2012 IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops), Lugano, Switzerland, March 2012

Process-Oriented Deployment of Ad-hoc Networks in Emergency Scenarios

Andreas Wolff and Christian Wietfeld
Communication Networks Institute (CNI)
TU Dortmund University, Germany
Email: {Andreas.Wolff,Christian.Wietfeld}@tu-dortmund.de

***Abstract*—In rescue operations, information acquisition from rescue personnel in the field is very crucial. Upcoming decision support systems also rely on information gathered in the field, like sensor data or video feeds. A condition for successful information sharing is a reliable communication network. During crisis, infrastructure networks are often unavailable or destroyed. Hence, personnel in the field have to establish an ad-hoc incident network. Due to its high data rates and low costs, IEEE 802.11 is suitable for networking rescue personnel at an incident area. In this paper, we present a feasible solution for deploying an IEEE 802.11 ad-hoc network in a process oriented way, without hindering rescue personnel and requiring extra resources. Our approach focuses on rescue operations where fire occurs or is at least possible. We propose to integrate wireless mesh routers in fire hose couplings so that these mesh routers cover the whole area of interest in a process oriented way. We show that our approach provides similar network coverage for small and medium areas, compared to selective positioning of wireless mesh routers using optimization algorithms.**

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, the whole disaster relief process is supported by information technology. The commanders utilize decision support systems, which use information gathered in the filed as input parameters. To transport the information from the field to the command and control center, a reliable communication network is mandatory. In case of a large scale disaster, communication infrastructure is usually damaged or congested due to panic calls and are therefore useless for rescue personnel. Existing dedicated networks for rescue missions, like TETRA, do not provide sufficient data rates to support multimedia emergency communication. Hence, rescue personnel have to deploy an on demand network.

Yarali et al propose the usage of wireless mesh networks to establish such a network [1]. A more detailed solution approach is provided by Fragkiadakis et al [2], whose proposed flexible network architecture provides a common networking platform for heterogeneous multi-operator incident networks, using wireless mesh network as core component.

From a theoretical point of view, optimal positions for mesh relays can be found, by solving the network optimization problem named Steiner minimum tree with minimum number of Steiner points and bounded edge length [3].

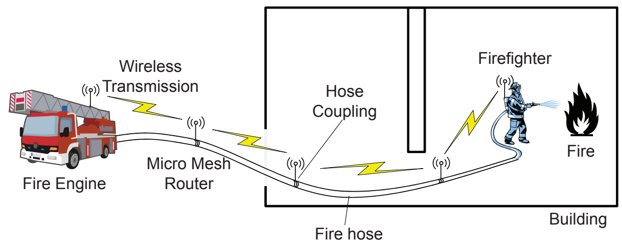

Figure 1. Process-Oriented Incident Network Deployment

But the before mentioned solution is only suitable for a quasi-fixed topology. In emergency scenarios, the topology frequently changes due to the movement of rescue personnel, and a direct connectivity between rescue personnel and a commander in chief hardly exists. Such scenarios are called disconnected polymorphous networks (DPNs). Huang et al. present the Weigh-and-Place Algorithm (WPA) for an optimal deployment of mesh relays in DPN scenarios [4].

These theoretical solutions are often not suitable in practice, because rescue personnel have to fulfill their main task and not to deploy an optimal network. In an earlier study we presented our dropped units concept with easy to use deployment rules [5], e.g. place dropped units at the corners of a building or at door passages. Similar devices are presented by Souryal et al [6]. Both approaches are based on the WiFi technology. One limitation of these solutions is that rescue personnel still need to place the relays manually. Therefore Liu et al. developed an automatic deployment system, consisting of a dispenser attached to a belt, which automatically drops a relay, if a certain signal strength threshold is reached [7].

