3.

Finally, a comment on the periodic probabilistic broadcasts in PSB scheme. A real network is always dynamic, and regardless which approach we select, a network area detection algorithm would have to be executed periodically, to capture the changes in network topology due to node failures or additions. The PSB broadcasts address this issue elegantly, serving both to stabilize PANA and to disseminate information on these network area changes.

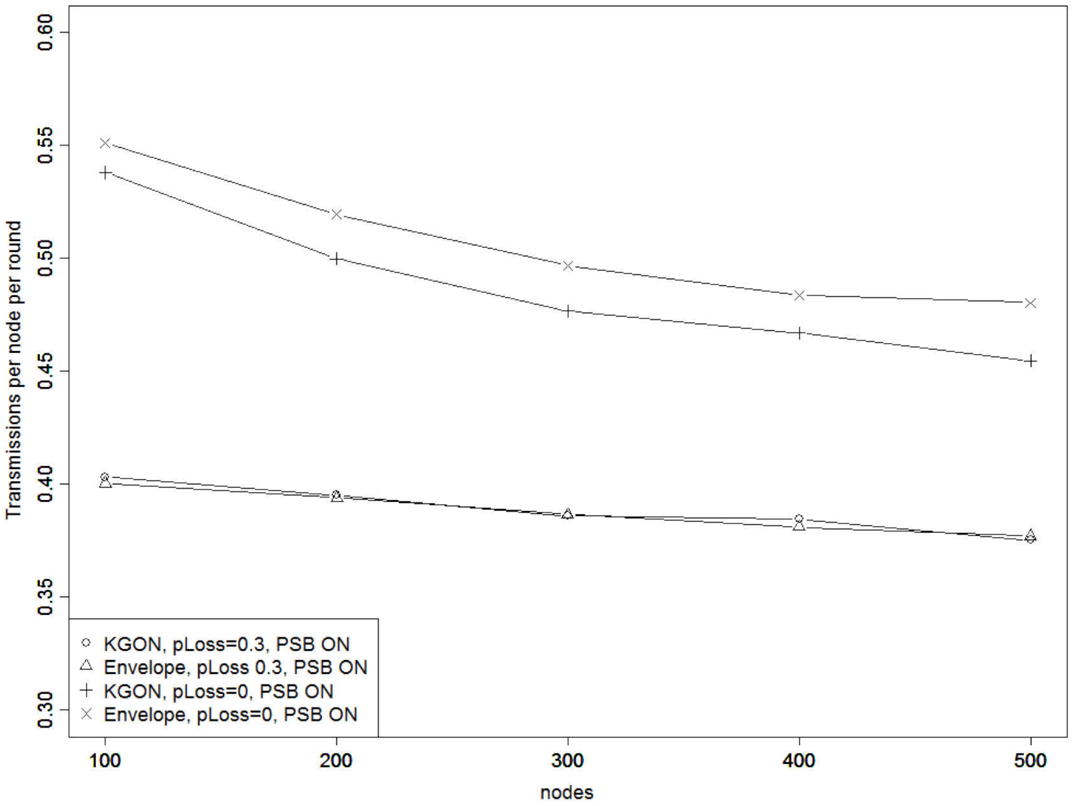

Fig. 51: Number of messages per node per round from initialization till stabilization time.

4.6. Related Work

A ‘boundary estimation problem’ known from WSN research [Sin04][Now03] is a problem of energy efficient detection of the isolines – defined as boundaries along which sensor readings are constant. Algorithms in [Sin04][Now03] use hierarchical computation and produce isolines which are $O(\sqrt{n})$ in size. Authors in [Bur06] redefine the boundary estimation problem for the WSN as the problem of representing a complex geometric shape realistically but using a small memory space. They seek an approximating polygon so that the approximation error does not exceed a given threshold. Because of this condition, the output size (number of points of the approximating polygon) is a priori unknown. The algorithm is suited for two-tiered network architectures with computationally strong nodes in an upper tier.

These boundary estimation/approximation algorithms require computationally strong nodes. Moreover, they require that initial, raw data is first gathered at the processing node prior to isolines calculation. In the addresses scenarios this initial information is identity of nodes with sensor readings fulfilling given criteria. In our case, input of algorithms [Sin04][Now03] are the perimeter nodes. Contrary, without information which nodes belong to the border of the network, ‘boundary estimation problem’ approaches are not applicable for the network area estimation.

The problem of identification of perimeter (border) nodes in WAHNs is addressed in [Fek05]. Authors propose a decentralized solution that requires second-order neighborhood information. The nodes locally compute their ‘restricted stress centrality’ (a graph-based metric), and they assume them as the perimeter nodes if the value of this metric is higher than a given threshold. However, there is no guarantee that a node does indeed belong to the boundary. The threshold value is network-specific and a priori unknown so it must be found experimentally for each network which seriously limits applicability of the whole approach. In a similar approach proposed in [Khe09] each node tests locally whether it lies in the convex hull of any subset of its neighbors (this algorithm also requires the second-order neighborhood information). The test is applied up to m^3 times for each node, where m is the node degree, causing a significant computational overhead. A centralized solution for perimeter discovery proposed in [Wang06] assumes a node degree of at least 10. The method has eight execution steps, and during a single execution, the network is flooded several times, where the number of floods grows with the network size.

The applicability of the presented perimeter discovery algorithms to real networks is limited. They assume uniform node distribution [Fek05] and very high average node degree of 200 [Khe09][Fek05]. Real-world networks are both sparse, where majority of nodes have degree of 2 and 3, and are irregular [Mil06][Mil07]. In addition, an influence of packet loss on the performance of the presented perimeter discovery algorithms is missing and can lead to algorithms’ failure. Finally, the discovery of perimeter nodes is only the first step towards a comprehensive solution that provides network area information to all nodes. As the subsequent step, needed in the ‘boundary estimation problem’ approaches, it would be necessary to disseminate this information to other network nodes.

There exist also a body of geometric approaches on linear [Jar73][Gal06] [Mor07] and nonlinear [Pen99][Mio07] shape preserving representations. For example, we examined the feasibility of popular and relatively simple Bézier curves, used to model smooth curves that seem like appropriate for modeling smooth border of an ad-hoc network. We found out that their representation is not efficient: a 4th degree Bézier curve needs four points on 2D plane for defining them; when using four connected Bézier curves of 4th degree we would have to use twelve points. Moreover, the computational overhead connected with use of nonlinear approaches, is too high for nodes with limited computational capabilities. On example of simple, cubic Bézier curves, nodes would have to locally execute a parametric calculations with a quadratic complexity in order to calculate a curve.

Polygons are widely used as a shape-preserving approximation and they can be simply manipulated even by nodes with low computational capabilities. The convex hull is a well-known polygon-based approximation of a set of points [Jar73][Raw87]. Convex hull is the smallest polygon that contains all points in a set estimated (in our case: all perimeter nodes). There are convex hull algorithms for the distributed systems where complexity for each node is linear [Gho83]. However, we do not use the convex hull to describe the network area for the following two reasons:

a) unknown and potentially big number of points in a convex hull may cause big traffic overhead, and b) the convex hull cannot adequately represent networks of a concave shape (Fig. 52). Our target wireless ad-hoc networks have an arbitrary shape.

Problem of computation of a polygon that best describes the region occupied by a set of points is addressed in [Gal06], where different goals of such description are discussed and methods based on Voronoi Tessellation and Delaunay Triangulation are compared. In [Mor07] a method using a *k*-nearest points for choosing next point of the possibly concave-shaped polygon describing the input set of points is proposed. However, the proposed methods do not scale with the system size, because in all these methods descriptor size is $O(n)$ where n is set of points on the plane, what causes excessive communication overhead, see 4.2.2.

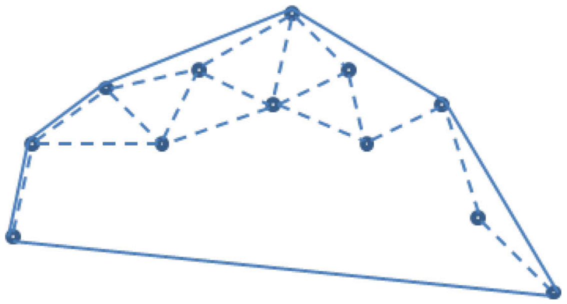

Fig. 52: Convex hull (solid line) does not describe a concave-shaped network well.

4.7. Conclusion and Future Work

The protocol PANA (Polygon Approximation of the Network Area), presented in this chapter, aggregates the nodes locations into a ‘network area’ approximation. ‘Network area’ expresses the geographical area occupied by network nodes and even more precise, the area where the network is able to communicate, i.e., it represents communication coverage. Information on the *network area* can be used in a wide spectrum of wireless applications, for instance in the applications calculating network capacity and coverage, network repair systems and data replication schemes.

Moreover, information on the network area is obligatory for assigning data to network nodes in GHT-like data stores, which use the network area as an address space. However, no appropriate protocol for a determination of the network area was proposed yet and network area was assumed to be known, what is not true in case of real-life ad-hoc networks that arise as an effect of a decentralized processes and occupy irregular geographical areas. PANA gives information on network area to all nodes and therefore enables the use of GHT-like data stores (e.g., [Rat02][Ara05][Tha06]) in real-life ad-hoc networks.

Network area estimation allows for a more efficient behavior of the geographical routing protocols, like GPSR [Kar00], too. In case where packet’s destination is inaccessible (not connected to source), a georouting protocol will forward it for possibly many hops before packet will loop and will be recognized as undeliverable. Such situation is possible when destination address was calculated or transmitted to the source incorrectly, or when the address was correct, but the network topology changed and there is no path anymore between destination and the source. Such change is especially likely in a disaster scenario, where a spatially correlated group of nodes can crush at once and previously connected network becomes partitioned. PANA reflects this information, and packets designated to such inaccessible location can be dropped, what saves systems limited communication resources.

We see the opportunities for PANA improvements and modifications. First improvement could concern the possibility of modification an existing view in case of the persistent, global changes in the network that render the old view as not valid any more. In its current form, PANA is only able to extend the network view and in case when persistent nodes removals are detected, algorithm reinitializes. However, a modification of a network view instead of overriding it might lead to a faster information dissemination, what can be important in a disaster scenario. Therefore, the possibility of a view reduction based on failure detector should be examined.

PANA is able to build simple polygons[61] as network descriptors only. It means that algorithm is not able to describe network holes. We believe that using self-intersecting polygons for expressing network holes is not the right approach and other options to express the existence of network holes should be examined. For instance, the knowledge about network holes (of a given minimum size) could be

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[61] Polygon consisting of non-intersecting line segments.

stored locally at their border nodes and around them, after a local hole-detection procedure is executed (this could be invoked when georouting switches to a void handling mode). Another possibility is to transport information about rough holes estimation (e.g., location and radius) throughout the network in a coded, efficient form (e.g., using a scalable Bloom filter [Alm07]).

Efficiency and scalability of PANA used in networks with localized traffic can be extended by setting up a maximum size of the node's view V_{MAX}. Nodes executing V_{MAX}-PANA would not extend their views beyond defined maximum size and after reaching this size they would stabilize and ignore information on changes in the network area outside V_{MAX} (centered with respect to node's location).

The limited view on the network area can be useful for applications that use localized queries, and in scenarios where all data (including replicas) is in a limited, known area (with respect to location connected with data), as it is in a location-centric storage (LCS) [Xin05][Dud09].

Chapter

5. Grid Approach for Limiting Extent of an Application's Activity

In this chapter the Grid Approach, a simple method for limiting the extent of activity of an arbitrary wireless application is proposed. The *extent of activity* expresses the geographical area where the network nodes are placed, which together perform a distributed application.

