Self-aligning wireless communication for first responder organizations in interoperable emergency scenarios

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Abstract - *This paper presents wireless gateways (WGW) - a wireless communication solution for first responder organizations. The system is based on 802.11 wireless LAN technologies. The core of the system is a self-alignment of directional antennas which span a kind of mesh network. The links between the WGWs can be up to 3.5 kilometers (line of sight), without the need of human interaction for setting up the network. Further the WGW offers wireless connectivity to end devices such as tablets of the first responders. The installation of a network based on WGWs does not need IT know how and can be performed by first responders on their own.*

Keywords: wireless gateway, first responders, communication, interoperability, mesh network, automatic alignment

1 Introduction

Both data and voice communication between first responders of the same emergency organization or across different organizations, is crucial for an effective cooperation during disaster management. Especially data communication offers the possibility to exchange relevant information across organizational and national borders, making the help more targeted and faster, thus saving more people.

One of the major problems right now is that after a large scale disaster the existing broad band network is often partially destroyed or overloaded. As the communication network is essential for a better and more efficient collaboration between first responders there is a critical need for setting up alternative communication means. In such a case, another issue arises: first responder organizations are not experts in setting up communication equipment, thus these systems have to be designed such that they are easy to setup.

The wireless communication system proposed in this paper is part of the work done within the IDIRA (Interoperability of data and procedures in large-scale multinational disaster response actions) [2] European project framework. IDIRA's main aim is to improve cooperation across responding organizations by enabling interoperability between different information systems that can mutually act as data sources or data consumers, and with connected devices used on the field. This leads to more efficient multi-national and multi-organizational disaster response actions.

IDIRA starts from the concept that interoperability has to be addressed at both organizational and technical level. This means that involved actors have to align their workflow and procedures first (organizational level). At technical level, the possibility to share data, leading to more efficient cooperation by working on the same set of information, is addressed through the choice of suitable protocols and software interfaces to interconnect information systems, and through the choice of standard data formats to represent and exchange relevant information. More, at physical level, the setup of a suitable network infrastructure is needed to cope with the requirements posed by such data exchange needs.

In this context, the IDIRA Mobile Container, also called MICS (Mobile Integrated Command and Control Structure) will be brought on scene and works as information hub for all the disaster related information. The MICS provides Inbound and Outbound interoperability software interfaces for data sharing with locally deployed information sources and consumers (like e.g. existing C&C systems). Different standard, non-proprietary data formats are defined to represent, in a structured way, different types of information: incidents, resources, and sensors information just to mention a few. The Emergency Data Exchange Language (EDXL) family of standards [3] is used for data about incidents, resources, and for situation reports. The EDXL-CAP (Common Alerting Protocol) [4] data structure is used for Inbound and Outbound incidents data sharing with alerting sources and C&C systems. The EDXL-RM (Resource Messaging) [5] standard allows sharing of data that are relevant for coordinating needs and availability of resources (resource needs and offers, status of resource deployment, and so on). EDXL-SitRep (Situation Reporting) [5] is mainly used to send observations and situation reports through mobile devices, by commanders in the field. To bring the maximum benefit indeed, the MICS needs the ability that the commanders on the field are able to exchange information with each other.

The basis for the abovementioned information exchange is a working communication network, consequently the wireless gateways (WGW) explained in this paper are a core part of the IDIRA system.

2 Related Work

First responder organizations nowadays use different technologies for communication. In the daily operation often mobile phones are used. After large scale disasters the mobile phone network is often overloaded or down due to power outage or destroyed infrastructure. Specifically equipment for first responders like radio or TETRA are used during their daily business and can also be used in case of larger disasters, as the technology is equipped with backup systems in case of power outage. The interaction of IDIRA with the users is performed via a map-based Web-GUI, the so called Common Operational Picture (COP). The initial load of the COP requests about 10Mbyte of data. During the operation disparate types of data are exchanged such as sensor information, information on incidents, dispatched resources and resources activities, situation reports, simulation results, voice and user positions. For a seamless operation of the Web-GUI a few Mbit of bandwidth are needed. TETRA can only be used for low bandwidth data communication and does not fit the described bandwidth needs of IDIRA. Also a native app is developed, needing lower bandwidths, nevertheless the TETRA bandwidth will not be sufficient to cope with several end-devices at the same time.

