Testing AGV Mobility Control Method for MANET Coverage Optimization using Procedural Generation

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ABSTRACT

In industrial applications continuous wireless connectivity of mobile clients can rarely by guaranteed. Lack of communication negatively impacts the performance of industrial automation systems, e.g. Automated Guided Vehicle (AGV) fleets. Utilizing industrial Mobile Ad-hoc NETworks (MANETs) and adaptive positioning systems can reduce the number of disconnections in these AGV fleets. Therefore the performance of the mobile systems (e.g. AGV fleet) is improved and factory efficiency increased.

In this work procedural simulation is used to examine wireless communication in industrial applications. This methods enables the observation of the interaction of mobility control system, network status and robotic system performance independently from a specific environment or scenario. Novel insights on the effectiveness of ad-hoc communication in industrial applications and the correlation of AGV fleet connectedness and AGV fleet transport performance are presented. Additionally a control method is proposed, which improves the network coverage of an industrial MANET and efficiency of AGV fleets.

CCS CONCEPTS

• **Computing methodologies** → **Simulation types and techniques**; • **Networks** → **Mobile ad hoc networks**; **Network simulations**; • **Applied computing** → *Industry and manufacturing*.

KEYWORDS

Mobile Ad-hoc Network, Mobile Robotics, Industrial Application, Coverage Optimization, Procedural Generation

ACM Reference Format:
Christian Sauer, Eike Lyczkowski, Marco Schmidt, Andreas Nüchter, and Tobias Hoßfeld. 2021. Testing AGV Mobility Control Method for MANET Coverage Optimization using Procedural Generation. In *Proceedings of Alicante '21: ACM 24th International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM) (MSWiM'21).* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Communication is one of the enabling technologies towards the paradigms of Industry 4.0. Wireless communication is especially important, as it enables the envisioned mobility and flexibility of future production facilities [1]. Many industrial applications require the availability of wireless connections. The lack of such connections can lead to inefficiencies or faults. Different works have tried to guarantee wireless connectivity to devices in industrial applications [2, 3]. However, the challenge of supplying network access remains in the dynamic industrial environment.

This work presents a scheme, which aims to improve the connectivity of Automated Guided Vehicles (AGVs). The connectivity of an AGV fleet impacts the performance of this fleet in terms of completed transports per time [4]. Previously Mobile Ad-hoc NETworks (MANETs) have been used to improve the availability of connections of these devices [5]. This work expands upon this approach by strategically placing AGVs with the goal to expand the coverage of the AGVs MANET and to supply communication channels to AGVs in zones without coverage. Such a strategy is useful, since most AGV fleets are not used to full capacity [6], leaving resources (AGVs) as inactive. These AGV can be utilized to supply connectivity to the active AGVs. Subsequently, these adaptively positioned AGVs are called relay-AGVs.

Several research questions are relevant in the context of this problem and examined in this work. Firstly, it must be determined if a MANET is effective in improving the connectivity of an AGV fleet in an industrial application. The impact of improved connectivity on the transport performance of the AGV fleet must then be shown. Secondly, it must be examined, if the mobility of AGVs can be controlled in order to improve the connectivity of an AGV fleet and as a consequence the performance of this fleet. It is expected, that the benefits by adaptively positioning AGVs is highly dependent on the circumstances (factory layout, transport orders, etc.). Therefore,

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MSWiM'21, November 22–26, 2021, Alicante, Spain
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ACM ISBN 978-x-xxxx-xxxx-x/YY/MM…$15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

another research question is: How can the previous questions be answered, without only gaining application specific insights? The contributions of this work are the answers to these questions:

1. A method to procedurally generate industrial applications in which to test the impact of ad-hoc networks and coverage optimization
2. Application independent observations on:
    - The correlation of AGV connectivity and transport performance
    - Benefits of MANETs on AGV connectivity and performance
3. A mobility control method for AGVs, which improves connectivity in a MANET, including decentralized methods to:
    - cooperatively learn the coverage and range of the MANET
    - choose positions for the placement of relay-AGVs
    - choose the most suitable inactive AGVs to serve as relay-AGVs

The industrial use case and the resulting parameters for the modelling of the use case are described in section 2. Additionally, two scenarios are introduced, which are subsequently used to examine the behavior of the AGV MANET and the proposed control algorithm. In Section 3 the method of using procedural simulation is introduced. This simulation is used to characterize the benefits gained by implementing an AGV MANET and the correlation of connectedness and fleet performance in section 4. The scheme for positioning AGVs as relay-AGVs is presented in section 5 and tested for two scenarios in section 6. After comparing this work and related work in section 7, the work is concluded in section 8.