Limitation of such understood extent of application's activity is accomplished in the proposed method by logical division of the network nodes in connected partitions (*communication groups*) that are placed in geographical areas of defined size, shape and order (*operating areas*) and by restricting the application message exchange to the same connected partitions. Therefore, Grid Approach (GA) assumes that network nodes are aware of their geographical locations.

Grid Approach (GA) exploits the fact that in wireless ad-hoc networks with short links nodes may communicate directly only with nodes placed in their vicinity, and on the other hand, if two nodes are close to each other there is, most likely, a link between them. Consequently, in a connected wireless network nodes selected by a convex area are likely to create a connected network subsection.

One wireless application may use GA-generated membership information for limiting the extent of its activity, while at the same time, another one can be executed in the whole network (or within different GA groups). For example, an application for disaster detection can calculate averages of environmental readings within areas of restricted size (GA-limited application) while an alarming application that disseminates alarms in case of a detected disaster is executed in the whole network (network-wide application).

The GA is summarized in Fig. 53. Nodes executing GA locally calculate their *operating area id*, which express their position in the *grid* used for the *operating areas* definition. Connected nodes with the same *operating area id* mutually create a *communication group* that cooperatively executes given GA-limited application.

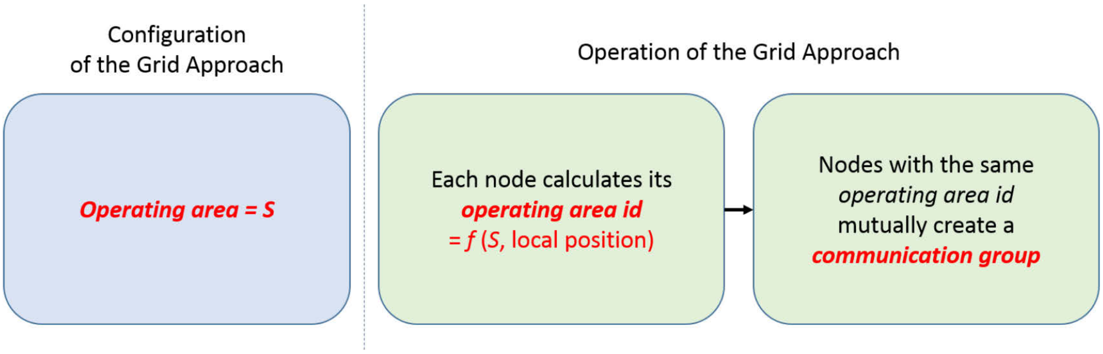

Fig. 53: Configuration and operation of Grid Approach.

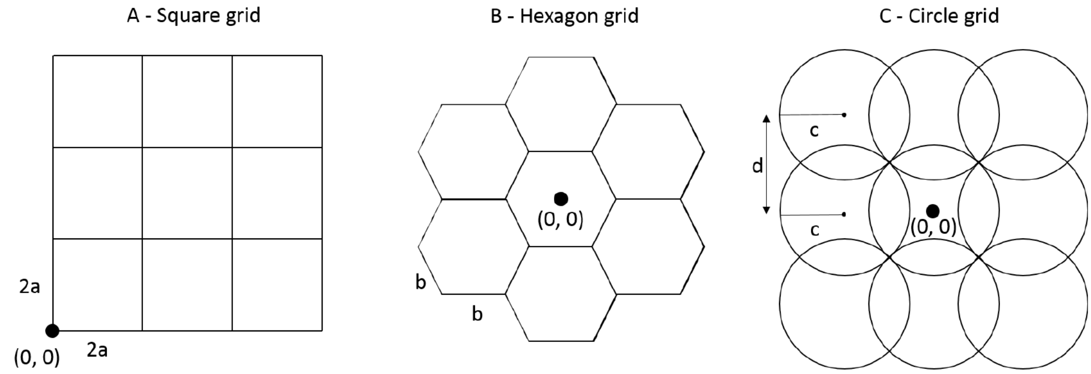

Fig. 54: Examples of grids used for the plane division. In Grid Approach a *square grid* (A) is used.

5.1. Grid

In Grid Approach we divide the plain using a *grid*. The parameters of a grid, i.e., size, shape and the relative location of areas to each other (see examples in Fig. 54) must be known to all nodes. An application may inform nodes in an arbitrary way about these parameters (e.g. by flooding, geo-multicasting, etc.), otherwise this knowledge can be built into an application at the installation time.

We use a grid that divides a plane into non-overlapping, square areas, but any other shape of network subsections can be defined and used in GA without changing the method's logic. For example a Hexagon or circle-grids can be used. When areas defined by the grid overlap, nodes in the overlapping areas (e.g., Fig. 54-C) must run multiple, independent application instances what results in more memory, and computational and communication overhead. However, when the application messages are small, data from different application instances (i.e., from different areas) produced at the same or similar time can be send in one transmission.

GA with non-overlapping square-grid divides up the network placement area into areas with no overlaps and no gaps (Fig. 54-A). The square-grid $a * a$ starts at point ($0, 0$) and divides the plane into squares with sides of lengths a. The grid position (i.e., its starting point) is not adjusted to the actual network topology. The problem of adjusting the grid position in such a way that the number of nodes in each square is optimized would be *NP*-complete and moreover it is questionable if it would bring an advantage in a large scale, irregular ad-hoc network.

5.2. Operating Area

Homogenous ranges isolated by grid are called *operating areas.* The operating areas control the extent of applications' activity.

5.2.1. Size

A size of the operating areas is a parameter of the method. It must be chosen accordingly to the application requirements, so the delivered services will be useful.

Some applications will use GA as a scalability measure to limit the number of nodes involved in the execution of the application. It will be important how many nodes are located in operating areas of a given size. This is a network-specific relation and must be assessed separately. Since GA divides the network blindly it does not give a guarantee on the number of nodes in operating areas and only network-characteristic distribution of number of nodes in operating areas can be expected. On the contrary, for irregular networks, as WAHNs, the number of nodes within different operating areas will differ. It is an important factor deciding about usability of Grid Approach and it will be assed in the Evaluation Section.

The size of the operating area is an informative factor for some applications. For instance, in environmental and disaster management applications information delivered by environmental sensors is often meaningful only with its location context describing the region characterized by given data, e.g., average temperature or minimum humidity. To do so, locations of all nodes that produced given characteristic can be transported through the network or the environmental application can use Grid Approach to divide the network in operating areas of desired, meaningful for the higher-level application size and deliver only two values: calculated aggregate and the operating area coordinates. We deliver appropriate protocol in Chapter 6.

Currently, there is no mechanism in GA that changes the operating area size or allows merging two operating areas. We discuss such possibilities in the closing section.

5.2.2. Identification Numbers

Based on the grid definition and own geographical coordinates, the nodes locally determine their position in the grid: their *operating area id*. In square-based GA a node *i* with coordinates (x_i, y_i) belongs to the *operating area (p, q)*, where:

$$p = \left\lfloor \frac{x_i}{a} \right\rfloor, q = \left\lfloor \frac{y_i}{a} \right\rfloor, \tag{9}$$

and $\lfloor \cdot \rfloor$ is the floor function[62]. An example of dividing the network with a square grid of size *a* starting at point (0, 0) and the resulting *operating areas ids* is in Fig. 55.

The coordinates delivered by the positioning system used may be inaccurate. A node might also be placed exactly on the operating area's edge. As a result, the same static node could be subsumed to different areas in the same algorithm run, and the algorithms might not deliver the correct results. The agreement on the nodes operating area can be realized by a simple additional subroutine, run at the node's initialization time. In this work, we assume that the process of assignment to nodes the operating areas ids is unambiguous.

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[62] Floor function maps the real number to the largest previous integer.

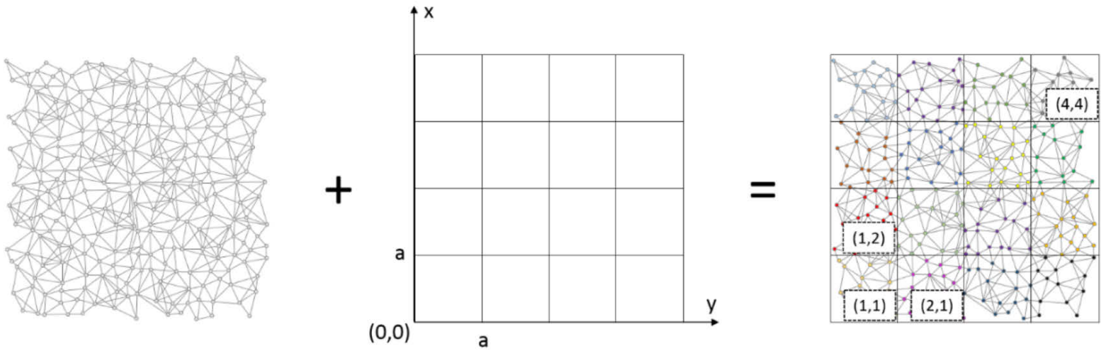

Fig. 55: An example of dividing the network in *GA*. All nodes in the same square of the grid have the same *operating area id*.

5.3. Communication Groups

In order to limit the extent of application's activity nodes identify their direct neighbors located in the same *operating areas* and exchange the application's messages only with these nodes. To accomplish this procedure messages are extended by the sender's *operating area identifier*. As a result, connected nodes belonging to the same *operating area* mutually create a *communication group* where the given application instance is executed and separated from execution in other communication groups.

In order to lower the amount of data sent, we can bound the value of the *operating area id* by adding *modulo* operation to the equations (9):

$$p = \mathrm{mod}\left(\left\lfloor \frac{x_i}{a} \right\rfloor, n\right), q = \mathrm{mod}\left(\left\lfloor \frac{y_i}{a} \right\rfloor, n\right) \tag{10}$$

The value of divisor *n* should be chosen in such a way, that nodes from different areas having the same *area id* are far enough from each other to assure that there can be no link between them. For example, divisor *n* equal seven for the grid granularity a= 3**R* (where *R* is nodes' communication range) guarantees, that nodes in different boxes of the same id are at least 21**R* away from each other, what makes their communication practically impossible (see 1.3.1.2). When using modulo operator with divisor seven, operating area ids uses only 6 bits for two coordinates. Thanks to this procedure, omitted in the presented equations for clarity, the amount of bits in wireless packets used for an area *id* is limited and small.

Because the position of the grid is chosen arbitrarily and the networks are irregular, it may happen that an operating area contains disconnected network segments. In such case the disconnected segments create separated *communication* group (see groups A and B in Fig. 56). Another unwanted effect are very small communication groups. Because the ad-hoc networks might be strongly irregular and additionally real-life WAHNs contain a significant number of nodes with just one neighbor [Mil02], GA may produce even a single-node communication groups.

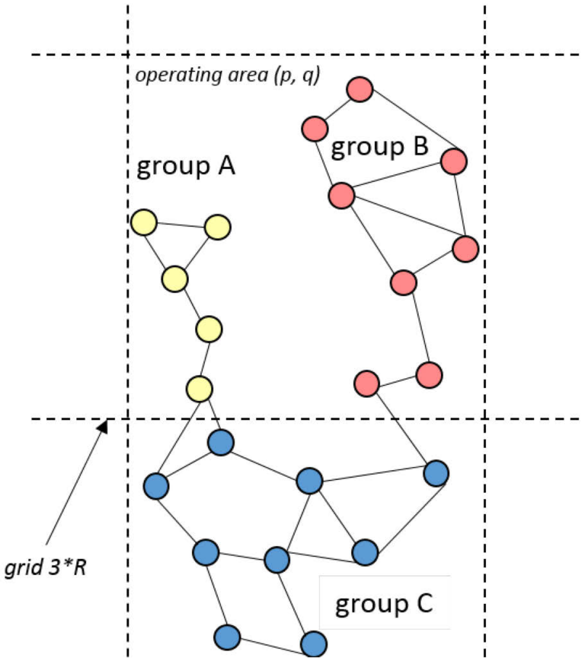

Fig. 56: Multiple *communication groups* in an *operating area* in a small wireless network.

