17th IEEE International Symposium on Computers and Communications (ISCC), Cappadocia, Turkey, July 2012

Performance Evaluation of Process-Oriented Wireless Relay Deployment in Emergency Scenarios

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***Abstract*—In emergency operations, upcoming rescue support systems, like first responders' helmet cameras, raise the need for reliable networks with high data rates and low latency. Typically, in such environments, existing infrastructure networks are often congested or, even worse, destroyed and are therefore useless for rescue personnel. Thereby, rescue organizations have recently offered increased attention to wireless mesh network as a high-performance and low-cost solution for an ad hoc incident network. In this paper, we evaluate the performance of a novel process-oriented way for wireless mesh relay deployment in emergency scenarios. Our approach tackles the problem of the management and the involving of rescue personnel in the placement of mesh nodes. For that end, we propose to integrate wireless relays in fire hose couplings so that these relays cover the whole area of interest in a process oriented way. The packet delivery ratio and round trip time of our solution approach is compared with the performance of the Steiner tree-based theoretical approach for optimized positioned wireless relays. We investigate three scenarios with a rising number of network nodes and senders. The results show that our solution approach achieves comparable performance to its theoretical counterpart, while being much more comfortable for network deployment and post-mission node collection.**

I. INTRODUCTION

Due to the rising number of large scale incidents, caused by natural or man-made disasters, the authorities are facing increasing challenges. To master these challenges, fast and secure exchange of information between rescue fighters and their command and control system is imperative. Thereby, nowadays, the whole disaster relief process is supported by information technology. Nonetheless, in case of a large scale disaster, public communication infrastructure needed for information exchange is usually damaged, or congested due to panic calls. Dedicated emergency services/networks such as TETRA suffers from insufficient data rates, max. 7 Kbit/s on one slot. For that matter, rescue organizations are giving wireless mesh networks (WMN) increased attention as an appropriate low-cost and high performance solution.

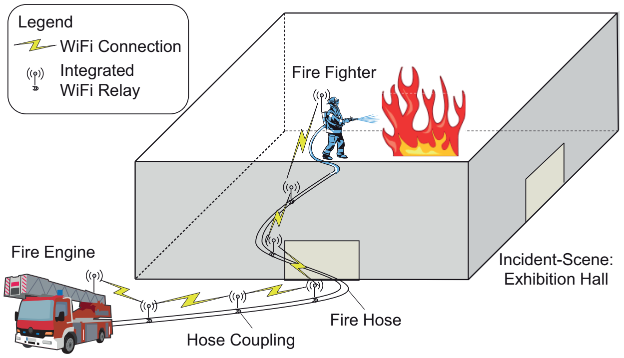

Fig. 1. Process-Oriented Incident Network Deployment

Yarali et al proposed the usage of such network in [12]. A more detailed solution approach is provided by Fragkiadakis et al [5], whose propose a flexible network architecture that provides a common networking platform for heterogeneous multi-operator networks in case of emergencies, using a wireless mesh network as a core component. Based on practitioners (fire brigades) requirements elicited within the project SPIDER [10], we optimized the setup of such a network by developing lightweight mesh routers, as described in [11]. Nonetheless, the fire brigades strongly stressed that, in addition to the light weight of the mesh router, they are interested in a solution, which does not hinder the disaster relief process nor requires extra human resources. An automatic dispenser [8] of wireless relays is a valid option to create such a network, but it is very time consuming to collect the relays at the end of a mission. Hence, a process-oriented deployment scheme is mandatory, which covers both placing and collecting of relays. To solve this problem, we propose to integrate the relay into the fire fighter's fire hose couplings. Fig. 1 gives a first impression of our proposed solution. By adopting our approach, the overall fire hose, which provides water to extinguish a fire, connects the fire fighter with the fire engine. The overall fire hose itself consists of several shorter fire hoses, which have a standardized length of 20m for the most common size B fire hoses in Germany. Through integrating Wi-Fi Relays into the fire hose couplings, the fire fighter inside the exhibition hall is wireless connected to the fire engine outside the building using a multi hop ad hoc network.

In the past, ad hoc networking attracted many researchers. As a core functionality, routing algorithms are one of the most researched fields. Abusalah et al [1] give a good overview of routing protocols and their security for wireless mesh networks. Resource constrained routing is discussed by Al-Karaki et al [2]. In addition to the routing protocol, the position of the nodes within the scenario has a great impact on the overall network performance. Younis et al [13] present strategies and techniques for node placement in wireless sensor networks.