In large scale disasters often satellite communication is used, which offers a good possibility to bring communication on scene (used as uplink technology). Different technologies and systems such as BGAN [7], VSAT [8] or Emergency.lu [9] are used by the first responders. For on scene communication between different commanders in the field satellite communication is too expensive and in the case of BGAN has only a very limited bandwidth.

For on scene communication a different system is needed. Bringing independent communication equipment such as WIMAX [10] equipment on scene has the drawback that licenses to operate the system are needed. A system specifically targeted towards broad band communication for PPDR (public protection and disaster relief) organizations is HiMoNN [11]. HiMoNN uses the frequency band 5150-5250 MHz with a transmission power of up to 8W according to the ECC Recommendation (08)04 [12]. It is capable of transmitting 28MBit/s over several kilometers. Unfortunately the system's usage is only allowed in a few countries and thus is not usable for an interoperable communication infrastructure in international disaster relief.

802.11 [13] based systems can be used all over the world, but have the major drawback that the distance between two devices is quite limited.

Meshed networks make use of end-user devices as repeaters (e.g. mobile phones). For example the mobile devices of users in the field are used as relay node for the communication of the forces. These relay nodes can be used to communicate with forces which cannot be reached directly. Nevertheless there has to be a full chain of devices between the communication partners, so that each device is able to reach another device. In case of large disasters it cannot be assumed that the density of devices is high enough that a meshed network across all the devices can be spanned.

The Optimized Link State Routing Protocol (OLSR) [14] is a routing protocol tailored to the requirements of wireless LANs. It is based on multipoint relays which reduce the routing overhead on the network.

In the work presented in this paper we try to extend the distance between 802.11 hosts by self-aligning directional antennas and we are using OLSR as routing protocol across the meshed wireless gateways.

3 System Description

Within IDIRA it has been decided that for on scene communication (in case of the public network is down or overloaded) an independent network based on 802.11 will be installed ad-hoc. The decision to setup an 802.11 based network ad-hoc after the disaster has advantages (e.g. no licenses needed, no pre-installation needed) but also has two major drawbacks:

- First responders are not trained to set up a communication network.
- 802.11 allow only a small distance between peers.

This paper presents a solution which can be used by first responder organizations to set up a communication network.

The system is based on automatically interlinking directional WLAN antennas. Directional antennas are used as this allows increasing the distance between two sites, compared to omnidirectional antennas. Due to the usage of directional antennas the signal strength will be higher and the noise level will be lower. This increase in the signal to noise ratio (SNR) allows higher throughput at similar distances or longer distances with similar throughput.

The full system is equipped into one case which is easy to install, as it only has to be mounted on a pole and switched on. After that the wireless gateway will automatically align its antennas to other wireless gateways and provide a wireless cloud as well as a LAN connection to the spanned network.

This system allows being setup by non trained first responders, and the distance between the peers can be extended compared to a WLAN using omnidirectional antennas, thus overcoming the main two drawbacks.

The main building blocks of the wireless gateway are presented in Figure 1. The system is mounted in a housing which consists of four layers. The top three layers (also referred to as modules) are built up identically. Each one consists of a wireless access point (which can also be configured as wireless client) connected to a directional antenna. Further a motor which allows rotating each antenna individually by 360° is mounted in each of the top three layers. In the bottom layer the core parts of the systems are installed. A small embedded PC as router (router-board) running OpenWRT firmware together with a switch provides connectivity between the WLAN stations and the rest of the system. The self-alignment algorithm is controlled by the router-board. The router-board is connected to a microcontroller which is responsible for the control of the rotation of the modules. It operates the motors and reads the sensor values controlling the rotation from the top three layers. The router-board is equipped with two WLAN modules one is configured to operate at 2.4GHz and used for connecting end user terminals. The second one is configured to operate in the 5GHz range and is used for the self-alignment algorithm of the remote WGWs.