Within the research project SPIDER [8], we were able to get in contact with practitioners of the fire brigade. They are only interested in a solution, which does not hinder the disaster relief process. An automatic dispenser 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. Therefore a deployment scheme is required, 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. We already created a prototype of

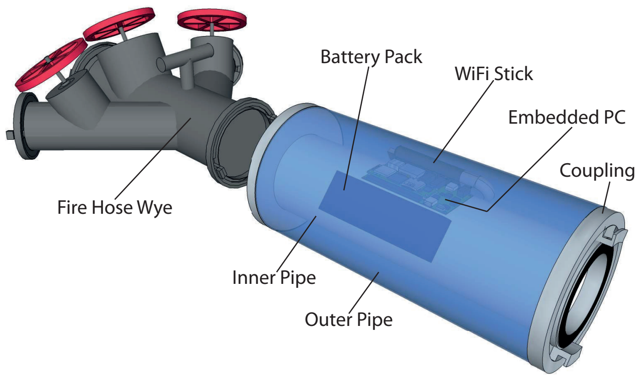

Figure 2. InCo-Relay with Translucent Cover

Figure 3. Prototype of InCo-Relay

the integrated relay which is depicted in Fig. 3. In this paper, we will show that our solution approach leads to network coverage, which is suitable to provide a reliable communication in small and medium 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 performance analysis and we conclude our work in section IV.

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 engine to the fire. There are standardized lengths of fire hoses. In this paper, we choose a length of 20m, 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 will 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. We use the available Optimized Link State Routing (OLSR) [9] Linux implementation olsrd version 0.6.1 as routing protocol. In Fig. 3 a photography of our InCo-Relay prototype is presented. The relay is coupled between two fire hoses.

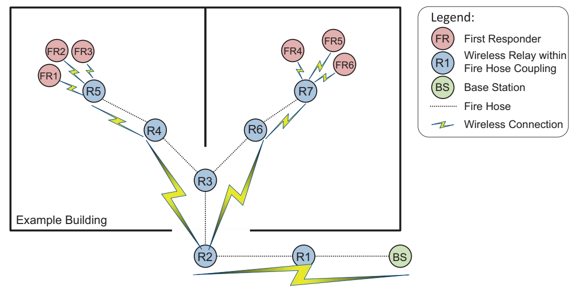

Figure 4. Network Topology: Base Station, Relays and First Responders

B. Resulting Network Topology

Using our proposed InCo-Relays leads to a characteristic network topology, which is depicted in Fig. 4. Due to the relative short length of a fire hose (20 meters for size B fire hose in Germany), a relay (R) is deployed relatively often. The fire engine hosts a base station (BS), which provides a connection to a wide area network, e.g. using a cellular network gateway or a satellite link. Each first responder (FR) maintains a route to a BS to keep in touch with the commander in chief, which results in a multi-hop connection between FR and BS over several relays. Often more relays are placed then necessary, hence redundant relays can be skipped. In Fig. 4 relay R1 and R3 are skipped, for example.

The high number of relays leads to unwanted interference. Hence, we propose the Interference Avoidance Algorithm (IAA) which disables redundant relays. For the topology shown in Fig. 4, relay R1 and R3 may be disabled, depending on the RSSI of each network connection. The received signal strength indicator (RSSI) is used to determine which relay is redundant. Furthermore, redundancy is important due to the usage of batteries. In case an InCo-Relay runs out of power, the IAA reactivates hibernating relays to close the communication gap, caused by the out-of-battery relay.

For mathematical description, two sets are created, $\mathcal{A}$ and $\mathcal{I}$. $\mathcal{A}$ represents the active relays and $\mathcal{I}$ represents the disabled ones. At the beginning of IAA, $\mathcal{A}$ and $\mathcal{I}$ are empty. First, BS is added to $\mathcal{A}$ and all redundant relays in communication range are disabled and added to $\mathcal{I}$ but one relay, which has a greater or equal RSSI of -86 dBm relative to a relay in $\mathcal{A}$. This last relay in communication range of $\mathcal{A}$, which has the lowest RSSI grater or equal -86dBm, is added to $\mathcal{A}$. The algorithm is repeated until all relays within the scenario are either in $\mathcal{A}$ or in $\mathcal{I}$.