In order to eliminate the one-node groups, a node that has no neighbors in its own operating area (a 'lonely node') joins a group of its connected neighbor by assigning itself the neighbor's *operating area id* and informing the neighbor about this fact. If a node has more than one connected neighbor and they are placed in different operating groups, the additional procedure is used, for example a closer neighbor is chosen. After a node detects a neighbor in its own area, it informs its current group member about leaving and goes back to the *operating area id* based on its location. We evaluate the group size in section 5.4.1.

5.4. Evaluation

We evaluated the Grid Approach by simulation executed in a custom-built Java simulator. We modeled stationary, location-aware, irregular, wireless ad-hoc networks with undirected graphs, where nodes create links only within their common transmission range *R* according to Unit Disk Graph (UDG) model i.e., two nodes are connected by link *if and only if* the Euclidean distance between them does not exceeds the communication range *R* [Cla90].

The node placement in tested networks matches the placement of existing, large-scale wireless networks [Mil07]. The distribution of node degree (number of neighbors) in this placement is strongly skewed to the left and has a long tail (see Fig. 1 in [Mil07]). Bridges and articulation points are frequent, and the networks contain both very sparse and very dense areas. Unlike the uniform-random node placement model, which is popular in the wireless community, this irregular placement allows for testing of communication group sizes produced with Grid Approach. To generate concrete topologies we used the non-deterministic NPART algorithm [Mil09] designed to create connected topologies with characteristic large-scale wireless networks. For an example of the network used, see Fig. 14 in Chapter 1 (p. 29).

We created 10 networks with 400 nodes each, and divided them into boxes of different size, from 1**R* to 10**R*, where *R* is nodes' communication range. We express the size of operating areas with the help of the nodes' common communication range *R*, in order to assess the size of communicating groups for wireless networks with diverse communication ranges. Presented results are averages over ten tested networks, within operating area size.

Through the evaluation, we assessed the number of nodes in the communication groups created by different grids. Also, we looked how often disconnected communication groups occur in the same operating area.

5.4.1. Communication Group Size

The size of communication groups built by the GA depends on the size of the operating area. A cumulative distribution function of the average communication group size for grids with very small granularity (2R, 3R and 4R) is shown in

Fig. 57. The bigger the operating area the more groups consist of multiple nodes (less curved CDF function).

Since division of the network in operating areas does not depend on the network position, some nodes (e.g., close to the network boundary) find themselves in gossiping groups which are too small for most applications. We analyzed the average percentage of nodes in very small (with sizes 1 or 2) and bigger (with size at least 6) groups. For box sizes greater than 2**R*, the Grid Approach creates groups which are in majority (78%) big enough for the disaster management alarming applications (at least 6 nodes), while boxes of size 2**R* are too small and create only 50% of big groups. Larger grids almost exclusively create bigger groups.

In order to increase the number of significant (big) communication groups, we evaluated a modified version of the algorithm (LPS+L, LPS + Lonely nodes) where nodes without any gossiping neighbors (and thus belong to the groups of size one) join one of the neighboring gossiping groups. The criterion for the choice can be geographical (the closest node) or quality-based (the neighbor with the best link). The LPS-L for boxes of size 2R and geographical criterion resulted in our experiments with 80% of gossiping groups of a size of at least 6.

Table 1: Ratio of smallest and bigger communication groups for small operating areas in Grid Approach without 'lonely nodes' procedure.

%	Grid 2Rx2R	Grid 3Rx3R	Grid 4Rx4R
|CG|=1	10.25	5.83	4.55
|CG|=2	8.85	6.30	3.80
|CG|>5	49.53	78.00	85.18

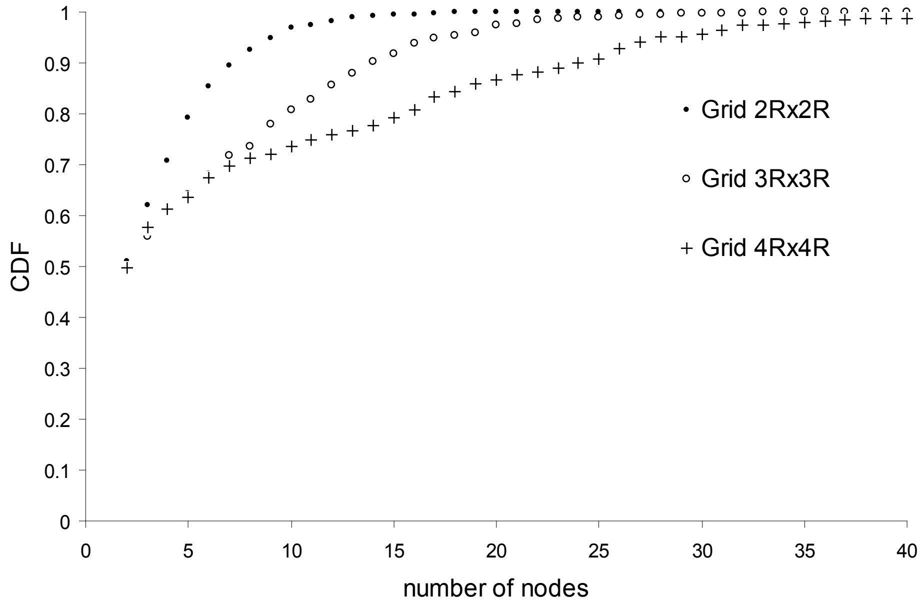

Fig. 57: An average distribution of the communication group size for small sizes of the operating areas, *R* is a common communication range.

5.4.2. Multiply Communication Groups in the same Operating Area

Multiple communication groups in the same operating area appeared relatively rare in the test networks. For all examined box sizes, not more than 15% of boxes covered the disconnected network parts. In almost all of these cases, we observed maximum *two* distinguished communication groups in the same operating area. An application using GA must be aware of the possibility that the nodes that execute it populate an area smaller than the defined operating area. However, this is also the case in all other communication groups, because the distribution of the nodes in the target networks may be irregular.

5.5. Related Work

Grid Approach divides the network in connected groups like well-known *clustering problem* and allows for message dissemination between nearby lying nodes like it is done by the *epidemic protocols with limited scope*. However, GA differs from this two techniques qualitatively. In the contrary to the clustering methods, GA does not introduce any additional message overhead, while it does not create a hierarchical backbone for the network-wide message dissemination nor it elects cluster heads. When comparing to the epidemic protocols with limited scope, GA puts a limit on the *geographical area* populated by nodes that execute the application, what might be important in some disaster management system, instead of limiting the path lengths or the time the packets are forwarded in the network, like the epidemic protocols with limited scope do. Second important difference is that GA allows the bidirectional communication within a group what allows for implementation of an arbitrary P2P application, while epidemic protocols execute the message dissemination only.

5.5.1. Clustering

Clustering in wireless ad-hoc networks can be defined as the grouping of nodes into manageable sets, called *clusters*. A cluster consists of a single cluster head and many member nodes. The goal of clustering in WAHNs is usually to avoid redundant topology information so the network can work more efficiently.

Clustering algorithms are often modeled as a graph problems, like minimum connected dominating set or spanning trees. In case of minimum connected dominating sets nodes in the dominating set represent the cluster heads and the other nodes are their neighbors. However, it is known that minimum connected dominating set problem is *NP*-complete. Additionally, an inherit dynamics of an ad-hoc network makes this problem even more difficult, while the changes in the network topology may render existing cluster structures not valid. Thus, various heuristics are used. Examples are protocols using Independent Dominating Sets [Bak81][Ger95][Oht03], Weekly Connected Dominating Sets [Che03][[Han06] or Connected Dominating Sets [Guh98][Das97-2][Wu01] [Gao05]. Other graph based clustering methods rely on the construction of spanning trees of the underlying network [Gal83][Awe87][Ahu89][Gar93][Ban00].

In sensor networks the clustering includes the problems of choosing set of active nodes and adjusting their radio power in order to extend networks life-time [Che14]. In the sparse WAHNs however, techniques from dense WSNs are not feasible as for the connectivity all network nodes should be operational. Also, in our goals networks, we assume a static communication range of nodes. For exhaustive surveys on the clustering methods in wireless ad-hoc and sensor networks see [Yu05][You06] and [Erc07].

Undoubtedly, traditional clustering is useful in the topology management, increasing the efficiency of a distributed algorithms and prolonging network's life-time. A set of clusters may provide the underlying physical structure with multicast communication for a higher level group communication which may effectively be used for resource allocation [Zah05][Lem06], fault tolerance, security key management, efficient routing or data harvesting. At the same time, clustering process is time and message consuming. Each node in the network is involved in message exchange during cluster head election and cluster assignment. Message overhead of known cluster approaches for WAHNs vary from O(*n* log*n*) to O(*n*), where *n* is number of nodes. Grid Approach differs from the clustering approaches in the following main aspects:

- No cluster heads are elected.
- The connectivity between neighboring groups is not supported (no backbone is constructed).

- Partitioning among nodes placed in the same operating area and variations in group sizes are possible.

In return, the network cost of dividing the nodes in groups in GA are *O*(*d*), where *d* is node degree. In a network where positions of direct neighbors is known (e.g., because it is required for other operations like georouting), the GA costs can be considered as *null*.

5.5.2. Epidemic Forwarding with Limited Scope

Epidemic algorithms refer to network protocols that allow rapid dissemination of information from a source through purely local interactions. In epidemic forwarding messages initiated by the source are rebroadcasted by neighboring nodes hop by hop until the entire network is reached. Epidemic forwarding with limited scope [Vah00][Faw06] on the other hand allows to limit the number of hops (or transmissions) of a data packet and can be used in data gathering applications, reactive mobile ad-hoc routing algorithms with caching or multicast algorithms. [Faw06] defines the self-limiting epidemic as a broadcast dissemination service for short messages in ad-hoc environments that is limited to a local scope around each source. [Vah00] defines epidemic routing as a problem of delivering a message with high probability to a *particular* host, while the usage of system resources (i.e., memory, network bandwidth, or energy) consumed in message delivery is minimized. However, epidemic forwarding with limited scope does not solve the problem of bidirectional communication among group of nodes in a wireless P2P application nor allows to limit the geographical area of the application activity, like the proposed in this work GA approach does.

5.6. Conclusions and Future Work

Grid Approach creates clusters of nodes (called ‘communication groups’) by performing a network tessellation with a defined *grid*, that describes so called ‘operating areas’ of a desired size. Nodes in resulting clusters have equal status, and the membership information is distributed: each node holds local knowledge of its direct cluster neighbors only. GA proposes to use this information for limiting the geographical extent of applications activity.

GA does not guarantee the average size of created groups, which depends on used grid granularity and the network characteristic; a number of small groups, potentially useless for the applications, usually appear. Nevertheless, in the evaluated, highly irregular topologies, which is unfavorable for GA-based tessellation, nearly 80% of clusters created with a 3*R*x3*R* grid, where *R* is nodes’ communication range, had a size of at least 6 and this result is better the bigger the grid’s granularity is. It is due to the fact, that ad-hoc networks with short links create topologies that spread in two dimensions and are not similar to chain topology.

Most important feature is that, in contrast to traditional clustering techniques, GA does not generate any communication overhead for creating membership information and can be used by systems that require scalability.