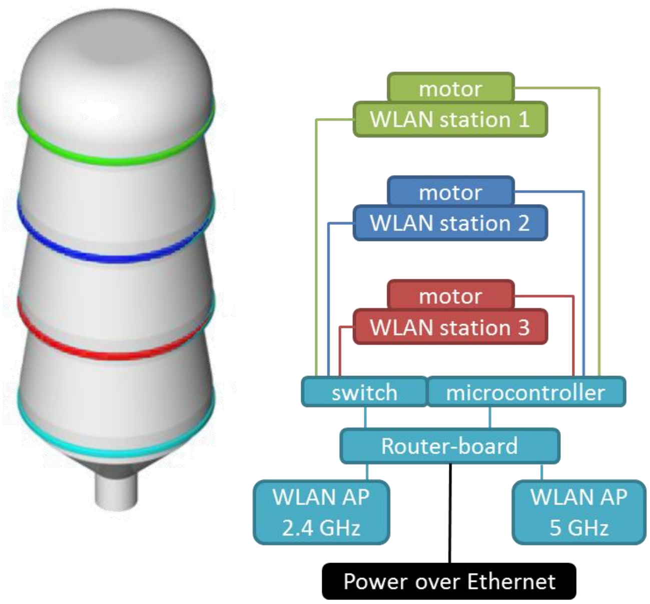

Figure 1. Main building blocks

4 Prototype Description

Based on the system description in chapter 3 a prototype has been designed and built. A modular plastic housing with four stacked layers of similar size has been chosen. A schematic overview of the prototype is shown in Figure 3.

The top 3 layers contain an electrical driven turntable which holds and rotates an embedded system with built-in directional antenna. This embedded system provides a 100Mbps Ethernet interface and a 5GHz 802.11n wireless interface with a 16dBi directional MIMO antenna.

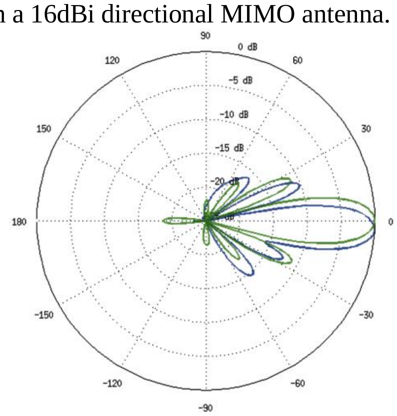

Figure 2. Nanostation M5 elevation [15]

All these features are covered by using a commercial product called Nanostation M5 from manufacturer Ubiquiti Networks. In total three such Nanostation M5s are embedded into the prototype. For easier integration the plastic housing of the Nanostation M5 was removed and only the bare electronics was mounted on the turntables. The antenna inside the Nanostation M5 has a non-symmetrical radiation pattern of about 42° azimuth angle and 15° elevation angle. The Nanostation M5s are mounted 90° rotated so that the relevant radiation angle for the mechanical antenna alignment process is now the narrow 15° angle. The directional antenna is dual-polarized to support the MIMO feature of the 802.11n wireless interface. Figure 2 shows the radiation pattern of both polarization planes for the 15° beam width.

The mechanical design enables to turn all three directional antennas independently 360° on the horizontal plane while having an outer casing that covers and protects all mechanical and electrical parts. Furthermore the electrical design enables to use common and cheap Ethernet interfaces as data link between all three radio devices and a superior network-routing module.

All three turntables are equipped with a DC gear motor and controlled via one central Arduino Leonardo microcontroller installed in the 4^{th} layer. This microcontroller is responsible for turning all three turntables to the desired position. The microcontroller is able to locate the home position of each turntable through a light-barrier attached to the turntable itself together with a reflector attached to the outer housing of each layer.