Algorithm 1 Interference Avoidance Algorithm (IAA)

Input: $\mathcal{R}$: Set of all relays in a scenario
Output: $\mathcal{A}$,$\mathcal{I}$: Set of active and inactive relays
Initialization: $\mathcal{A} = BS$
repeat
  for all $x \in \mathcal{R}$ such that $RSSI(x, \mathcal{A}) \geq -86\, dBm$ **do**
    if $RSSI(x, \mathcal{A}\ )$ is lowest in range **then**
      $\mathcal{A} = \mathcal{A} \cup x$
    else
      $\mathcal{I} = \mathcal{I} \cup x$
    end if
    $\mathcal{R} = \mathcal{R} - x$
  end for
until $R = \emptyset$

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 (DR is data rate).

Table I
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

Currently IAA is investigated theoretically and is controlled by a central instance which knows the entire scenario. For a real implementation a distributed version of IAA is favorable. The distributed version of IAA is subject to future work.

Using IAA in addition to a routing algorithm, for example OLSR, even polymorphous networks are supported due to the self-healing capabilities of routing protocols. If one of the active routers $\mathcal{A}$ fails, e.g. is running out of battery power, one of the inactive relays $\mathcal{I}$, which is able to replace failing one, is activated. This can be done by a passive scanning and analysis of the network traffic by the inactive relays. Hence, inactive means $\mathcal{I}$ relays are not involved in multi-hop transmissions and have no routing protocols running, but they periodically, e.g. every 30 sec., analyze the traffic to detect bottlenecks.

III. Performance Evaluation

For the performance evaluation, we investigate four different scenarios, which differ in area size and number of terminals, representing first responders. For each scenario, two base stations are present (see Fig. 5). One is located in the lower left corner (BS1) and the other one is located in the upper right corner (BS2) of the scenario. Since we assume that first responders (FR) move straight to their assigned position, the InCo-Relays are located on a straight path between either BS1 or BS2 and FR according to the distance. Hence, for a first evaluation, we can use a simplified model of our IAA, which enables ether every fifth or tenth relay, depending on wireless relay's assumed transmission range. We investigate transmission ranges of 100m and 200m. The number of required relays is calculated using MATLAB.

The position of the nodes is uniformly distributed. Usually, locations of first responders are not uniformly distributed on an incident scene, but located at a few hot-spots, e.g. near a fire. We chose a uniform distribution because of a better comparability of the results with [4] and due to the effects of the clustering of first responders near hot-spots. The clustering leads to less required relays, because only one multi-hop connection from BS to the cluster is required. Hence, the effect of a rising number of nodes within the scenario is decreasing, if clustering takes place. To reduce clustering effects, we chose a uniform distribution of nodes' location.

Each scenario is calculated 500 times, using random node positions. The required number of relays for a scenario is the mean of the calculated results. The parameters of the four scenarios are presented in Table II. We chose these parameters to allow for a comparability with results presented in [4]. In a real scenario, the number of first responders might be significantly higher.

Table II
SCENARIO PARAMETERS

Scenario	Playground size	No. of Terminals
1	$400m \cdot 400m$	4
2	$600m \cdot 600m$	9
3	$800m \cdot 800m$	16
4	$1000m \cdot 1000m$	25

In this paper we evaluate simple scenarios without any obstacles. This allows for a focus on quasi ceteris paribus comparison of our proposed InCo-Relay concept with pre-calculated relay positions using existing algorithms.

To evaluate the results of our simple scenarios, a comparison with an optimal relay placement is desirable. In literature, the problem of optimal relay placement in the Euclidean plane is called Steiner tree problem with minimum number of Steiner points and bounded edge-length (STP-MSPBEL). There has been extensive research in this field.