2 USE CASE

In this use case AGVs in industrial applications are considered. These vehicles transport goods, tools and material within a production facility. Other variants might assist in assembly task or execute simple object manipulation. AGVs most often act as a fleet of $\leq$ 10 to $\geq$ 100 vehicles [7]. Different control schemes for these vehicles exist. In the following a control scheme in accordance with the VDA5050 [8] standard is assumed.

In this standard the AGVs are coordinated by a central fleet controller. The AGVs send status messages to the controller and receive orders from the controller. This causes the interrelation of AGV fleet connectedness and transport performance of the AGV fleet. In general, if less AGVs can be reached with an order message, then less AGVs are fulfilling orders and the general performance of the fleet decreases. The performance of the fleet is generally defined as number of completed transport tasks per hour per AGV () / / +). The connectedness of the AGV fleet is best described as the percentage of reachable AGVs in relation to the complete fleet size (0 % to 100 %).

2.1 Basic simulation characteristics

The key characteristics of the simulation are:

- **AGV movement**
  The mobility models described in [4] and [6] are used. The AGVs use paths to drive through the production facility. Along these paths task points are placed. The AGVs receive orders to fulfill tasks at these task points. The behavior of the AGVs depends on the communication network, since the AGVs do not move without an active order, issued by the fleet controller. The AGVs subsequently choose the shortest path from their current position to the task position.
- **Signal attenuation**
  Signals can fade due to distance or be blocked by obstacles. The presence and position of these obstacles impacts the coverage of infrastructure and ad-hoc networks alike [9, 10]. In this work the multi-wall model (i.e. attenuation factor model) was used, which models signal fading and shadowing. It was previously shown, that this model is suitable for indoor [11] and industrial [10, 9] applications.
- **Network infrastructure**
  The fleet controller is a software entity present in the connected enterprise network. Therefore, the mobile devices must be connected to this entity. Access Points (APs) act as gateways to either directly (non ad-hoc network) or indirectly (ad-hoc network) connect the AGVs to the fleet controller. The placement of these APs and the coverage provided by them is an important aspect of the application.

There are specific design requirements to the adaptive network imposed by the industrial use case. One of the most important requirement, which contrasts previous work in this field, is that the position of the relay-AGVs can not be freely selected. The AGVs can only move on specific paths and prolonged parking at a position is only possible in certain positions, further described as parking-points. The relay-AGVs positions must be selected from the group of parking points. Any task position might be used as a parking position, if another task position can be used alternatively, this would mean, that occupying the parking position would not impede with any transport task.

The usage of the adaptive position control for AGVs is interesting in two different scenarios. The static scenario describes a factory with non-complete coverage by the APs. The dynamic scenario is a modern factory with complete coverage. In this scenario the environment changes at a certain point in time, including movement of obstacles and technical faults of APs.

2.2 Static scenario

In the static scenario the APs provide non-complete coverage to the factory. The non-adhoc (infrastructure) network, the ad-hoc network and the ad-hoc network with adaptively controlled AGVs (further as adaptive network) are applied to these factories. Within the running AGV fleet the performance () / / +) of the fleet and the connectedness are monitored.

2.3 Dynamic scenario

In the dynamic scenario a modern factory is examined, which was planned with network coverage in mind. In these factories initially full coverage is provided. However, at one point in the simulation the environment is changed. These changes recreate typical situations from real production facilities. The first change is that a certain percentage of the signal-attenuating obstacles are moved or replaced. This represents the continuous evolution of real production facilities. Secondly, a defined percentage of the APs ceases operation. This recreates typical faults, like miss-configuration