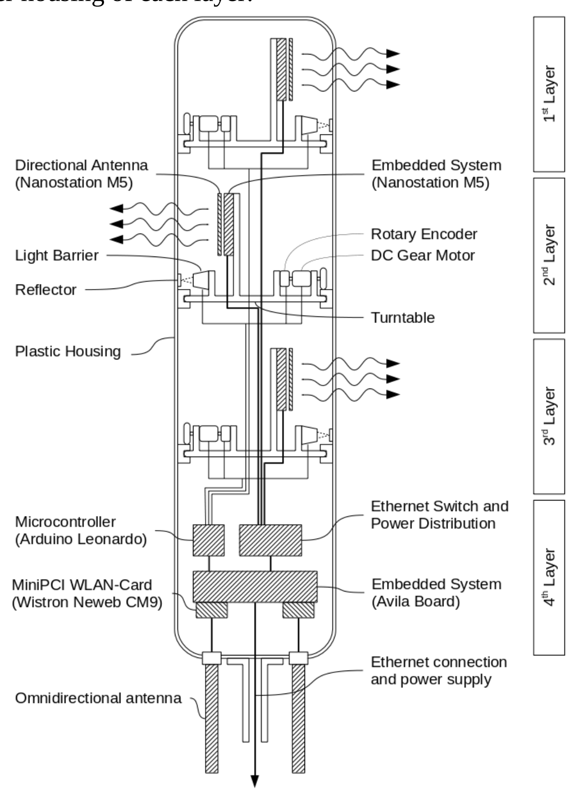

Figure 3. Prototype schematic overview

The exact positioning of the turntables is controlled through a feedback signal from an incremental rotary encoder. This rotary encoder is directly attached to the output shaft of the DC gear motor. The feedback signal also helps to detect mechanical problems like stuck or broken gear elements. It provides a cyclic 2-bit pattern through two output signals. These pulses are used to measure the alignment of the turntable by incrementing or decrementing a software counter. Furthermore this bit-pattern can also be used to detect the actual direction of rotation.

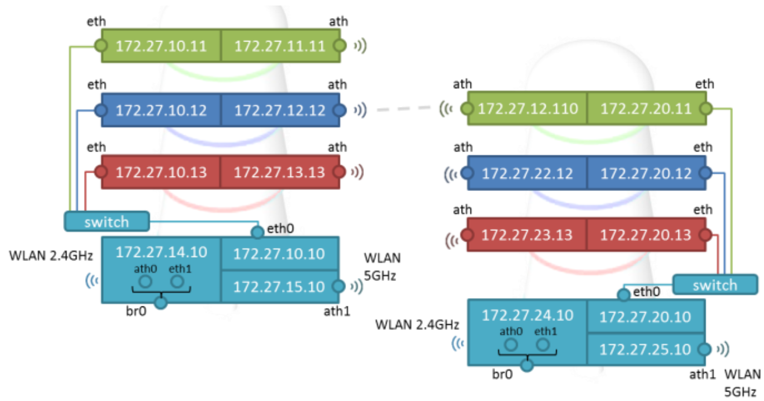

Figure 4. IP addressing scheme for two connected nodes

The software inside the microcontroller is responsible for reading and parsing text commands via serial interface and providing status information like the actual position of each turntable via the same serial interface. An initialization routine is implemented to home all turntables after power-up. During normal operation the microcontroller controls the DC motor and counts the pulses from the rotary encoders until the desired position is reached. As soon as a rotary encoder sends pulses while the motor is not in operation the software indicates a problem.

The microcontroller is not aware of cardinal directions. Instead it's only aware of the angular displacement of each turntable based on its home position. The software accepts additional commands to store the actual turntable positions in a non-volatile memory. This stored position is recovered when the device powers up and the homing procedure is finished. The microcontroller is connected to the prototypes main logic board via serial interface.

The main logic board is an industrial grade embedded board called Avila from manufacturer Gateworks. It is based on an Intel IXP425 CPU and features two 100Mbps Ethernet ports and 4 MiniPCI. Two out of the 4 MiniPCI slots are equipped with CM9 wireless cards from manufacturer Wistron NeWeb. These cards are based on Atheros AR5213A chips and can be configured for 2,4GHz or 5GHz operation. They are well supported via ath5k open-source Linux wireless driver.

The Arduino microcontroller and the Avila embedded board are both installed in the lowest (4^{th}) layer of the prototype setup. As backplane connection between all 4 layers a 5-Port 100Mbps Ethernet Switch is installed into the 4^{th} layer. This switch is also responsible for providing power via Ethernet cable to the 3 Nanostation M5s. As the chosen microcontroller, motors and sensors are powered by 5V also a DC/DC converter is installed in this layer.