Table III
SYMBOLS AND ABBREVIATIONS

Symbol	Meaning
$\mathcal{TS}$ = $\{\mathcal{T}^1 \cdots \mathcal{T}^T\}$	A set of network topologies
$\mathcal{B}$ = $\{B_1 \cdots B_S\}$	A set of base stations
$\mathcal{L}$	Set of candidate locations for relays
$\mathcal{R}$	Placement Solution, $\mathcal{R} \subseteq \mathcal{L}$
RPA_m	Relay Placement Algorithm

A comprehensive overview is given by [10]. Almost all work in this field is based on Lin and Xue's [11] 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.

A. Algorithms for Optimizing Relay Positions

The before mentioned approach provides a solution for a monomorphous network, where nodes do not move. Since first responders usually move within the scenario, a solution approach for polymorphous networks is more suitable. Hence, we compare our results with previous work of Huang et al. [4], who propose three algorithms for placing minimal number of relays in polymorphous networks. Huang proposes two heuristic algorithms, Topology Stitch Algorithm (TSA) and Topology Iterative Algorithm (TIA), which are built upon constrained relay placement algorithms for monomorphous networks with a single topology. Furthermore they propose the weigh-and-place algorithm (WPA), which optimizes relay placement across topologies with balanced load.

In the following, the three algorithms are described in more detail. The description is taken from Huang et al [4].

The Topology Stitch Algorithm (TSA) is listed in Algorithm 2. Initially relays are deployed independently for each topology to guarantee connectivity. Then all deployed relays are stitched together and redundant relays are removed. The pruning process removes relays one by one. After each removing, the connectivity requirement for every terminal in the topology is checked and removing is undone if connectivity is lost. TSA uses the pruning process to minimize the amount of required relays.

Algorithm 2 Topology Stitch Algorithm (TSA)

Input: $\mathcal{TS}, \mathcal{B}, \mathcal{L}$
Output: Placement solution $\mathcal{R}$
$\mathcal{R} = \emptyset$
for all $\mathcal{T}^t$ $in\ Topology$ **do**
  $\mathcal{R} = \mathcal{R} \cup RPA_m(\mathcal{T}^t, \mathcal{B}, \mathcal{L})$;
end for
Prune Redundant Relays;

The Topology Iterative Algorithm (TIA) is listed in Algorithm 3. For each topology, relays are placed one after another. An Additional parameter $\mathcal{R}$ is given to RPA_m to take into account the relays placed from topologies considered earlier. At the end of Algorithm 2, redundant relays are removed by a prune procedure. RPA_m needs a modification to place relays at positions specified in the input parameters $\mathcal{R}$ at no costs.

Algorithm 3 Topology Iterative Algorithm (TIA)

$\mathcal{R} = \emptyset$
for all $\mathcal{T}^t$ $in\ Topology$ **do**
  $\mathcal{R} = \mathcal{R} \cup RPA^*_m(\mathcal{T}^t, \mathcal{B}, \mathcal{L}, \mathcal{R})$;
end for
Prune Redundant Relays;

TSA and TIA are both greedy algorithms. Relays are placed to maximize the connectivity of the processed topology. TSA relies on the pruning process to remove redundancy generated by each topology. TIA is smarter than TSA, because of its consideration of the relationship between the current topology and earlier processed topologies. The current topology maximally use the connectivity provided by already placed relays in $\mathcal{R}$. The processing order of topologies has a great impact on TIA's performance.

The Weigh-and-Place Algorithm (WPA) is a two-stage process. First, an iterative relay placement (IRP) takes place, which is listed in Algorithm 4. After completion of IRP the WPA in Algorithm 5 is executed.

IRP is based on linear relaxation with iterative rounding. The iteratively calculated relay placement solution is denoted as $\mathcal{R}$. At the beginning $\mathcal{R}$ is empty. The min cost flow problem OPT^t is solved for each topology, considering the cost only on the out-edges of locations outside $\mathcal{R}$. Thus the objective function is adjusted to $\sum_{l\in\mathcal{L}\setminus\mathcal{R}} \sum_{j:\widehat{lj}\in E^t} x^t_{lj}$. The optimal objective value obtained from OPT^t is denoted as f^t. If all commodities can flow along placed relays $\mathcal{R}$, i.e. $\sum_t f^t = 0$, $\mathcal{R}$ is returned as the solution. Otherwise, the location l^* is picked with highest weight and added to the placement solution $\mathcal{R}$. Because a location is added upon each call and there are $|\mathcal{L}|$ candidate locations to consider, IRP is guaranteed to terminate.