Some applications would profit from the possibility of a dynamic change of the operating areas’ size defining the location of cooperating nodes. For instance, such a need could be triggered when the number of sensors or the behavior of the observed environment changes significantly. A mechanism of dynamic adjustment of an operating area size is therefore an interesting follow-up of the presented work. One efficient w-r-t communication idea is to implement a mechanism that unites or divides existing areas based on communication groups’ local decisions. Alternatively, a new grid definition can be transported through the network, what allows for choosing the operating areas with better granularity than the joint or divide scheme.

Chapter

6. Localized Aggregation for WAHNs

Gossip-based aggregation does neither require maintenance of any global network state nor knowledge of network structure for solving the *aggregation problem*, defined in [Baw03] as:

The Node Aggregation Problem:

Device a scheme to enable any node in a P2P network to issue a query that computes an aggregate function (MIN, MAX, COUNT, SUM, AVG) over data residing at nodes in the network.

Therefore it is an attractive approach for solving the aggregation problem in resource-limited wireless ad-hoc networks (WAHNs). However, existing gossip-based aggregation is designed for graphs with good expansion and is inefficient in the target, sparse and irregular wireless ad-hoc networks [Kem03]. As such, it could not be used in the disaster management scenarios that motivate this work (Scenario 3 and 4 in Sections 2.2.3 and 2.2.4).

In this chapter, we propose Local Push-Sum (LPS), a gossip-based aggregation algorithm for location-aware WAHNs that solves following *localized aggregation problem*:

The Localized Node Aggregation Problem:

Device a scheme to enable any node in a wireless ad-hoc network to issue a query that computes an aggregate function (MIN, MAX, COUNT, SUM, AVG) over data residing at nodes within defined vicinity.

Proposed LPS protocol calculates *local* aggregates, i.e., aggregates based on sensor readings of nodes placed in some vicinity, instead of calculating aggregates of the whole network. To accomplish that, LPS uses the Grid Approach (Chapter 5) proposed earlier in this work and is therefore an example of a Peer-to-Peer application that uses Grid Approach as a building block for achieving scalability. LPS is based on the gossip-based aggregation protocol push-sum [Kem03], but is tailored for resource-limited wireless networks and can be used in a network with an arbitrary expansion.

In LPS nodes communicate only with their immediate neighbors and by using a wireless broadcast. This removes a need for the multihop communication, increases algorithms efficiency and leads to faster information dissemination and shorter stabilization time. Besides using less bandwidth than the original version, LPS removes the need for the leader election process while counting network nodes (present in the original version) and terminates autonomously. Thanks to this it can be successfully used as a building block for autonomous disaster management applications in large-scale wireless networks, for instance in early warning systems considering events that can be detected based on exceeding threshold values of the environmental readings.

We analytically analyze LPS worst case efficiency in wireless networks with low expansion (Section 6.3) and we evaluate it by simulation on irregular WAHNs with topologies reassembling topologies of existing ad-hoc networks.

6.1. Push-Sum Algorithm

The push-sum algorithm proposed in [Kem03] solves the following *node aggregation* problem defined in [Baw03]: in the network of *n* nodes, where each node *i* holds a value x_i, compute an aggregate function of these values in a decentralized and fault-tolerant fashion.

In push-sum, nodes iteratively share *values* to be aggregated and *weights*, used by the algorithm for the correct aggregate estimation, with randomly chosen partners. For some aggregates, such as the *sum* of initial values x_i or a *node count* aggregate, the push-sum requires an asymmetric initialization: only one node must initialize a designated weight with 1 while all others initialize it with 0. For the average, all nodes initialize uniformly.

For expander graphs [Hoo06], the push-sum algorithm converges to the target value in at most:

$$O(\log n + \log\tfrac{1}{\varepsilon} + \log\tfrac{1}{\delta}) \tag{11}$$

rounds with probability (1-δ), where ε is the relative aggregation error [Kem03] and a round is a period when every node sends a message and receives zero, one or more messages from other nodes.

For topologies with slowly mixing random walks, like topologies of wireless ad-hoc networks, no convergence speed guarantees or estimates exist yet. This renders the push-sum unusable for the non-expanders, as the termination condition is unknown. Also, push-sum does not solve the asymmetric initialization problem for the *node count* aggregate needed in alarming protocols, what prohibits the objective self-organization of such applications. Furthermore, push-sum does not allow the aggregation extent to be localized. Finally, the costs of creating the appropriate system view (i.e. *partial view* [Lei10]) that enables choosing random gossiping partners among system members are not included in the algorithm's analysis. This overhead cannot be ignored and should be preferably avoided in the resource-restricted wireless environment.

6.2. Local Push-Sum Algorithm (LPS)

We propose the local push-sum protocol (LPS), a fully self-organized modification of the push-sum protocol [Kem03] optimized for locality-aware, stationary, wireless ad-hoc networks (WAHNs[63]). LPS calculates an *average* of numeric values x_i hold by aggregating nodes and *counts* the aggregating nodes using a diffusion process, as in [Kem03].

In order to calculate the average and count, the nodes maintain three gossiping values: sum $s_{t,i}$ and weights $w1_{t,i}$ and $w2_{t,i}$. Gossiping values are initialized by a starting node as (x_i, 1, 1) and by all other nodes as (x_i, 1, 0), where x_i represents a sensor reading of a node *i*. At the time 0, the starting node *i* is activated and sends the messages to its gossiping partners $GN_{0,i}$ and activates them, too. At each subsequent time step *t*, each active node follows the algorithm:

LPS algorithm:

```
Let {($s_r$, $w1_r$, $w2_r$)} be all tuples sent to i in round t-1
Let $s_{t,i}:=\Sigma_r s_r$, $w1_{t,i}:=\Sigma_r w1_r$ and $w2_{t,i}:=\Sigma_r w2_r$
Let $GN_{t,i}$ be a set of gossiping partners of i in round t
Send $(\frac{s_{t,i}}{|GN_{t,i}+1|}, \frac{w1_{t,i}}{|GN_{t,i}+1|}, \frac{w2_{t,i}}{|GN_{t,i}+1|})$ to all $j \in GN_{t,i}$ and i (itself)
$\frac{s_{t,i}}{w1_{t,i}}$ and $\frac{w1_{t,i}}{w2_{t,i}}$ are the estimates of, respectively, the average and node count in step t.
```

In the following subsections, we propose four significant contributions for the classic push-sum-gossiping protocol, which lead to localization of the aggregation, less communication traffic and faster algorithm termination with tunable accuracy: 'Avoiding multihop communication', 'Limiting the aggregation extent', 'Efficient initialization of the protocol' and 'Self-organized algorithm termination'.

6.2.1. Avoiding Multihop Communication

Instead of choosing a single, random gossiping partner, as it is in original algorithm, we let the nodes to share their gossiping values with their direct wireless neighbors only. Eliminating the need of contacting a random neighbor leads to the elimination of the overhead of the multihop communication with a remote partner (Fig. 1) and moreover it eliminates the overhead connected with the search for a random gossiping partner, too. In return, each node redistributes its data in equal parts among multiply gossiping partners in a single round and with a single 'send' operation, because all gossiping partners of a node that are its immediate neighbors can be contacted at once by a single (local) broadcast transmission. This improves the convergence time and economizes limited bandwidth and energy.

During a runtime, nodes may leave or join the network, because of the instability of links and nodes, disaster, network expansion, etc. The nodes must track the

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[63] See Sections 2.2 and 2.5 in Chapter 2.

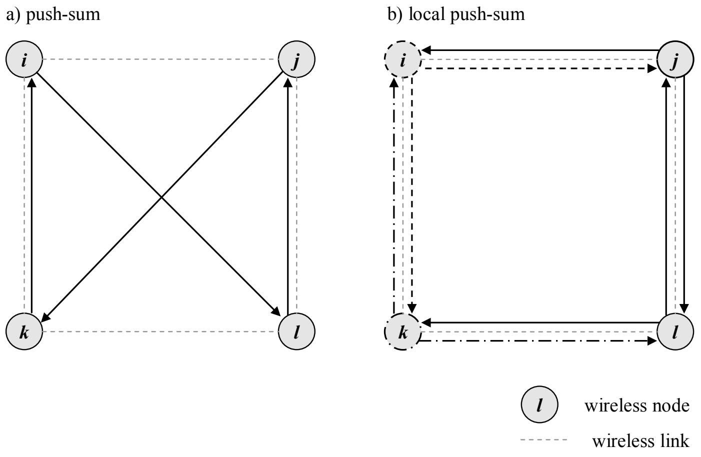

Fig. 58: Messages sent in one round over a small wireless network. Messages in push-sum (a) must be sent in multiply hops, when the direct wireless link does not exist, while LPS (b) sends messages only to direct neighbors. In the above example, node *i* executing the push-sum algorithm (a) sends a message only to one, randomly chosen gossiping partner, node *l*, while in LPS the same node *i* sends one message simultaneously to its both direct neighbors, nodes *j* and *k* (b).

number of their active gossiping partners *GN* and adjust the gossiping messages accordingly.

LPS distinguishes two cases of changes in the *GN* set. When a gossiping partner disappears temporarily, gossiping messages created for a lower number of partners are issued. Reappearing of the gossiping partner assures that the algorithm will converge (i.e. the mass conservation property [Kem03] is secured). When a node notices a permanent absence of any active gossiping partner, the current aggregation process is biased until the next aggregation round starts. However, a disappearance of a single node influences only aggregates' calculation over one aggregation area.

The problem of detecting neighbors can be solved by one of the existing techniques, such as that based on the signal-to-noise ratio (SNR), a MAC layer link detector or a heartbeat link detector (HLD) [Mar04]. In LPS we assume the existence of one of these mechanisms, so the nodes can correctly determine their current direct neighbor set and can also correctly decide if a neighbor has failed permanently or is only temporarily unreachable.

6.2.2. Limiting Aggregation Extent with Grid Approach

In order to limit extent of aggregation to nodes placed in defined vicinity, the Grid Approach is used. In Grid Approach a chosen grid divides the network area in *aggregation areas* of defined size and all nodes are allowed to exchange messages only with their direct neighbors within the same *aggregation areas.* Connected nodes belonging to the same aggregation areas create in that way gossiping groups that calculate aggregates characterizing given aggregation areas only.

To accomplish that, gossiping messages are extended by the sender's *aggregation area identifier*. Nodes calculate their own *aggregation area identifiers* based on their location and grid parameters (see equations (9)(10) from Section

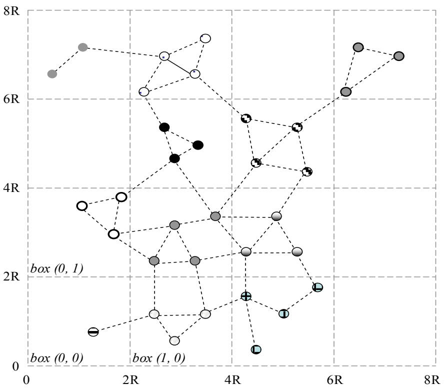

Fig. 59: Grid 2R×2R over a wireless network. Connected nodes in an aggregating area (grid box) create a gossiping group.

5.2.2), and identify their direct neighbors located in the same aggregation areas in order to adjust the set of gossiping neighbors $GN_{t,i}$ and, accordingly, values in gossiped messages (lines 3 and 4 in LPS Algorithm, Section 6.2).

The size of the grid determining aggregating areas is application-specific and must be chosen carefully. The bigger the aggregating area, the more nodes are involved in the single LPS instance what increases the robustness of the calculated aggregates against compromised readings and environmental noise, but also increases the convergence time. In section 6.4 we present LPS evaluation for different aggregation area sizes.

An example of division of a network area in aggregating areas and resulting gossiping groups in a small WAHN is presented in Fig. 2.

6.2.3. Efficient Initialization of the Protocol

LPS calculates the *average* of sensor readings x_i and *counts* the nodes in a gossiping group. Because of the *count* aggregate, the gossiping must be initialized by exactly one, starting node. Only this node assigns '1' to the weight responsible for calculating the count aggregate (*w2*). All other nodes must initialize like ordinary nodes with weight *w2* equal '0'.