The Nanostations are configured to operate as router and run a modified Ubiquiti firmware including the OLSR routing protocol. On the Avila embedded board OpenWRT with the OLSR package is running. The OLSR configuration has been modified such that Ethernet links have a cost of 0.1. Figure 4 shows the IP addressing scheme of two connected WGWs.

The system has been designed such that it can be transported and installed by one person. Therefore a battery-pack which lasts about 12 hours, together with a tripod and a telescopic 6m pole build a full system setup which can be installed in the field.

5 Alignment Algorithm

Figure 5 shows a simplified flow-diagram of the alignment algorithm performed by the WGW.

After providing power to the WGW via PoE the WGW will start to initialize. During the initialization sequence the home position of the modules is identified and a self-check of the system is performed. After the initialization all three modules start to scan for remote WGWs. For each module individual start and stop positions are defined. The default step size is 5°. The modules start with an offset of 120° to each other so that all directions are scanned as fast as possible. The scan will continue until the stop position for the module has been reached or a remote WGW has been identified. Based on experiments we have defined a threshold such that weak signals below -87dBm are not taken into account. The scan is performed for the WLAN spanned by the 5GHz omnidirectional antenna of the remote WGW. The Nanostations M5 are configured to operate in AP mode because in station mode scan results are cached over several scans. As we perform one scan per direction this would falsify our scan results. One scan takes about 7 seconds.

If a remote WGW has been identified one directional antenna will rotate to the position with the best signal and the module will be configured such that it will connect to the remote omnidirectional antenna. After the connection is established the WGW will request a connection with a directional antenna at the remote WGW.

When the requesting node receives the confirmation the connection to the remote WGW omnidirectional antenna is canceled, and the local WGW is configured to connect to the remote directional module. The local module is configured as client with the SSID of the remote module. Further the IP address is set appropriately for the remote module (see Figure 4). If the request is rejected the module will continue with scanning for remote WGWs.