It is possible that IRP places redundant relays, i.e. loops, because it is greedy at each iteration. To remove those redundant relays, WPA listed in Algorithm 5 prunes them after IRP algorithm. WPA tries to remove placed relays one by another and checks if the connectivity requirement is violated for every terminal topology.

B. Resulting Number of Required Relays

Fig. 5 gives an example for the InCo-Relay placement in scenario 1 and 2. Since each FR deploys his own fire hose, redundant relays may be present. Furthermore in this performance evaluation, a simplified IAA model is used. Both simplified IAA and normal IAA are not optimal

Algorithm 4 Iterative Relay Placement Algorithm (IRP)

Input: Relay Placement solution $\mathcal{R}$
Output: Relay Placement solution $\mathcal{R}$
for all Topology T^t **do**
  Solve OPT^t with objective
  function $\sum_{l\in\mathcal{L}\setminus\mathcal{R}}\sum_{j:\widehat{lj}\in E^t} x^t_{lj}$. Let the optimal solution be (x^*) and optimal objective value f^t.
  $w^t_l = \sum_{j:\widehat{lj}\in E^t} x^{t*}_{lj}$
end for
if $\sum_t f^t = 0$ **then**
  return $\mathcal{R}$;
end if
$w_l = \sum_t w^t_l$; $l^* = arg_{l\in\mathcal{L}\setminus\mathcal{R}}\max w_l$.
return $\mathcal{R}$=IRP($\mathcal{R}\cup\{l^*\}$)

Algorithm 5 Weigh-and-Place Algorithm (WPA)

Input: $\mathcal{TS},\mathcal{B},\mathcal{L}$
Output: Relay Placement solution $\mathcal{R}$
$\mathcal{R} = IRP(\emptyset)$
// Prune Redundant Relays;
for all $r\ in\ \mathcal{R}$ **do**
  $\mathcal{R}' = \mathcal{R} - r$;
  if For any $\mathcal{T}^t$, all terminals are 1-BS-connected and BSs' loads are balanced in $\mathcal{T}^t\cup\mathcal{B}\cup\mathcal{R}'\cup\{\mathcal{C}\}$ **then**
    $\mathcal{R} = \mathcal{R}'$;
  end if
end for

solutions. Hence, we expect more relays for IAA compared to algorithms, which optimize the locations of relays. For example, in scenario 2 depicted at bottom of Fig. 5, at least R2, R4, R11 and R13 are redundant and could be removed.

The simplified IAA just enables every fifth or tenth InCo-Relay, depending on the investigated transmission range, as described before. For the evaluation, the straight path between a FR and the BS is divided by the transmission range, resulting in the active number of InCo-Relays for connecting that FR to BS. There is no redundancy avoidance. Even if two nodes are located next to each other, both nodes are connected to the BS using their own fire hose path resulting in redundant relays. Redundancy avoidance using full version of IAA will be evaluated in future works.

The result of our InCo-Relay approach for a transmission range of 100m is depicted in Fig. 6. For the small scenario only 7 InCo-Relays are required. This is comparable to the optimal solution. For the second scenario 24 InCo-Relays are necessary to connect every FR to one of the two BSs. Compared to the optimal results, which require about 17 relays, 24 relays also acceptable. For scenarios covering a larger area, the straight connection of each FR to one of the two BSs leads to a great number of relays, namely 61 for scenario 3 and 122 for scenario 4. The optimal algorithms