While in push-sum an external process selects the starting node, in LPS this process is transparent to the higher application. For the automatic selection of the starting node, we supplement each gossip message with a gossip run *id*, and use the distributed selection of the winning round proposed in [Ter07-1]. In that scheme, each node initializes as a starting node by choosing a random gossip *id* and starting a gossip round with that *id*. When a node receives a gossiping message with another gossip *id*, it ignores it when this gossip *id* is smaller then the current one. If the incoming message has a higher gossip *id*, the node reinitializes as an ordinary node and joins this gossip run. For the connected network, this procedure assures that at some time all nodes will take part in the single run of the algorithm with the highest gossip *id*.

Although this procedure is effective, it generates a number of useless messages. The LPS limits the number of starting nodes: a node initializes the gossip if and only if it is closer to some point in space known to all nodes (such as the starting grid point) than all of its gossiping partners. Our experiments show that only a very small group of nodes start simultaneously when using our heuristic, in those rare cases when the gossiping groups create a particularly positioned concave shape. In most cases, only one node in the group starts the gossip, which saves bandwidth and energy consumption.

6.2.4. Self-organized Termination

Our experiments with push-sum and LPS for different placement models and the wide range of variances of values to be aggregated, showed that after a short starting period (measured in the number of rounds), the values of estimates change monotonically: differences between node's estimates in consecutive rounds are always smaller. We exploit this fact for the termination condition.

Let the nodes to remember the value of the old estimate (from the round *t-1*) and to calculate the relative change δ_S in every round *t* as:

$$\delta_S = \frac{\left|estimate_{t-1} - estimate_t\right|}{estimate_{t-1}} * 100\% \quad . \tag{12}$$

A node assumes it has converged to the target value if within consecutive *T* rounds it does not detect any significant relative change δ_S (above the threshold *delta*) in its aggregate's estimate. A node stops gossiping also in the case, when all of its gossiping partners converged.

6.3. Convergence of the LPS

The speed of push-sum (11) is known only for graphs with good expansion [Kem03]. Wireless ad-hoc networks do not have good expansion: short range links and ad-hoc node placement result in weekly connected networks with articulation points and bridges [Milic06].

Formally, we can express the value of a node's *i* gossiping sums $s_{t,i}$, $w1_{t,i}$, $w2_{t,i}$ in each round *t*, as:

$$s_{t,i} = \sum_{l \in GN_{t-1,i}} \left(\frac{1}{GN_{t-1,l}+1} * s_{t-1,l}\right) \quad , \tag{13}$$

$$w1_{t,i} = \sum_{l \in GN_{t-1,i}} \left(\frac{1}{GN_{t-1,l}+1} * w1_{t-1,l}\right) \quad , \tag{14}$$

$$w2_{t,i} = \sum_{l \in GN_{t-1,i}} \left(\frac{1}{GN_{t-1,l}+1} * w2_{t-1,l}\right) \quad , \qquad (15)$$

where $GN_{t,i}$ is the set of gossiping neighbors of *i* in the round *t*, subjective to every node.

For analysis of the convergence speed, we model a stationary, homogenous, locality-aware wireless ad-hoc network with a unit disk graph (UDG) model [Cla90]. In this model, a link between two nodes exists if and only if they are placed at most R away from each other, where R is the common communication range. As a consequence, the set of gossiping neighbors in the LPS does not change and we can replace GNt-1,i with GNi in (13)–(15). Nevertheless, expressions for calculating the number of needed rounds t after which aggregates converge to the target value represent the class of NP-hard maximum flow multi-commodity flow problems [Kle95].

At this time, we notice that the higher the average nodes degree the bigger the average number of gossiping neighbors GN_i. For higher average number of gossiping partners, gossiping sums change faster according to the values of other nodes and node's local estimates approach global aggregates in smaller number of rounds. In other words, a graph will have bigger expansion and the convergence speed will taper to (11) from Section 6.1.

In order to draw the upper bound for the convergence speed of LPS algorithm over irregular networks, we assume that the connected network has got the worst (smallest) possible expansion, namely that a network is a chain. For the chain network, first and last node have one gossip neighbor and all other two, so for the UDG model expressions for the gossiping sums (13)-(15) take a simpler form: for the chain of *N* nodes x_i, $i \in (1..N)$ each gossiping sum $g_{t,i} \in (s_{t,i},\ w1_{t,i},\ w2_{t,i})$ can be expressed as:

$$g_{t,i} = \frac{1}{2} g_{t-1,i} + \frac{1}{3} g_{t-1,i+1} \qquad \text{for } i=1,$$

$$g_{t,i} = \frac{1}{2} g_{t-1,i-1} + \frac{1}{3} g_{t-1,i} + \frac{1}{3} g_{t-1,i+1} \qquad \text{for } i=2,$$

$$g_{t,i} = \frac{1}{3} g_{t-1,i-1} + \frac{1}{3} g_{t-1,i} + \frac{1}{3} g_{t-1,i+1} \qquad \text{for } i \in (3..N-2),$$

$$g_{t,i} = \frac{1}{3} g_{t-1,i-1} + \frac{1}{3} g_{t-1,i} + \frac{1}{2} g_{t-1,i+1} \qquad \text{for } i=N-1,$$

$$g_{t,i} = \frac{1}{2} g_{t-1,i} + \frac{1}{3} g_{t-1,i-1} \qquad \text{for } i=N.$$

Using regression analysis, we deliver polynomial equations for the number of rounds needed as a function of number of a chain length and the required accuracy. Note, that for this number of rounds (see plot in Fig. 60) all nodes estimate given aggregate at least with the desired accuracy. Our experiments show however, that majority of nodes reach the target corridor much faster and the average accuracy is much higher than nominal.

Among *average* and *node count* aggregates, *node count* has slower convergence time, what is an effect of the higher variance of the gossiping sums used for calculating node count estimates (see step 5, LPS algorithm, Section 6.2). For reaching the good node count, LPS must run for many steps, until the weight *w2* (initially equal 0 on all nodes but one) spreads equally in the network. Averages on the other hand depend on sensor readings xi that have usually much smaller variance then weights *w2*. As our experiments show (Section 6.4.1), *average* converges usually an order of magnitude faster than *node count*.

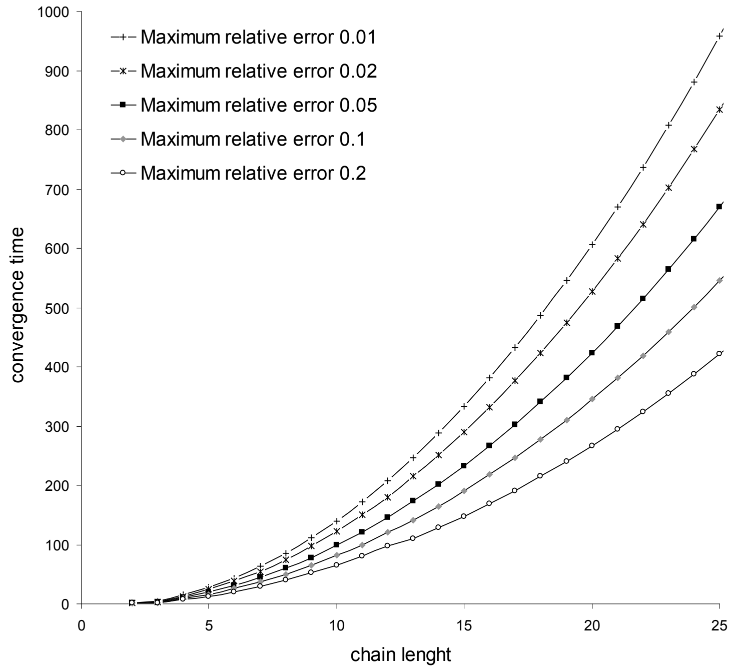

Fig. 60: Convergence time of the node count aggregate for the chain network.

Hence, we limit the LPS convergence time for the UDG model of any network with *N* nodes, as the convergence time of the *node count* aggregate in the *N*-nodes simple chain, where the gossip is started by one of the edge nodes (the worst case). However, we are interested in the convergence time for the *aggregating area* that limits the geographical extent covered by gossiping group (*box* in Fig. 59). To do so, we look at the maximum chain length that can be included in such area (the worst case).

Aggregating areas are squares in LPS. For simplicity, we express the square sizes with the nodes common communication range *R* and a small natural number *k*.

Only a limited number of wireless nodes with communication range $R > 0$ can be put in a square so that they create a simple chain. At some point, new nodes will always create loops in the topology, which increase mixing times and improve the box's convergence time. We approximate the length of the maximum simple chain in

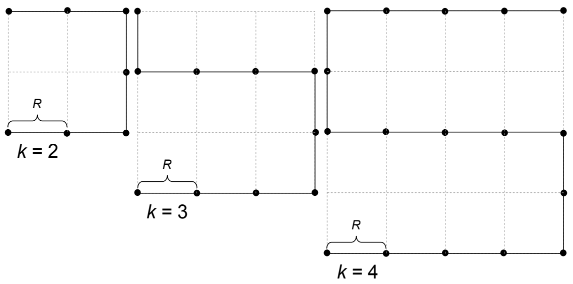

Fig. 61: Grid-chains in squares *k*R* × *k*R* for different *k*.

the *k*R* × *k*R* square by the length of the *grid*-chain in that area, where the *grid*-chain is the longest simple chain in a *k*R* × *k*R* square grid graph (Fig. 4). The length of *grid*-chain equals *g*, where:

$$g = \begin{cases} \left\lceil \frac{k}{2} \right\rceil * (k+2), & k = 2*n+1; \forall n \in Z \quad (odd \quad k) \\ \frac{k}{2} * (k+2) + (k+1), & k = 2*n; \forall n \in Z \quad (even \quad k) \end{cases} \tag{16}$$

The convergence time of LPS for the box *k*R* × *k*R* is then limited by the convergence time of the *g*-nodes simple chain, where *g* is calculated based on *k* according to (16).

It is possible to put a longer simple chain of wireless nodes in the *k*R* × *k*R* square, but the probability of such node placement is low: most of the box's area is covered by the transmission ranges of at least two nodes.

We will show that the convergence time of LPS for a *grid*-chain of length *g =f(k)* (16) is a valid upper limit for the convergence time of the majority of tested irregular topologies for the UDG model.

6.4. Evaluation

We evaluated the LPS by simulation, on graphs representing wireless networks modeled with the UDG model (see Network Model in Section 2.5). Simulations were executed in the custom-built Java simulator.

We ran the LPS extensively on 10 networks with 400 nodes each, divided into boxes of different size, from 1*R to 10*R, where R is nodes' communication range. All presented results are averages. Depending on the box size, we acquired from 153 (for box size 10*R) to 2368 (for box size 1*R) data points for Fig. 62 and Fig. 63.

The node placement in tested networks matches the placement of existing, large-scale wireless networks [Mil07]. The distribution of node degree (number of neighbors) in this placement is strongly skewed (see Fig. 1 in [Mil07]). Bridges and articulation points are frequent, and the networks contain both very sparse and very dense areas. Unlike the uniform-random node placement model, which is popular in the wireless community, this irregular placement allows the testing of gossip-based aggregation in harsh but realistic conditions. To generate concrete topologies we used the non-deterministic NPART algorithm [Mil09] designed to create connected topologies with characteristic [Mil06][Mil07]. For an example of the network used, see Fig. 14 in Chapter 1.