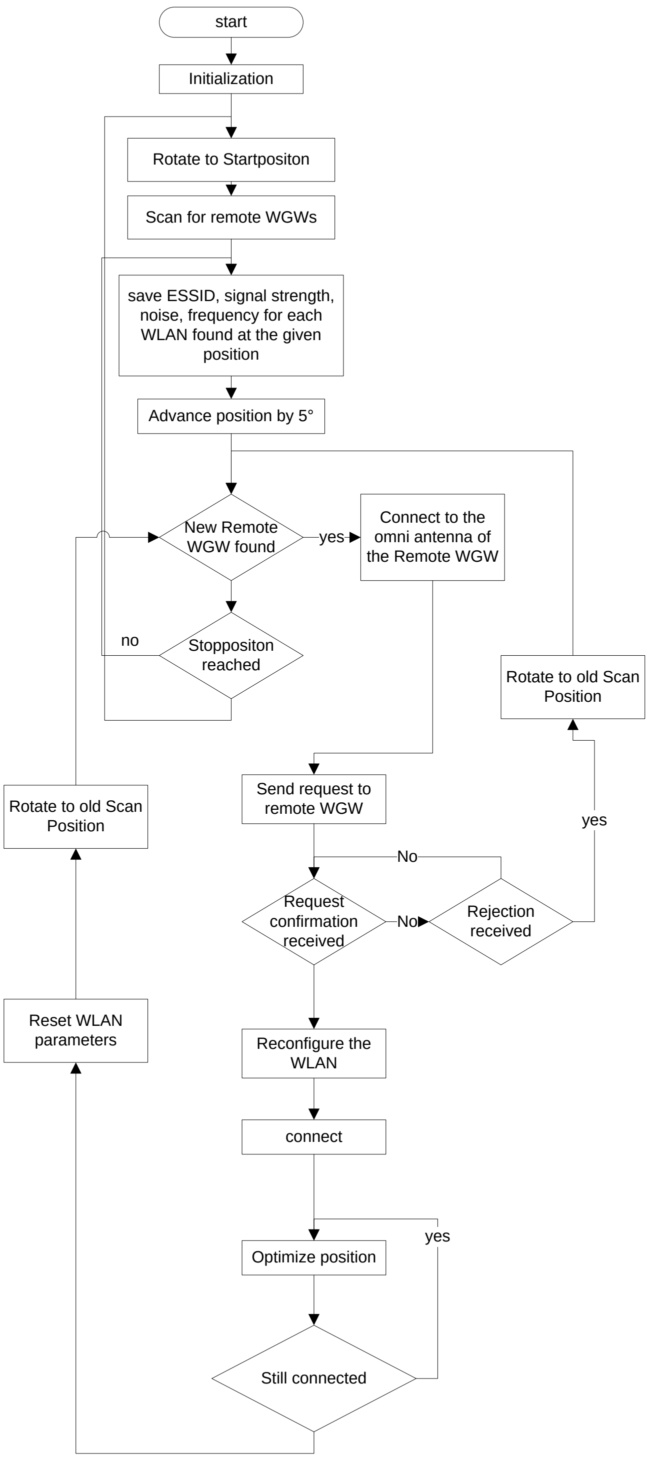

Figure 5. Local Alignment Algorithm

Modules which are not connected will continue to scan for remote WGWs. All established connections are monitored, and if one of them is lost the module will be reconfigured and will start to scan for remote WGWs again or connect to another previously located WGW.

If new scan results show that the remote WGW can be reached with a better signal at a different position the position of the module will be adjusted such that the optimal signal strength is ensured.

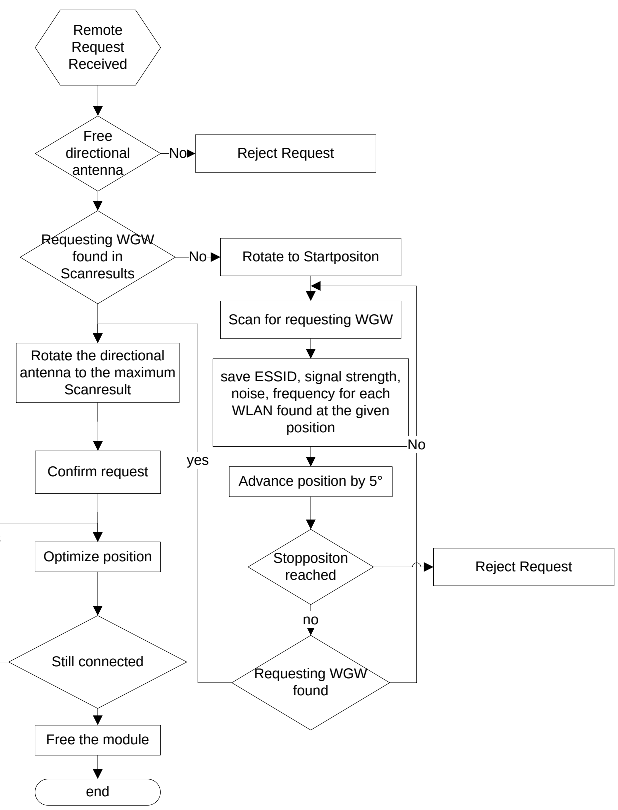

Figure 6. Remote Alignment Algorithm

Figure 6 shows the sequence performed at the remote WGW when a request has been received. Each time when a request is received the remote WGW tries to fulfill the request and assign one of the directional antennas to the requesting node. If at the remote WGW all directional antennas are used by other WGWs the request cannot be fulfilled and will be rejected. Otherwise the scan results will be searched for results of the requesting WGW. If a scan result exists a directional antenna will be rotated towards the direction of the best scan result and a confirmation for the request will be sent to the requesting WGW. If no scan result for the requesting WGW is present a 360° scan will be performed using all not assigned modules. The scan will run until the requesting WGW is found or the stop positions for the involved modules are reached. If the stop positions are reached without identifying the requesting WGW the request is rejected, otherwise the request is confirmed and an antenna is rotated to the position where the requesting node has been identified with the best signal strength. As long as the connection is established the position will be optimized (adjusted) to ensure the maximum signal strength.