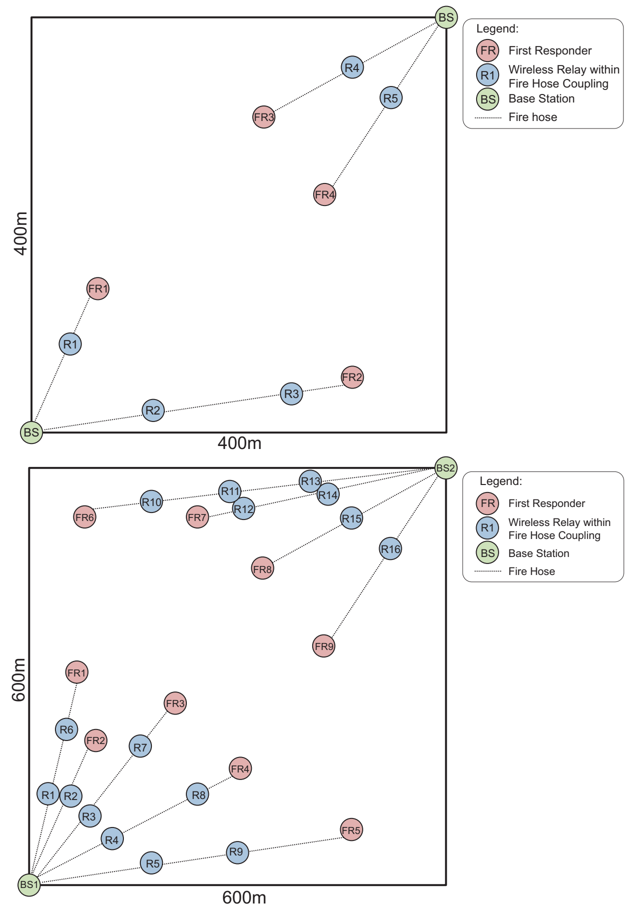

Figure 5. Exemplary InCo-Relay placement for scenario 1 and 2

require about 29 relays for scenario 3 and 45 for scenario 4.

If the maximum transmission range is set to 200m, the required number of relays for the different scenarios is depicted in Fig. 6. Again, for small scenarios our InCo-Relay approach leads to a similar number of required relays. In this case, even scenario 3 is covered by a comparable number of relays. The number of required InCo-Relays for scenario 3 is 27, whereas about 18 relays are required, using optimal positions. In scenario 4 twice as much InCo-Relays are required, compared to 27 relays for the optimal positions.

The results lead to the conclusion that our approach is suitable for small and medium networks. Keeping in mind that a rising number of relays increase the redundancy and that redundancy is important due to the usage of battery powered relays, our approach is valid even for large scenarios. Furthermore the cost per relay will decrease with a rising number of required relays.

IV. Conclusion and Future Work

In this paper we proposed a novel positioning concept that aims to support rescue personnel to easily deploy a

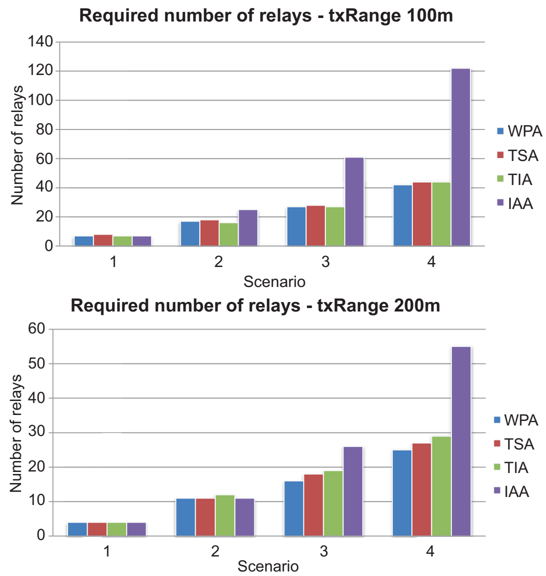

Figure 6. Results using txRange of 100m and 200m per relay

communication network, without hindering rescuers to fulfill their main objective. We introduced InCo-Relays which are deployed along the way of fire hoses. Hence, no dedicated person for network deployment is required. Using our Interference Avoidance Algorithm, the number of active relays for connecting first responders to base stations is only slightly higher for small and medium scenarios compared to solutions, which are based on optimization algorithms. 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.