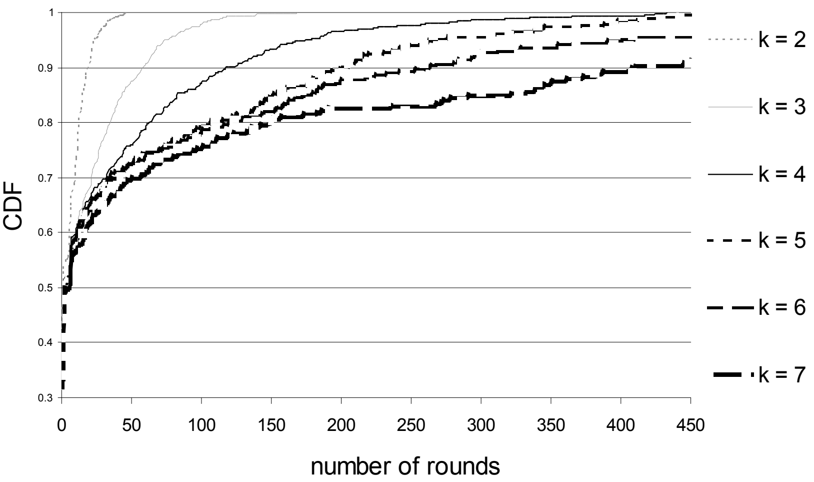

Fig. 62: Convergence time (measured in number of algorithm rounds) for the node count aggregate in boxes of size *k*R* × *k*R* for different *k*, and the $\varepsilon = 5\%$.

Through the evaluation, we assessed the convergence time to the real values, the parameters for self-stabilization and the number of nodes in the gossiping groups created by different grids. Also, we looked how often disconnected gossiping groups may occur in the same box.

6.4.1. Convergence time

We used 12 termination conditions for convergence time evaluation: for ε of *average* and *node count* of 0.1%, 1%, 2%, 5%, 10% and 20%. We tested the LPS on random (different ranges) and exponential distributions of the values x_i. We noticed that the variance of the aggregated values alone determines the algorithm's convergence time. In presented experiments, the sensor readings to be aggregated are random values from range 0-200. In all cases, *average* converges faster then *node count*, up to an order of magnitude.

Convergence time to the real values (known to the omnipotent observer), measured in the number of rounds, depends on the box size and on the desired relative aggregation error ε:

$$\varepsilon = \frac{|real\_value - estimation|}{real\_value} * 100\% \quad . \tag{17}$$

The convergence times for irregular networks varies strongly. Fig. 62 shows the results for the *node count* aggregate where the maximum ε is 5%. However, the majority of nodes reach the target corridor much faster. We focus on the majority of cases, and show the maximum convergence time for the 80th and 90th percentiles of the boxes tested. We compare these results to the convergence of the networks with grid and *grid*-chain placement. In regular grid placement model, nodes are located at intersections of a rectangular grid where a size of a cell is chosen so that all nodes that are not on the grid border have degree of four. Grid networks with the average degree of four converge to the true value always faster then irregular topologies. With a probability of at least 0.9, the irregular topologies we tested converge to the true value in the number of rounds upper-bounded by the convergence time of the *grid*-chain. Typical convergence times for small boxes are moderate (Fig. 63).

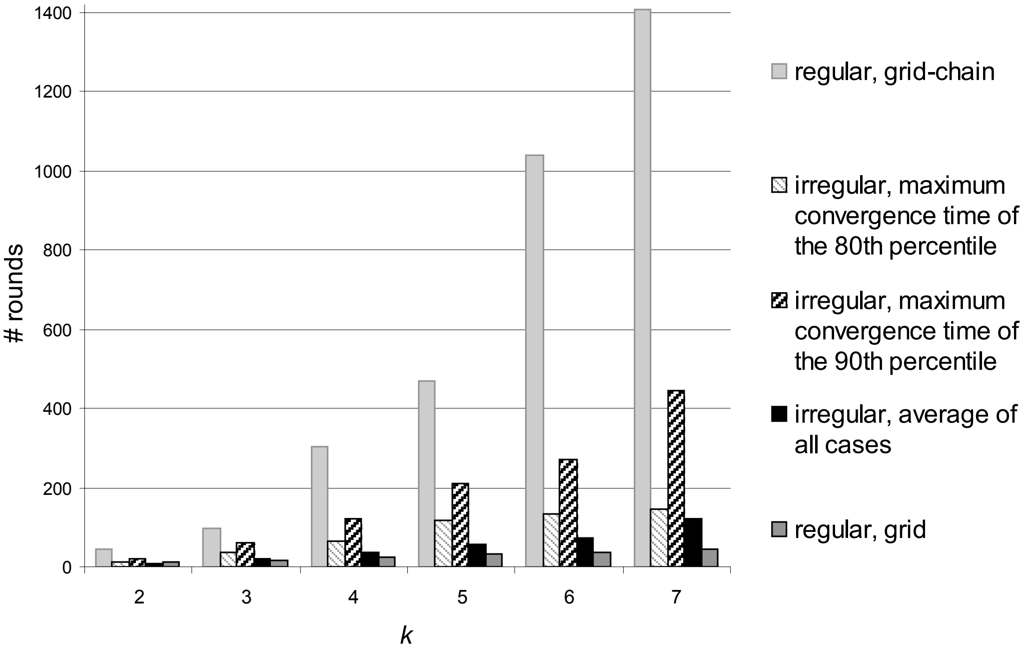

Fig. 63: Convergence time for the *node count* aggregate for grids *k*R* for different *k*, for the 80th and 90th percentile of boxes, compared to the times needed by the *grid*-chain and grid topologies. ε = 5%.

For comparison, we also implemented the original push-sum. Like in the LPS, we assumed that nodes have knowledge only of their immediate neighbors, so the random gossiping push-sum partner is chosen from this set. Thus, the overhead connected with creating a system partial view that allows for choosing a system-wide random gossiping partner is avoided. The original push-sum without the limitation of the aggregation scope converges in 3300 to 15300 rounds for the evaluated networks, comparing to maximum of 420 rounds of 90th percentile of all nodes in LPS for the box sizes up to 7**R* (Fig. 63). For fairness, we evaluated push-sum with the extent limitation (defined by a *k*R* grid). With the extent limitation, the push-sum needs always at least two times more rounds to converge than LPS for the same aggregation scope. Explanation is that evaluated networks have degree distribution with a mode equal 2 [Mil07].

6.4.2. Self-stabilization

To assess proposed self-stabilization process, we test the LPS for an extensive set of values of parameters *T* and *delta*. The stabilization process is based on the changes in the *node count* only. Initially, nodes' estimates of the *node count* are 1. Our approach proves correct: the algorithm stabilizes and all the nodes calculate aggregates with a satisfactory error ε. Moreover, the same parameters can be successfully used for aggregation areas of different sizes. For example, for *T*=5 and *delta*=10%, aggregates in all examined aggregation area sizes are calculated with an average error below 5% and with the standard deviation below 4% (Fig. 64); the number of needed rounds reflects the results for the 90th percentile in Fig. 63. We conclude, that *delta* is the maximum relative error for any calculated aggregate.

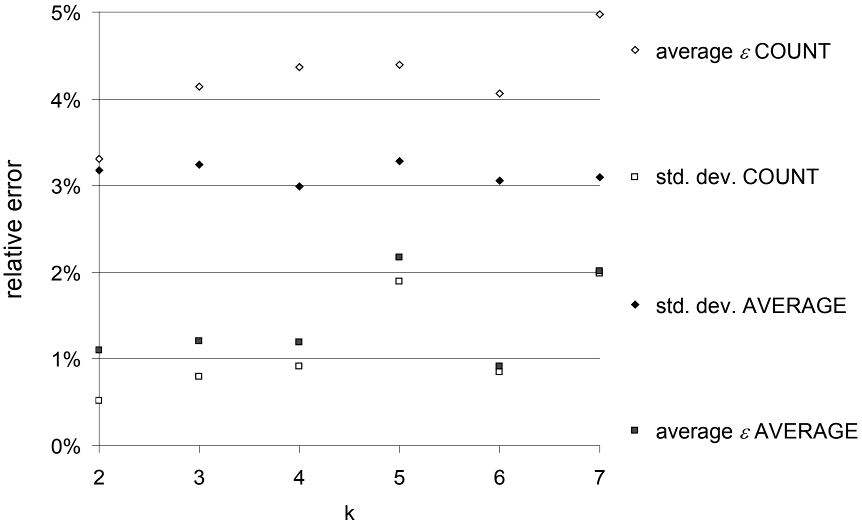

Fig. 64: Accuracy of aggregates for self-stabilization with T=5 and delta=0.1, for different aggregation area sizes *k*R*.

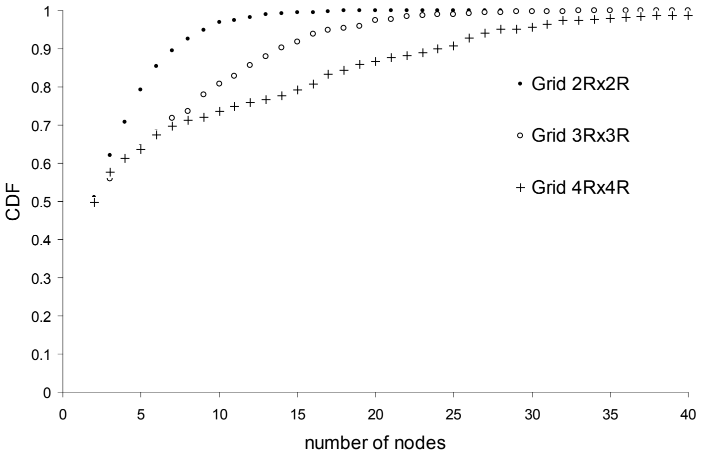

Fig. 65: The average distribution of the group sizes for small grid granularities.

6.4.3. Gossiping group size

The size of gossiping groups in LPS depends on the network topologies and parameters of Grid Approach only. Since we have used the same topologies for LPS evaluation as for the Grid Approach evaluation, all results can be seen in Chapter 5. We notice only, that even for operating areas of a small size 2**R*, where *R* is nodes communication range, 80% of all gossiping groups where of a size at least 6, what may be big enough for the target DM processes. However, because LPS calculates *average* and *node count* simultaneously, at each time a node can assess the results and decide on the validity of calculated aggregates based on the estimation of the number of nodes that took part in the aggregation.

As we already stated in Chapter 5, disconnected gossiping groups in the test networks appeared relatively rare and in almost all of these cases there were maximum two distinguished gossiping group in one aggregating area. An application using LPS must be aware of the possibility that the collected data describes an area smaller then the defined box. However, this is also the case in all other gossiping groups, because the distribution of the nodes in the target networks may be irregular.

In order to assure that the nodes do not cover smaller geographical area than required for the event detection, it is possible to allow the nodes to build the local view on the geographical extent of the gossiping groups with the Grid Approach-limited PANA protocol with the simplest estimator.

6.5. Related Work

Reaching agreement among remote processes is one of the most fundamental problems in distributed computing. Decentralized methods for consensus problem that are known to work well in a relatively static environment, e.g., for parallel applications [Zhu07], are studied in [Cha82][Cha77][Tsi86]. One approach to improve fault tolerance in dynamic distributed systems, which is measured by the maximum radius of impact caused by a given fault, is presented in [Sco04], but this approach assumes a reliable communication channel between each pair of system processes.