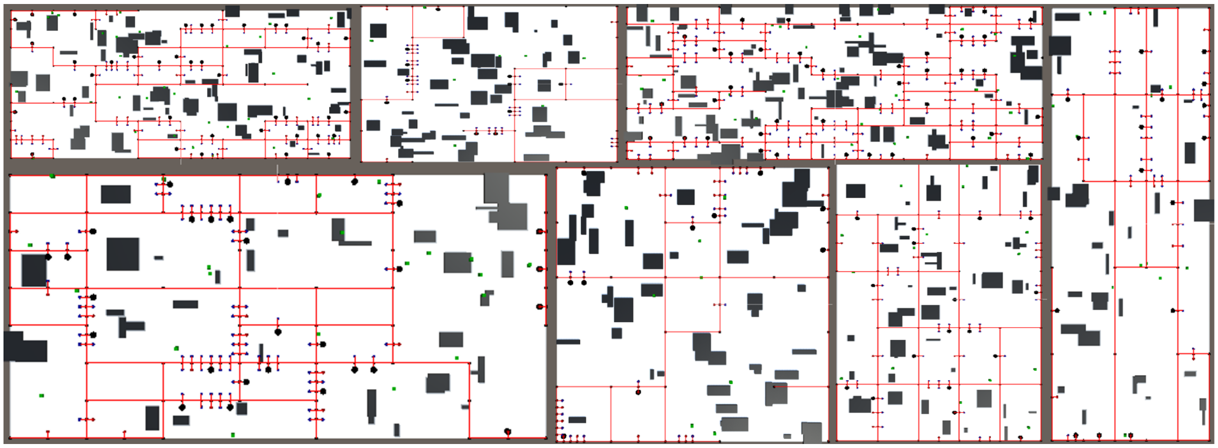

Figure 1: 7 examples of procedurally generated factories. Legend see figure 2.

Figure 2: Visual presentation of the procedurally generated factory model.

or faulty firmware updates. The same parameters as in the static scenario are observed. Of particular interest is the change in performance in connectedness caused by the environmental change. Different degrees of performance degradation are expected from the different communicating systems.

3 PROCEDURAL SIMULATION

A particular challenge is that the behavior and performance of any solution would highly depend on the factory environment it is applied to. It is not possible to create a single environment or a small number of different environments which reproduce the average system behavior.

In [12] procedural generation is used to solve a similar problem. A multitude of applications are generated, the simulation results are automatically analyzed and novel insights can be generated. In this work a very similar solution is chosen. The results (performance and connectedness) from hundreds of different procedurally generated factories are combined in order to examine the system behavior independently from any singular application scenario.

In the following the procedure to create simulated factory environments is described. The generated factory models contain all previously described required characteristics. The parameters for generating the factory environments are summarized in table 1.

The following steps and sub-steps procedurally create the industrial environment. The steps are subsequently described in more detail.

```
Generate factory floor space
Generate AGV navigation graph
    Generate basic manhattan graph
    Erode regular grid
    Place task points
    Define parking points
Place AGVs
Place obstacles
Place access points
```

The generation process is based on a random seed. Each time a decision based on randomness is made, this seed is used. This means that by using the same seed, the same factory can be recreated.

The first step is "*Generate factory floor space*". In this step the size and general dimensions of the factory is decided. In the first step a random factory size between a minimum value and a maximum value is selected. Any generated factory has a rectangular floor plan. The side lengths of the factory are decided by the factory size and a relation factor $A_($ by the relation $A_(= \frac{!_x}{!_y}$ between the factories length in the G and $\sim$ dimension. The relation factor is also randomly selected.

The process of generating the navigation graph start by generating a manhattan layout. The density of this layout is given by $_6$, randomly selected from a specified range. This density defines the average distance between two parallel lanes in the manhattan grid, and is therefore defined in $<$. All nodes created within this grid are of default type (neither task position, nor parking position). The next step is deleting nodes (and their connections) from the grid to create an irregular path layout. Most factories do not have a perfect grid layout. Thus, a certain percentage $\%_{=3}$ of all nodes is deleted. Task points are added to the navigation graph. Task points, that are in close proximity to one-another are classified as parking points.

After the navigation graph for the AGVs is fully generated, the AGVs can be placed. AGVs are placed on $\%_{+}$ of all task positions. Additionally, signal-attenuating obstacles can also be placed within the factory. The number of obstacles $=_>$ is selected from a predefined range. The obstacles must not intersect the previously placed navigation graph. The position of each obstacle is randomly

Table 1: Table of subsequently used parameters

Parameter	Value	Unit	Description
	7000 Ÿ Ÿ 150000	$<^2$	Factory floor size
A(	0"33 Ÿ A(Ÿ 3		Ratio of x and y length of the factory
6	7 Ÿ 6 Ÿ 20	<	Distance between paths in navigation graph
%=3	10 Ÿ %=3 Ÿ 30	%	Irregularity percentage of navigation graph
%) %	100	%	Number of edges to which task points are added
3) %	2	<	Distance of task points to original graph edge
3) % <8=	5	<	Minimal length for edges to add task points to
3<8=%	5	<	Maximum distance of two task points for parking point classification
% +	50	%	Number of AGVs in relation to number of task and parking points
=>	10 Ÿ => Ÿ 100		Number of obstacles
(>	1 Ÿ (> Ÿ 10	<	Size of obstacles
% %	75	%	Number of APs, expressed as ratio to number of AGVs

selected on the factory floor, while the size (> is randomly chosen. The size in x and y dimension are chosen independently.