For the performance evaluation of our proposed process-oriented relay deployment we compared two commonly used routing protocols: *Optimized Link State Routing* (OLSR)[4] and *Better Approach To Mobile Ad-hoc Networking* (BATMAN), which are suited for emergency network deployment due to their proactive behavior. Barolli et. al [3] provide a good performance evaluation of these two protocols. The proposed solution is investigated in the SPIDER use case scenario, which is a fire in an exhibition hall during a fair. Due to the complexity of the scenario, the evaluation is performed in simulation. For that end, we did experiments with real hardware in a test bed to get a valid parameterization for

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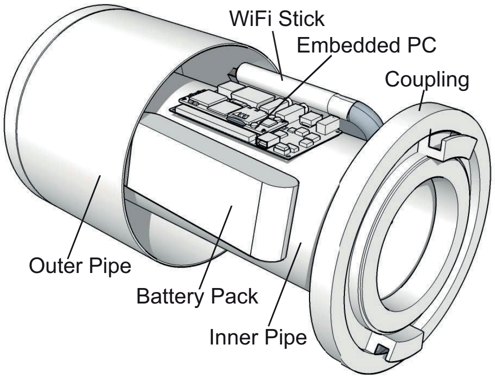


Fig. 2. InCo-Relay With Partly Opened Cover

the simulation. After modeling the setup of the test bed in simulation and verifying the test bed results, the simulation is extended to evaluate our integrated relay deployment scheme in the mentioned use case emergency scenario.

In this paper, we show that our process-oriented relay deployment scheme leads to packet delivery ratios, which are suitable to provide a reliable communication network in emergency scenarios. The rest of the paper is organized as follows. In the next section our process oriented relay deployment is described in detail. Section III presents our methodology, followed by the performance analysis in section IV. We conclude our work in section V.

II. PROCESS ORIENTED RELAY DEPLOYMENT

In case of an emergency, especially if fire occurs, fire fighters arrive at the area of incident by fire engine. To extinguish the fire, they have to deploy a fire hose from the fire engine to the fire. There are standardized lengths of fire hoses. In this paper, we choose a length of 20 meter, which is the standard length of fire hoses in Germany. Hence the overall fire hose consists of several 20m hoses. Each 20m hose is coupled together using standardized fire hose couplings.

A. Coupling Integrated Relay

We propose to integrate a wireless relay into the fire hose couplings, which we call Inter-Coupling-Relay or *InCo-Relay* in the following. Hence, fire fighters deploy an ad-hoc network while deploying their water supply. Our proposed InCo-Relay is depicted in Fig. 2. It consists of two couplings, which fit to the couplings of fire hoses, and two pipes between those two couplings. The inner pipe has the same diameter as the fire hose and is traversed by water. The outer pipe covers the relay hardware, which consists of an embedded PC, a WiFi USB Stick and a battery Pack. Our prototype InCo-Relay (see Fig. 3) consists of a Gumstix Overo Earth with Summit expansion board as an embedded PC connected to a D-Link DWA-160 WiFi USB Stick. The system is powered by a USB-Powerbank, which provides 2000 mAh using an integrated LiPo battery. The InCo-Relay has a power consumption of about 380 mA in idle mode and about 400 mA during WiFi transmission. Hence the relay can operate up to five hours at maximum. The embedded PC is operated by a Linux 2.6.36 kernel running a Debian system. In Fig. 3, a photography of our InCo-Relay prototype is presented. On the left, a closed InCo-Relay is shown, which would be coupled between two fire hoses. On the right, the cover has been removed to show the internal hardware.