The alignment sequence typically lasts between five and 15 minutes.

6 Results in the Field

Due to the rotating directional antennas the system benefits from a better signal to noise ratio, and consequently reaches higher throughput of the connection.

To show the practical gain we have installed two wireless gateways in a distance of about 2.2km with a vertical drop of about 100m. Each of the WGWs has been mounted on a 6m pole. We have rotated one of the directional antennas in a reduced step size of 2° and scanned for the WLAN of the remote 5GHz omnidirectional antenna. The sending power for omnidirectional antenna and for the Nanostations was optimized to 30dBm EIRP. For scanning for remote nodes the Ubiquiti Nanostations are running in AP mode and the command *iwlist ath0 scan* is used for the scanning. Figure 7 shows the noise and signal levels of the remote omnidirectional antenna. The maximum signal to noise ratio (SNR) in this case is 14dB at 186°. This direction is chosen for the connection between the two wireless gateways. After the connection between the two directional antennas is established, the SNR increased to 15dB. Compared to a connection between the two omnidirectional antennas the gain in SNR is 6dB, as the SNR for the omnidirectional connection is only 9dB. The figure also shows the secondary lobe of the antenna where the center is about 25° off the major lobe. The SNR at the secondary lobe is too weak for a successful connection.

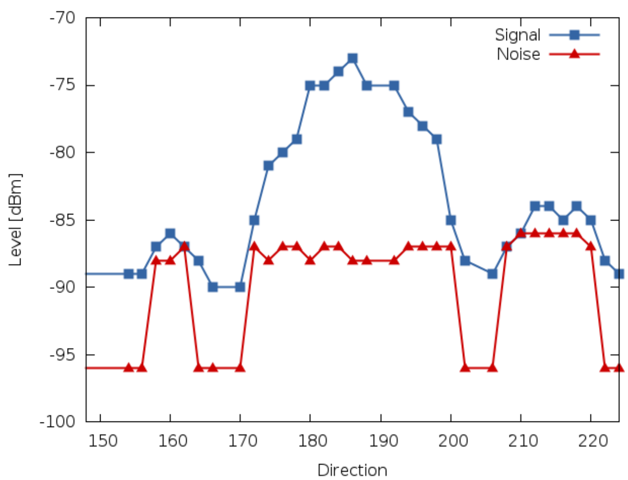

Figure 7. Noise and Signal level of remote omnidirectional antenna

The self-alignment algorithm of the system has been extensively tested in the field. The system has been used to provide access to the COP for first responders. Several installations have been performed therefore. To evaluate the influence of the distance between the WGWs measurements in a rural area north of Salzburg have been performed. Several test points have been identified for the installation of the WGW. The WGWs were mounted on a 6m pole and the automatic alignment has been started. The automatic alignment algorithm successfully establishes links over a distance of about 3.5 kilometers. For larger distances the scan for the remote omnidirectional antenna fails and a connection to the remote omnidirectional antenna is not possible. Nevertheless a software controlled manual alignment of two Nanostations can be performed. The interface for manual alignment is designed such that it can be used by non expert users. After a successful alignment the signal and noise levels and throughput have been measured. The measurements have been performed between two ASUS netbooks directly connected to the WGW. To orchestrate the measurement the MINER software [16] has been used. The throughput measurements were done using iperf [17].