The placement of APs depends on the simulated scenario. In the static scenario the number of APs depends on the number of AGVs, where # % = % % · # +. In contrast, for the dynamic scenario, the APs are placed in a manhattan grid, in a way, that their placement guarantees coverage.

The parameters of the procedural generation were chosen based on experience of real industrial applications. ,A(, 6 and %0=3, parameters, which describe the factory floor, are chosen from ranges that can be observed in typical application scenarios for AGV fleets. The AGV navigation graph parameters %) %, 3) %, 3) % <8= and 3<8=% were chosen based on a specific AGV fleet application in the context a of electronics production facility. % +, =>, (> and % %, which describe the wireless network in terms of clients, access points and obstacles, are again chosen based on experience from real applications. The presented values and value ranges generate results, which are comparable to the empirical measurements in [13]. In future work further examination of these parameters is recommended.

Figure 1 presents some examples for procedurally generated factories, which are results of the described process. This visual representation is further described in Figure 2, which acts as a legend to Figure 1.

The factory model is subsequently added to a custom simulation tool [4]. In this tool the wireless communication according to the IEEE 802.11 bgn standard is simulated. More details regarding propagation models, interference modelling etc. are described in more detail in [4]. The AGVs are controlled according to the VDA5050 standard.

4 BENEFITS OF AGVS UTILIZING A MANET

Within the now available factory models, two question must be answered. Firstly, can a MANET between AGVs effectively improve the connectivity of the AGVs to the fleet controller? Secondly, is an improved connectivity correlated to an improved transport performance of the AGVs? Both of these questions were part of previous work ([4, 5]), but the procedural factory generation enables, for the first time, an examination these questions without being specific for a certain industrial application / factory layout.

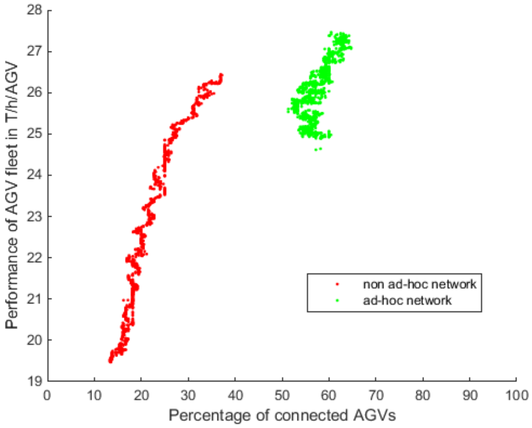

Figure 3: Relation of AGV connectedness and AGV fleet performance for the non ad-hoc and ad-hoc AGV fleet.

As previously described the connectivity of the AGV fleet is described in terms of percentage of AGVs connected to the fleet controller in relation to the complete fleet size. The simulation implements the AGV communication in accordance to the VDA5050 standard. The AGVs periodically (every 3 s) send their current status to the fleet controller. The fleet controller can be reached via any of the APs within the factory. The fleet controller classifies an AGV as connected, if the last status message was received not longer than 3 s ago. The fleet controller acknowledges the status messages. The AGV uses these acknowledgements to determine its connection status. If more than two sequential status messages are not acknowledged, the AGV perceives itself as disconnected. The following measurements present the networks connectedness as sensed by the fleet controller.

Figure 3 presents two system characteristics based on approximately 10 000 h of simulated AGV operation in about 380 different factories. Firstly, it shows that, generally, a higher AGV fleet connectedness correlates with a higher fleet transportation performance. Secondly, the figure shows, that the ad-hoc network generally achieves a higher fleet connectedness and also higher AGV fleet performance compared to non ad-hoc networks.