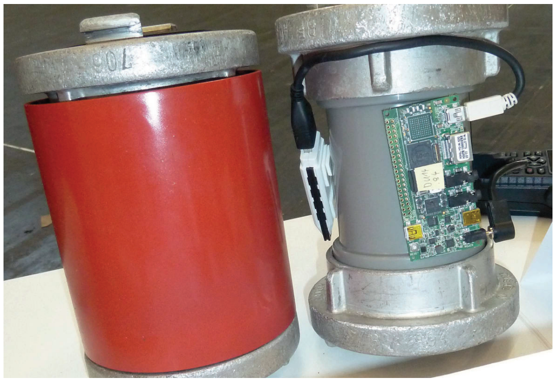


Fig. 3. Prototype of InCo-Relay

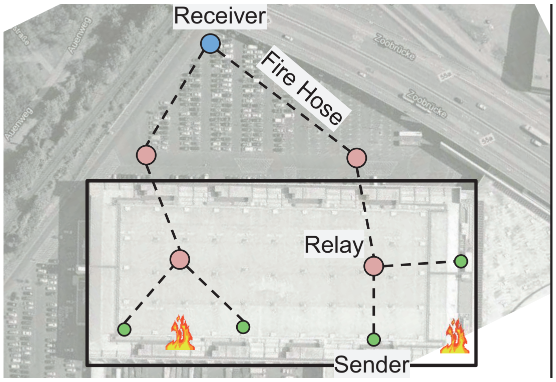


Fig. 4. Small Scenario at Exhibition Hall and Four Senders

B. Resulting Network Topology

Using our proposed InCo-Relays leads to a characteristic network topology, which is depicted in Fig. 4. A satellite image of our use case scenario, an exhibition hall at cologne fair, is placed at the background of this figure. The blue node is the receiver, representing the officer in charge, who receives data from the first responders (FR) in the field, marked in green. Receiver and sender are wireless connected through our proposed InCo-Relays, which are depicted in red. Due to the relative short length of a fire hose (20 meters for size B fire hose in Germany), InCo-relays are deployed relatively often. The officer in charge's command vehicle (CV) provides a connection to a wide area network, e.g., using a cellular network gateway or a satellite link. Each first responder maintains a route to CV to keep in touch to the commander in chief, which results in a multi-hop connection between FR and CV over several relays. Often more relays are placed then necessary, hence, redundant relays can be skipped. In Fig. 4 only relevant relays are depicted. Skipped relays, which are redundant, are not included in the figure. To reduce the

Algorithm 1 Interference Avoidance Algorithm (IAA)

```
Input: $\mathcal{R}$: Set of all relays in given scenario
Output: $\mathcal{A}$,$\mathcal{I}$: Set of active and inactive relays
Initialization: $\mathcal{A} = CV$ (Command Vehicle)
repeat
    $\mathcal{L} = x$; $x \in \mathcal{R}$ such that $RSSI(x, \mathcal{A}) \geq -86\,dBm$
    $\mathcal{A} = \mathcal{A} + min_{RSSI}(\mathcal{L})$
    $\mathcal{I} = \mathcal{I} + (\mathcal{L} - min_{RSSI}(\mathcal{L}))$
    $\mathcal{R} = \mathcal{R} - \mathcal{L}$
until $R = \emptyset$
```

TABLE I

MINIMAL REQUIRED RSSI AT RECEIVER

RSSI [dBm]	-86	-86	-85	-83	-81	-76	-73	-72
DR [Mbit/s]	6	9	12	18	24	36	48	54

interference, caused by the redundant relays, we propose the Interference Avoidance Algorithm (IAA) listed in Algorithm 1. This algorithm distinguishes all relays $\mathcal{R}$ in a scenario in two groups: active relays, represented by $\mathcal{A}$, and inactive relays, represented by $\mathcal{I}$. The algorithm initially starts at the command vehicle. In a first step, all relays in communication range (RSSI $\leq$ -86 dBm) are added to $\mathcal{L}$. Relays in $\mathcal{L}$, which are at the border of the wireless cell, are added to $\mathcal{A}$, all others are added to $\mathcal{I}$. Then the set of undistinguished relays $\mathcal{R}$ is reduced by $\mathcal{L}$. From the border relays, this is repeated until no relay is left in $\mathcal{R}$.

The reason for a RSSI of -86 dBm is the minimal required receiver sensitivity at antenna connector of the WiFi USB Stick used in our prototype. The specification of that sensitivity for the DWA-160 in IEEE 802.11a mode is given in Table I. In this paper, IAA is executed prior to the simulation. In future work, a distributed version of IAA will be analyzed. This future version will be sensitive to changes in the topology of the network, e.g., if the battery of an InCo-Relay is running low. With respect to power loss, our approach of placing redundant relays every 20m is also positive, since inactive relays can be reactivated to heal bottlenecks after a relay failure. IAA can use passive scanning for failure detection to avoid interference by inactive relays.