There are different approaches to the distributed decision problem in wireless networks. On one spectrum there are voting techniques, that explore network topology, i.e., define cluster-heads in the network graph [Stojme02], find multi-point relays [Qay02], or members of a backbone tree [Chla87] which build a connected dominating set of the graph in order to establish some hierarchy for the voting scheme (e.g., decision trees [Bah10]). However, this class of solutions suffers from two main problems. First, if a member of dominating set fails, sensors that depend on the failed member may not receive information. This affects the reliability of the network and voting process, and requires expensive mechanisms to maintain dominating sets over time. Besides, using dominating sets affects the load-balancing properties of the network, and drains the battery at some nodes much earlier than others. Wireless applications usually prefer uniform energy consumption across nodes, and therefore, strict hierarchical assignment of responsibility may not be suitable. Voting schemes are feasible for small and stable networks like sensor networks for detecting a residential fires [Bahn10], but are not a good solution for intrinsically dynamic and big wireless ad-hoc networks.

An alternative to voting for reaching a consensus is *aggregation of sensor readings* [Makhl09][Makhl14], where aggregation is a process that combines several numerical values into a single representative value. This value can be a counts of input values, their sum, average, minimum or maximum.

Distributed aggregation methods can be classified into architecture-specific approaches and generic approaches [Mass06]. Gossip-based aggregation is a generic approach and has been adapted to work with highly distributed systems [Ter07-1]. Besides multiple trees [Baw03] and statistical estimators, it has successfully been used in P2P overlay networks modeled with random multigraphs [Ter07-2]. However, the existing protocol overhead and dissemination speed are only guaranteed for P2P-style networks with good expansion [Kem03][Ter07-1][Vou07].

Nevertheless, we need to reduce the message load significantly in order to make gossiping feasible for wireless ad-hoc networks, modeled with sparse graphs with low expansion. Additionally, current protocols rely on existence of the leader node for counting nodes and compute aggregates over the whole network instead of some (defined by application) localized geographical regions.

One known method for using geographic information in wireless networks is to increase the mixing times of random walks [Dim06][Ben08]. However, this method creates additional routing messages and does not provide information from specific geographic areas. Agglomerative clustering proposed in [Sch09] can find nodes located nearby in a locality-unaware network based on communication latencies. But, this method only works well in P2P systems with balanced delays.

A broadcast-based gossip for calculating averages is proposed in [Ays09]. The method calculates totals over nodes in the whole network and is not able to count the nodes. Moreover, the calculations at node have a rather high complexity, what might be a problem for some nodes with limited computational capabilities.

Estimating the ratio of sensor types in a cluster of static or mobile nodes and making it available for all the cluster members is addressed in [Tab14]. However, our goal is to inform all nodes in a group about the absolute number of sensors in that group.

An algorithm for estimating the number of neighbors of a node in a mobile ad-hoc network based on the nodes identifiers is presented in [Eve11]. The target networks consist of powerful end-devices, such as mobile phones or PDAs, where memory and energy constrains are not a problem. The idea is based on assigning the random identifier to each device. The same paper proposes to count the network nodes based on the broadcasting the estimated number of neighbors, and number of neighbors of the neighbors and so on. In the target networks of this dissertation, which are possibly battery–powered, strong resource limited WAHNs, such amount of the communication overhead and memory footprint connected with the proposed method are infeasible.

LPS is a generic approach to a distributed aggregation problem, and it builds upon gossip-based aggregation [Kem03]. However, LPS uses local broadcast as a communication primitive only and exploits geographic information by logically restricting the gossiping to local groups, which leads to four desired properties:

- Instead of having aggregated values of the whole network, LPS provides aggregated values from geographic areas of a specific size.
- Termination of the LPS is much faster than for the push-sum (two order of magnitude for the evaluated networks with 400 nodes), and independent from the network size.
- Within an aggregation group, node failures are automatically covered by other group members. Each node has a current estimation of the group's aggregated data, which makes LPS highly fault tolerant.
- Also, wireless neighborhood information is used in LPS for selecting gossiping partners. All immediate neighbors of a node are reached simultaneously in a single ‘send’ operation, what further reduces the bandwidth and energy consumption.

6.6. Conclusions and Future Work

In this chapter we studied a gossip-based aggregation approach in irregular, wireless networks. Gossiping is already applied to a wide set of volatile and distributed systems for fault tolerant information aggregation and dissemination. Yet, our results show, that the amount of created signaling traffic and the measured protocol runtime makes gossiping hardly applicable to address disaster management applications in large wireless-ad-hoc networks.

A gossip-based aggregating algorithm for disaster management monitoring and alarming systems executed in WAHNs must respect both DM requirements and WAHNs' characteristic and limitations. These are the need of high accuracy and location-context of delivered aggregates, promptness of receiving the results, self-organization of the algorithm, efficiency of communication and scalability. LPS supports these requirements in the following way:

LPS is efficient with respect to communication overhead. It uses small messages (less prone to transmission errors), uses no unicast i.e., no multihop communication, no flooding, but the efficient local broadcast instead. Additionally, because of the extent of algorithms activity is limited (according to the requirement of the specific DM higher-level application), the communication overhead scales with the network size and grows only when the extent of aggregation grows.

LPS delivers localized aggregates, and the extent of its activity is limited by the Grid Approach proposed within this dissertation (Chapter 5). Limitation of LPS extent combined with the possibility of tuning the expected accuracy of the delivered results (i.e., the relative error of aggregates approximations) results in foreseeable and tunable convergence times.

LPS is robust to nodes failures. It reacts to a persistent loss of any aggregating neighbor with its reinitialization, so the mass conservation property is fulfilled and the algorithm always delivers correct results. This feature is important in any unattended and unreliable WAHN and especially in target DM applications, where nodes may be damaged due to a disaster.

Node density is volatile in some areas of a network with a non-uniform placement model. As a result, areas of the same size include a varying number of sensors. LPS makes it possible to assess the importance of delivered aggregates like *average* or *maximum* by counting the nodes that deliver raw data. *Node count* increases the significance of information, and can be directly used by the alarming application, e.g. by issuing an alarm only when at least *k* sensors have recorded an increased temperature.

We showed by extensive simulations that LPS converges up to two orders of magnitude faster than the current state of the art gossiping approach for the tested networks. In addition, we propose to freely adjust the error rate δ_S which allows for choosing the desired level of accuracy versus efficiency for each application.

We plan to evaluate the LPS with a realistic channel model (such as the path loss model). Another remaining challenge is the frequency at which the node sends gossiping messages that could depend on the density of nodes in the aggregation area. We believe that more bandwidth and energy can be saved with an adapted frequency model.

Chapter

7. Conclusions, Contributions and Future Work

This dissertation is about improving efficiency, scalability, and fault-tolerance of P2P algorithms in static, location-aware Wireless Ad-Hoc Networks (WAHNs) used in Disaster Management (DM) support.

WAHNs, self-organized, covering huge geographical areas, and equipped with environmental sensors are an attractive platform for disaster management applications. Their employment in DM processes like collecting data for environmental modeling, emergency communication in a disaster zone and automatic hazard detection can help to avoid and lessen impact of natural disasters on humans and their property. To realize these goals, WAHNs must deliver reliable, efficient, scalable, and self-organized, Peer-to-Peer (P2P) data storage and distributed consensus services.

Because of a strong resource-limitation of the wireless environment, it is a challenge to reach efficiency and scalability of any distributed algorithm in a wireless network. In disaster scenarios, we additionally consider:

- Possibility of a spatially correlated network damage caused by a disaster, which may happen in any part of the network (see Section 2.6).
- Situations where no information on network topology and traffic pattern is available (unknown disaster/sink location).
- Networks, which arise as an effect of a decentralized node placing process, which therefore may be irregular and contain both very sparse and very dense parts.

An assumption made in this dissertation is that wireless network is *location-aware*, meaning that each node knows its own position and positions of its direct neighbors. Such assumption is not new. The same location information is already used in geographic routing protocols (e.g., [Kap00][Li12][Xia12][Gha15][Jum13] [Sid13]) and GHT-Geographical Hash Tables, key-data stores designed for the wireless networks ([Rat02][Gho03][Tam04][Tha06]). However, as we showed in Chapter 3, there is an important information missing that prohibits the efficient use of all this approaches in WAHNs. This is an information of the geographical area of the network, i.e., *network area*. Without this information, geographical key-data stores cannot distribute data in the network evenly and instead they store them on small subset of nodes only (see Section 3.5.4). In addition, without network area information the geographic routing protocols will unnecessary consume resources to forward packets to inaccessible destinations.

In order to improve efficiency, scalability, and fault-tolerance of chosen P2P algorithms in location-aware WAHNs we propose to employ two new high-level position-based information based on nodes' local position-awareness. This new position information are:

1) *Approximation of the network area*, where *network area* expresses the geographical area covered by the wireless network. Knowledge of network area let the nodes to recognize how big the network is and where it is situated, and consequently allows them to recognize their own relative position in the network.
2) *Group membership* determined by node placement. Groups are build out of connected nodes occupying disjoint areas of a defined size and shape. Nodes executing a P2P algorithm may perform the algorithm information exchange only with neighbors with the same group identification number. Consequently, the geographical area where an algorithm instance is active is limited.

This information present at each network node improve or make operational following P2P algorithms in WAHNs:

Efficient routing: geographical routing is the only routing protocol that avoids network flooding at any time. With the knowledge about *network area,* any geographical routing protocol may instantly drop routs to inaccessible destinations and increase overall efficiency. It increases also the communication efficiency of GHT – like key-value stores as they use geographical routing for packet forwarding.

Scalable key-value store: GHT – like key-value stores are scalable data stores designed for location-aware wireless networks. Information on *network area* allows for implementation of GHT – like systems in real-life WAHNs of unknown node placement area. Without network area information the GHT – like data store does not load balances resources nor allow for realization of the structured replication (SR).

Fault-tolerant replication: With the information on *network area*, the GHT-based structured replication [Gho03] can be used for reaching one-damage tolerance to a disaster defined as in Section 2.6. Another possible option is location-centric data replication scheme similar to [Xing05], where with use of network area information number and locations of replicas is system-wide known.

Data aggregation: Gossip-based data aggregation that uses proposed *group membership* can efficiently calculate local aggregates over sensor data in environmental and alarming applications. Local data aggregates can be also used for efficient resource allocation, leader election, synchronization based on voting or other tasks in distributed systems.

7.1. Contributions

The main contributions of this dissertation are:

- Polygon Approximation of Network Area (PANA)
- Grid Approach (GA), and
- Local-Push Sum (LPS).

Polygon Approximation of Network Area (PANA) ([Gei13], Chapter 4) simultaneously discovers and approximates the geographical area covered by the wireless network and delivers this approximation to all network nodes. PANA approximates network area with a small descriptor, which in spite of its small size is able to describe the network area of irregular ad-hoc networks accurately (F-measure = 0.9 for all tested networks, from 50 to 500 nodes). PANA is robust and efficient, because it is gossip-based and uses small messages for constructing the approximation of the real network area.

PANA enables the use of GHT-like stores, including Resilient Data-Centric Storage R-DCS [Gho03] in real-life, irregular WAHNs. Information on network area improves also efficiency of georouting protocols as GPSR [Kar00]. With this information, geographic routing protocols may avoid routing to inaccessible destinations. Especially in bigger wireless networks, this might save significant amount of network resources. In addition, many other applications can profit from knowing the network area, e.g., for the diagnosis of the network communication- of sensing- coverage, or in the scenario of reconnecting network partitions with an autonomous flying nodes [Sim12].

Grid Approach (GA) (Chapter 5) is a cost-free (w.r.t. the communication) algorithm for division the network nodes in *operating groups* by distributed assigning each node a group identification number based on its location and application-defined network area tessellation. Connected nodes located within the same sub-area of a defined size and shape have the same group identification number, determined by a sub-area location. Effectively, Grid Approach divides network area in disconnected geographical areas of a limited maximum size. A P2P algorithm may use this information for limiting the set of nodes that execute it. This on the other hand allows assessing the expected costs of a P2P algorithm executed in such groups, and therefore allows designing scalable systems. Additionally, the Grid Approach allows disaster management and environmental applications to directly incorporate vicinity and location information into their decision processes (e.g., calculate average humidity over square areas 100 m^2 large). Grid Approach assumes that definition of grouping areas (grid) is present at each node, as well as local position information.