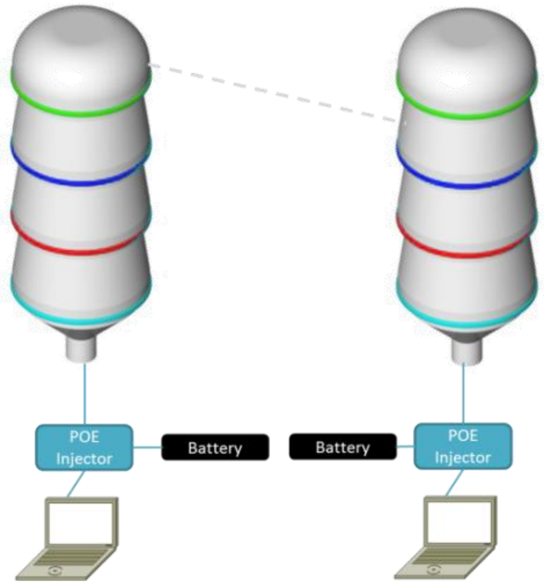

Figure 8. Measurement Setup

Figure 8 shows the setup for these measurements. Figure 9 shows the values for signal and noise levels in dBm and Figure 10 shows the measured throughput across the link. The SNR decreases from 18dB to 5dB. For distances up to 1.5km the throughput is close to the maximum speed of the Fast-Ethernet interface of the Nanostation M5. Even at a distance of about 5.5km the throughput has been in the region of about 20Mbit/s, which is sufficient for first responder communication needs.

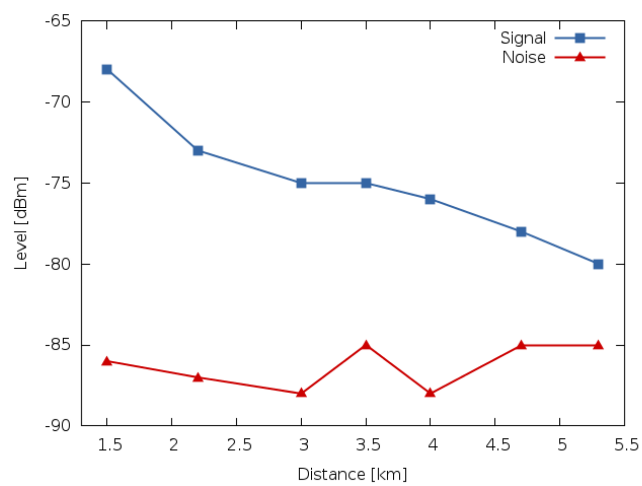

Figure 9. Signal strength and Noise level

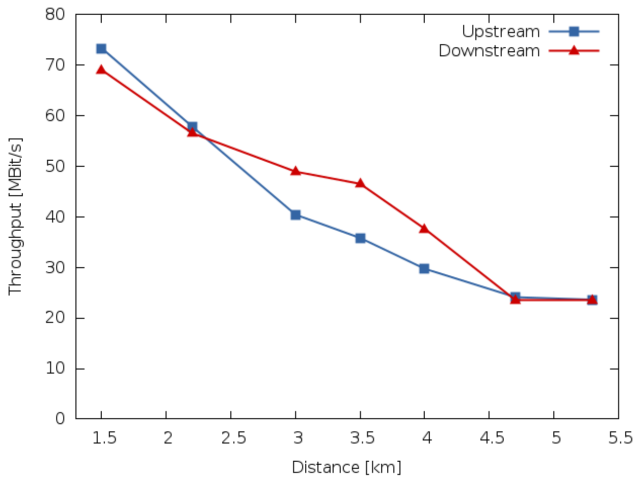

Figure 10. Throughput

7 Conclusion & Future Work

This paper presents a novel approach for a broad band communication network for first responders in case of large scale disasters. The network is based on self aligning directional 802.11 antennas. Using directional antennas increases the distance between two sites, and the self alignment algorithm ensures that the network can be setup by untrained first responders.

The automatic alignment algorithm tries to identify the maximum signal to noise ratio (SNR) for the connection and align the antennas accordingly.

Results of measurement performed with the first prototype show that the self alignment algorithm can establish connections across a distance of up to 3.5km. For larger distances the alignment can be manually controlled via an easy to use software interface.

The prototype fulfills the throughput requirements of the first responders. The major focus here is on the usage of the IDIRA system, as the prototype is part of this project.

In the future it is planned to advance the interface for the manual control of the alignment. Further the robustness of the automatic alignment algorithm will be improved. All the decisions of the algorithm are now based on local available information. This may not lead to the optimal network setup as setting up different links would lead to a more robust meshed network. Consequently it is planned that when several Wireless Gateways (WGWs) are connected to each other, the optimization of the connections will be performed with a global focus. This will allow optimizing the links within the meshed network to be more robust in case of link failures or removing WGWs.

Acknowledgment

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