III. METHODOLOGY

The discrete event-based simulation environment OMNeT++ [6] and its INETMANET framework are used to model a multi-hop network in simulation. The latter comprises the simulation of the standard network protocols as well as the here considered mobile ad hoc network protocols namely, BATMAN and OLSR. Mobile ad hoc routing protocols typically deal with setting up optimal multi-hop packet routes from source to destination on the fly, depending on a communication link metric (in other words, depending on the node position). In that context, the aforementioned two proactive protocols are by far the most established one in the practice, especially static scenarios with dynamic environments.

For the evaluation of our process-oriented deployment process, our approach is compared to scenarios with pre-computed positions with respect to an optimized number of relays. This optimization problem for relay placement in Euclidean plane is known as Steiner tree problem with minimum number of Steiner points and bounded edge-length (STP-MSPBEL). There has been extensive research in this field. A comprehensive overview is given by Misra et al [9]. Almost all work in this field is based on Lin and Xue's [7] approach, who provide a steinerization scheme which is based on minimum spanning trees. The minimum spanning tree can be found using Kruskal's or Prim's algorithm.

Figure 4 depicts the initial network setup used for that matter. All nodes are static, since the node positioning is of interest. For a fair comparison, the protocols are configured with their optimal parameters with respect to packet delivery ratio, based on several tests. Table II illustrates the network and traffic models used, the different scenarios addressed, and the most relevant protocol configurations. We analyze three scenario sizes, small, medium and large, with increasing number of nodes and number of senders. For all scenarios, only one receiver is present. The node's positions for each scenario is either selected due to optimization with respect to minimal number of required relays, denoted by $minRelay$, or by following our process-oriented deployment along fire hoses, denoted by $InCo$. The data rate of the traffic load provided by the senders in scenarios with the same size is the same, e.g. traffic in scenario small$_{InCo}$ = $4 \cdot 1.536 Mbit/s$ = small$_{minRelay}$ = $2 \cdot 3.072 Mbit/s$. In scenario large$_{minRelay}$, four nodes are transmitting with $3.072 Mbit/s$ and two nodes with $1.536 Mbit/s$.

TABLE II

SIMULATION SETUP

Common Network and Traffic Models

Parameter	Value
Nodes Transmission Range [m]	250
Mobility Pattern	Static
Antenna Type	Omni-directional
Mac Layer	802.11a
Channel Model	Free-space
Simulation Time [s]	300
Number of Simulations	10
Traffic Model	CBR-UDP
Packet Size	512 Bytes
Network Buffer Size [Packets]	100

Scenario Specific Network and Traffic Models

Scenario	**# nodes**	**Data Rate [Mbit/s]**	**# senders**
small$_{InCo}$	8	1.536	4
medium$_{InCo}$	16	1.536	8
large$_{InCo}$	22	1.536	10
small$_{minRelay}$	4	3.072	2
medium$_{minRelay}$	8	3.072	4
large$_{minRelay}$	12	1.536/3.072	6

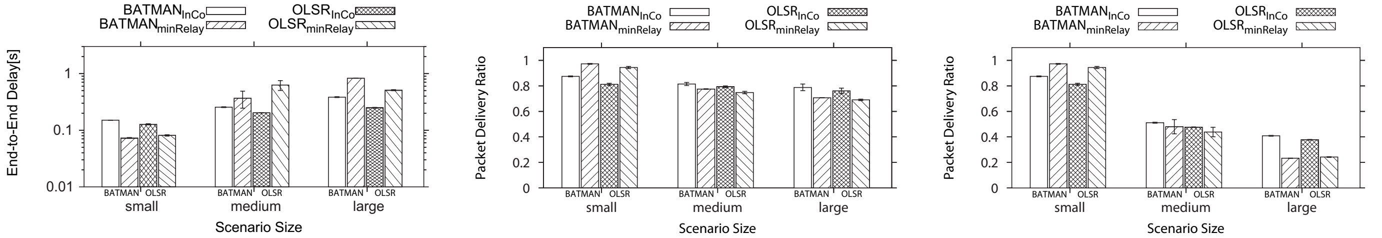
All scenarios were simulated 10 times with heterogeneous seed values for each simulation run. The seed values of a run were the same for BATMAN and OLSR.