Local Push-Sum (LPS) ([Gei10][Gei12] Chapter 6.2) calculates localized aggregates of a numeric values. LPS is a modification of the push-sum, an existing gossip-based data aggregation algorithm for well-connected networks [Kem03] that does not scale in sparse WAHNs. LPS on the other hand is redesigned and adjusted to wireless environment: it uses local broadcast as a communication primitive only and initializes and terminates autonomously, fulfilling therefore the goals of efficiency and self-organization. LPS limits the geographical area of its execution and reaches scalability with the Grid Approach. In order to assure the quality of information for the higher-level application, LPS is easily able to couple aggregates and for instance along to the *average* or *maximum* of sensor values it can deliver the *number* of aggregating nodes, too. Counting is one of the most difficult aggregation in a distributed system and its enabling in WAHNs is an important contribution of this dissertation.

All proposed protocols exploit natural communication scheme in wireless networks: the local broadcast, what increases their communication efficiency. They tolerate packet loss and do not put any expectations on the topology of the underlying network, nor density of nodes distribution, what makes them usable in any ad-hoc network. They are evaluated in a custom-built Java simulator, on graphs representing irregular wireless networks with 50 to 500 nodes. Used node placements follow the characteristic of the existing, large wireless ad-hoc networks [Mil07] with both very sparse and very dense parts. Networks are generated with the probabilistic algorithm NPART [Mil09]. Wireless effects in the simulations are modeled by introducing a non-zero packet loss probability for all links.

Additional contributions of this dissertation is the analysis of the upper bound of the convergence time for the gossip-based aggregation in non-expanders, counted in algorithm rounds (Section 6.3), and the analysis of the lower bound of the number of the perimeter nodes in any irregular wireless ad-hoc network (Section 4.2.1). In addition, in the course of this dissertation has been proven, that the existing structured overlays that do not use the physical locations of nodes in a decision process for resource allocation are not able to supply fault tolerance to spatially correlated crash of nodes even for a large number of replicas of each object [Gei09].

7.2. Future Work

Continuation of presented research includes: advanced evaluation of presented algorithms, improvements and modifications to PANA and Grid Approach, incorporation of proposed new position information in data stores and analysis thereof, and finally delivering comprehensive solutions to the motivating DM scenarios: emergency communication system, disaster data storage, and early warning system.

First issue is better evaluation of the presented algorithms. It includes use of a more realistic propagation model that captures various wireless effects like e.g., diffraction, reflection, refraction and signals interference (see Section 1.3.1.2). (Presented results are based on the same probability of a packet loss for all links.) In addition, evaluation with less difficult topologies that these generated with NPART [Mil09] is needed. For instance, the poor results of LPS w.r.t convergence round for some nodes (Fig. 63) can be related to these network parts created by used NPART algorithm, which are difficult for a gossiping algorithm, e.g., when two very dense network areas are connected with a bridge, which creates a bottleneck for the information dissemination. In the real – life application, the density of nodes in very dense parts might be reduced by an additional subroutine so the LPS (or PANA) must not deal with very high node density.

There are also many open questions considering PANA and ideas for its usage and improvement. For instance:

- What is the relation of PANA’s accuracy versus to the number of vertices used for the network area approximation? (In this dissertation only 4 and 8 vertices are evaluated).

- The frequency of exchanging views can be adjusted so the algorithm uses less communication. We noticed that algorithm with message losses greater than zero and without PSB converges faster. It is a subject of research to find a rule for the optimized forwarding rule.
- Currently, PANA can extend its network view, and in case of observed permanently lost neighbor, the algorithm initializes. Is there an efficient way to incorporate information about lost neighbors in the old PANA view without overriding it?
- In its current form, PANA describes network's area outside border only. Is there any efficient way to represent network holes (void areas) and further improve approximation of a real network area? Follow up research is about efficient and scalable representing of such information.
- Another direction is research on 3D model of PANA, as in the real-world nodes are not placed on the plane. Or is the 2D approximation good enough?
- Finally, we propose to research on PANA as a fault detector in ad-hoc and sensor networks as in [Che06][Elh07], as PANA's network view represents alive nodes and combined with historical views, can be used to deduce new faults.

Considering Grid Approach, an analysis of the influence of the inaccuracy of positioning system on the group membership is needed, as well as design of necessary subroutines that prevent flickering between two groups for the nodes placed on the border of the grid. Also, an useful extension of Grid Approach is dividing network with a honeycomb-, instead of a square-grid, as they express vicinity even better. Another question is how Grid Approach could be used in order to introduce hierarchy of operating areas.

Finally, there is an open question, how heterogeneous nodes would change usability of the proposed algorithms.

GHTs distribute replicas with density depending on the network area. With the knowledge of the network area a replication system can adjust density of replicas in such way that desired distance between replicas is reached. Future work should include incorporation of PANA into GHT-like data stores (with special emphasis on [Rat02] and [Gho03]) and their structured replication (SR) and a resilience analysis for this systems and assumed fault model (see Section 2.7). The influence of the accuracy of the network area estimation on the resulting data survivability should be assessed.

Another approach for reaching data fault-tolerance that can be developed since network area is known is to use location centric storage directly and design new replication scheme that is efficient (with respect to number of copies and search) and guarantees distance between replicas independently form the network size. Sketch of such replication scheme is in Fig. 33 on page 77.

Another continuation of the presented research is a search for the replication scheme that reaches data *availability* and not only its *survivability* (see Section 2.7), where we understand data availability as data’s instance reachability from a querying node. This topic is important in WAHNs used for DM support, because of the danger of network partitioning due to a disaster.

Finally, a follow up research is delivering comprehensive solutions to the motivating DM scenarios: emergency communication system, disaster data storage, and early warning system, that use protocols and algorithms proposed in this dissertation, as described in Section 2.3.

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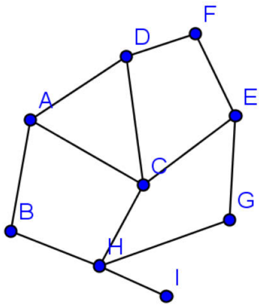
Glossary

Actuator	An electrical, hydraulic, or pneumatic device that controls a mechanical device, e.g., turns it on or off, adjusts or moves.
Algorithm	A set of rules that precisely defines a sequence of operations be performed. Algorithms exist that accomplish calculation, data processing, and automated reasoning. Specific algorithms are named method, procedure, or technique. The process of applying an algorithm to an input to obtain an output is called a computation.
Articulation point (AP)	A node (or vertex) whose removal partitions the network (graph).
Bandwidth (or capacity)	The data rate measured in bits per second.
Bridge	A communication link (or edge) whose removal partitions the network (graph).
Capacity	The total amount of data that can be transmitted in the network.
Communication overhead	Number of transmitted (sent) data packets.
Contention zone	A geographical area that belongs to the communication ranges of multiply nodes.
Congestion zone (Conzone)	A part of the network where nodes gather and transmit data at higher rates than other network nodes.
Directional (beam) antenna	Antenna that radiates greater power in one or more directions allowing for increased performance on transmit and receive and reduced interferences.
Extent of an application's (or algorithm’s) activity	The geographical area where the network nodes are situated, which together perform a distributed application (or algorithm).

Face	A region of a plain bounded by edges of a planar graph that are not crossed by any other edge, including the outer, infinitely large region.  In the picture, the faces are ABHC, CEGH, ACD, CDFE, (the inner faces), and ADFEGHIHB (the outer face).
Geographical information (position information)	Information about network nodes' geographical locations.
Geographic routing, (georouting, position-based routing)	A routing principle that relies on geographic position information.
Isotropic antenna	Antenna that radiates equal power in all directions and has a "spherical" radiation pattern.
Local broadcast (broadcast)	Sending a message to all nodes direct neighbors.
Locality-aware network	A network where each network node knows its own geographical position.
Natural hazard	A natural geophysical, climatological or biological phenomena that can have devastating impact on humans and their property. Examples: earthquake, wildfire, flood.
Network flooding (flooding, network-wide broadcast)	Sending a message to all network nodes
Network node (node)	Network device that is capable of sending, receiving, or forwarding information over a communications channel and originates, routes and terminates the data in the network.

Node degree	Number of direct neighbors of a node, i.e., neighbors connected with a single link.
Omnidirectional antenna	Antenna that radiates radio wave power uniformly in all directions in one plane, with the radiated power decreasing with elevation angle above or below the plane, dropping to zero on the antenna's axis. This radiation pattern is often described as "doughnut shaped".
Peer-to-peer (P2P) architecture	A distributed architecture that partitions tasks or workloads between peers. Peers are equally privileged, equipotent participants in the application (system, network). Peers form a peer-to-peer network of nodes.
P-waves (Compressional waves, Seismic Primary waves)	*Compressional* waves (i.e., change the volume of the material they pass) that are longitudinal in nature. P waves are pressure waves that travel faster than other waves through the earth to arrive at seismograph stations first, hence the name "Primary". These waves can travel through any type of material, including fluids, and can travel at nearly twice the speed of S waves. In air, they take the form of sound waves, hence they travel at the speed of sound. Typical speeds are 330 m/s in air, 1450 m/s in water and about 5000 m/s in granite.
Service	A functionality that enables access using a defined interface to one or more systems capabilities, exercised consistent with specified description, parameters and policies.
S-waves (Shear waves, Seismic Secondary waves)	*Shear* waves that are transverse in nature. Following an earthquake event, S-waves arrive at seismograph stations after the faster-moving P-waves and displace the ground perpendicular to the direction of propagation. Depending on the propagation direction, the wave can take on different surface characteristics; for example, in the case of horizontally polarized S-waves, the ground moves alternately to one side and then the other. S-waves can travel only through solids, as fluids (liquids and gases) do not support shear stresses. S-waves are slower than P-waves, and speeds are typically around 60% of that of P-waves in any given material.

Scenario	A narrative description of interactions between users and computer system and the usages of the computer system. In this work used to show reasoning behind decisions made when designing proposed protocols.
Shake map	A map showing ground movement and shaking intensity following major earthquakes.
Simple polygon	Polygon consisting of non-intersecting line segments.
Throughput	An average rate of successful message delivery over a communication channel.
Wireless Ad Hoc Network (WAHN)	Wireless infrastructure-less network. Nodes are connected dynamically in an arbitrary manner communicate with each other using only decentralized and distributed methods. Connections between out-of-range nodes is realized through multihop communication. All nodes behave as routers and take part in discovery and maintenance of routes to other nodes in the network as needed.
Wireless Mesh Network (WMN)	Networks formed by a group of end-users, called Mesh Clients (MC), and an infrastructure that supports and facilitates their communication with the Internet (mesh of wireless points MPs or mesh routers MR); these infrastructure mesh nodes are mostly static, have more capabilities than MCs and relay but do not generate data traffic. In broadband WMNs, the infrastructure also includes some Mesh Gateways, a.k.a. Mesh Portals or Base Stations, that are connected to the backhaul Internet tier via e.g. fiber or a wireless Point-to-Multipoint (P2MP) protocol such as 802.16

Selbständigkeitserklärung

Hiermit erkläre ich, dass

- ich die vorliegende Dissertationsschrift selbständig und ohne unerlaubte Hilfe angefertigt habe,
- ich die Dissertation an keiner anderen Universität eingereicht habe und keinen Doktorgrad im Fach Informatik besitze, und
- mir die Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät II vom 17.01.2006, zuletzt geändert am 13.02.2006, veröffentlicht im Amtlichen Mitteilungsblatt Nr. 34/2006, bekannt ist.

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