In the future we want to address larger scenarios and therefore evaluate strategies to reduce the number of redundant relays. Furthermore, we want to evaluate the performance of our InCo-Relays during a fire drill with our project partners from a German fire brigade. In addition to the analytical evaluation of the InCo-Relays, we will deploy a simulation environment, which allows us to investigate the influence of different routing protocols on the network performance.

The usage of more complex simulation environments enables the evaluation of more realistic deployment scenarios, e.g. buildings and fire hoses not following a straight path between BS and first responders.

With respect to the Interference Avoidance Algorithm we will work on intelligent handling of failures and self-healing properties via re-enabling of inactive nodes. Due to the limited battery lifetime of InCo-Relays energy balancing issues will also be addressed to improve network lifetime.

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

References

[1] A. Yarali, B. Ahsant, and S. Rahman, “Wireless Mesh Networking: A Key Solution for Emergency & Rural Applications,” *2009 Second International Conference on Advances in Mesh Networks*, pp. 143–149, Jun. 2009.

[2] A. G. Fragkiadakis, I. G. Askoxylakis, E. Z. Tragos, and C. V. Verikoukis, “Ubiquitous robust communications for emergency response using multi-operator heterogeneous networks,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, no. 1, p. 13, 2011.

[3] X. Cheng, D.-Z. Du, L. Wang, and B. Xu, “Relay sensor placement in wireless sensor networks,” *Wireless Networks*, vol. 14, no. 3, pp. 347–355, Jan. 2007.

[4] Y. Huang, Y. Gao, and K. Nahrstedt, “Relay Placement for Reliable Base Station Connectivity in Polymorphous Networks,” in *Sensor Mesh and Ad Hoc Communications and Networks (SECON), 2010 7th Annual IEEE Communications Society Conference on*. IEEE, 2010, pp. 1–9.

[5] A. Wolff, S. Subik, and C. Wietfeld, “Performance Analysis of Highly Available Ad Hoc Surveillance Networks Based on Dropped Units,” in *2008 IEEE Conference on Technologies for Homeland Security*, no. May. Ieee, May 2008, pp. 123–128.

[6] M. R. Souryal, A. Wapf, and N. Moayeri, “Rapidly-Deployable Mesh Network Testbed,” *GLOBECOM 2009 - 2009 IEEE Global Telecommunications Conference*, pp. 1–6, Nov. 2009.

[7] H. Liu, J. Li, Z. Xie, S. Lin, K. Whitehouse, J. a. Stankovic, and D. Siu, “Automatic and robust breadcrumb system deployment for indoor firefighter applications,” in *Proceedings of the 8th international conference on Mobile systems, applications, and services - MobiSys ’10*. New York, New York, USA: ACM Press, 2010, p. 21.

[8] S. Subik, S. Rohde, T. Weber, and C. Wietfeld, “SPIDER: Enabling interoperable information sharing between public institutions for efficient disaster recovery and response,” in *Technologies for Homeland Security (HST), 2010 IEEE International Conference on*. IEEE, 2010, pp. 190–196.

[9] T. Clausen and P. Jacquet, “Optimized Link State Routing Protocol (OLSR),” in *RFC 3626*. IETF, 2003, pp. 1–76.

[10] S. Misra, S. D. Hong, G. Xue, and J. Tang, “Constrained Relay Node Placement in Wireless Sensor Networks to Meet Connectivity and Survivability Requirements,” *IEEE INFOCOM The 27th Conference on Computer Communications (2008)*, no. 1, pp. 281–285, 2008.

[11] G. Lin, “Steiner tree problem with minimum number of Steiner points and bounded edge-length,” *Information Processing Letters*, vol. 69, no. 2, pp. 53–57, 1999.