IV. PERFORMANCE EVALUATION

To evaluate the performance of our scenarios, we measured the two key performance indicators: packet delivery ratio (PDR) and average delay.

The average end-to-end delay of received packets for the scenarios is shown in Fig. 5(a). The average delay depends on the scenario size. For the small scenario, optimal relay positions perform better (since lower delay is better) than our approach. For medium and large scenario, our approach provides lower delay. This is due to the IEEE 802.11 DCF congestion, which leads to high backoff counters and therefore transfer delays.

The PDR is depicted in Fig. 5(b) and 5(c). In Fig. 5(b) the overall network load is the same for all scenarios (6.144 Mbit/s). The results show that BATMAN performs slightly better than OLSR, independent of scenario size and used deployment scheme. In the small scenario, the optimal deployed relays deliver about 10% more packets than the process-oriented InCo-Relays, which deliver about 80% of the offered load. For the medium size scenario, the difference between optimal positioned relays and InCo-Relays is below 5%. Both deployment schemes ($minRelay$ and $InCo$) deliver about 80% of the offered load. For the large scenario, nearly the same PDR is reached, because of the tuned data rate at the sending nodes to match 6.144 Mbit/s overall network load.



(a) Average Delay of Received Packets (b) PDR for Equal Network Load (6.144 Mbit/s) (c) PDR for Network Load (6.1, 12.2, 15.3 Mbit/s)

Fig. 5. Average Delay and Packet Delivery Ratio of all Three Scenarios of Table II

In Fig. 5(c), the overall network load rises with increasing scenario size. Hence, the PDR is decreasing due to collisions. Keep in mind that we optimized the number of relays with respect to minimal required number of relays in case of $_{minRelay}$. The minimal number of relays and the offered load of about 15 Mbit/s transferred by 6 senders to one receiver in the middle of the scenario leads to a congestion of the IEEE 802.11a DCF queue. Due to the redundant routes, our InCo-Relay approach is more efficient than the approach with minimal number of relays (large$_{minRelay}$). Using our approach, about 40% of the packets are delivered, whereas only 20% of the packets were delivered in case of minimal number of relays.

On top of that, one major advantage of our approach in comparison to its counterparts is protecting the mesh nodes from physical attacks. Where this kind of attacks have been always a major concern by the design of security mechanisms for wireless mesh networks. Thereby, by adopting our approach, physical attacks are more or less negligible. Because, by integrating the mesh nodes into the fire hose couplings, it becomes very hard for an attacker to steal such a node. Hereby, protecting the network against external attacks becomes the main issue. Nonetheless, for this type of attacks, a profusion of security mechanisms already exists, based on the assumption that the attacker doesn't possess the credential a legitimate node incorporates. Thus, our approach doesn't only improve the network setup but it also enhances its security.

V. CONCLUSION AND FUTURE WORK

In this paper, we evaluated the performance of a novel positioning concept that integrates the task of setting up an incident network into the rescue process, by mainly integrating the relays into the fire hoses. Our approach essentially aims to deploy the on demand network in a very convenient way without the need of extra human resources. Keeping in mind that fire fighters usually do not know where the optimal positions are and do not have the time to place relays at specific positions, our InCo-Relay concept is easy to use and is conform to the rescue process. Furthermore, after the rescue mission, the relays attached to the fire hoses can be simply collected while collecting the fire hoses.

We evaluated our approach together with the Steiner tree based minimal relay approach in three differently scaled scenarios using two routing protocols, namely BATMAN and OLSR. The results show that our InCo-Relay approach has a comparable performance to its counterpart in small and medium scenarios. It even outperforms the well-known theoretical approach in large scenarios. As a result, our InCo-Relay does not only provide an attractive solution to set up incident networks, but it also performs well and brings strong security countermeasures against physical attacks with.

In future work, we intend to validate our approach in a small scenario in the practice in cooperation with our project partner, the German fire brigade. Besides, we aim to experimentally investigate the impact of the water flow on the link quality using our approach and eventually to adopt water based energy harvesting as an alternative power supply.

ACKNOWLEDGMENT

This work is conducted within the SPIDER Project (Security System for Public Institutions in Disastrous Emergency ScenaRios) and is funded by the German Federal Ministry of Education and Research (BMBF) – 13N10238

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