If an AGV in the non ad-hoc network reaches a task destination where no connection is available and no additional task is buffered, this AGV remains disconnected. This naturally lowers the capacity of the AGV fleet, since the number of operational AGVs is reduced. It is possible to implement fall-back solutions for such a scenario, which can reestablish communication. The AGV might drive to the last point with connection, the start point of the last task or a specified point in the factory. The examination, which of these solutions is the most effective is beyond the scope of this work and the effects of such systems and their favorable design is part of future work.

5 RELAY NODE POSITIONING

The planned next step to further improve the AGV MANET is to use the mobility of the AGVs in order to improve the coverage of the MANET. It is envisioned, that this leads to an increased network connectedness and therefore higher fleet performance. This strategy is further described as adaptive networking, due to the adaptive positioning of the AGVs.

The basic idea of the strategy is, that once the AGV receives a task, it checks if a connection to the fleet controller is possible at the destination of the task. If a connection will be possible, the AGV starts the task. If no connection will be available, it will request assistance to ensure connectedness. The request for assistance begins with determining suitable relay positions within the factory. Afterwards, suitable AGVs must be selected to act as relay-AGVs.

The process of adaptively positioning AGVs has therefore three steps:

1. Learning the network coverage
2. Selecting suitable relay positions
3. Selecting suitable AGVs to act as relays

In the following these three steps are described and communication and control solutions for these challenges are proposed.

5.0.1 Learning network coverage. Once the AGV receives a task, it must determine if it will need assistance to ensure connectedness or if it does not. For this, it must predict the possibility to connect to the fleet controller at the destination of the task. This prediction is done with a learning system. For each possible task destinations a connection probability is determined. The AGV learns this probability based on observations.

Each time the AGV is at a position $?$ a counter $\#_{?}$ is incremented with a defined frequency. If the AGV perceives itself as connected to the controller the counter $\#_{2?}$ is also incremented. The probability $\%_{?}$ to be able to connect to the fleet controller is:

$$\%_{?} = \frac{\#_{2?}}{\#_{?}} \tag{1}$$

The ability to connect to the controller from a position can not be expressed as a false/true-value. The dynamic nature of the network and the environment requires a probability value. This simple learning approach is limited by the movement of the observing AGV. The AGV can not know the probability to connect to the controller from a destination, if it was not at this destination at an earlier time. This system is functional, but needs a long time to know the connection probability values of task destinations.

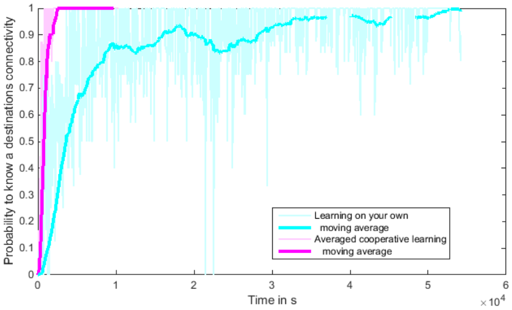

Figure 4: Comparison of speed of learning connectedness.

The system is expanded to a decentralized, collaborative learning system. The goal of this expansion is to improve the effectiveness of the learning with minimal impact on the network in terms of amount of shared data. The approach is, to exchange learned data between AGVs in order to increase the learning speed. Decentralized means, that no coordination of the learning or central aggregation of data is required.

It is proposed, that each AGV broadcasts learned information at a specified interval (e.g. 3 s). In each broadcast the $\#_{?}$ and $\#_{2?}$ of a random $?$ with $\#_{?}$ ¡ 0 is sent. On receiving such a broadcast the received $\#^{A}_{?}$ and $\#^{A}_{2?}$ can simply be added to the already known $\#_{?}$ and $\#_{2?}$. This produces a communication overhead of less than 50 byte/s/AGV.

The learning system was implemented with and without the collaboration in the same factory. The likelihood, to know a destinations connectedness probability was recorded. The results can be seen in Figure 4. It can be seen, that after less than 3000 s (≤1 h) all AGVs know the connectedness probability of all destinations, if collaborative learning is implemented. In contrast, after more than 55 000 s (≥2 days) the non-collaborative approach still does not know a probability for all destinations.

For subsequent simulations the collaborative learning approach is used. Now, that the AGVs know the connectedness of their destinations, they can determine if they need assistance or not. Firstly, if no probability is known, the AGVs assume, that they need relay assistance. Secondly, if a probability is known and it is under a certain threshold, the AGV also assumes, that it needs assistance. The next step is to determine the best positions for the assisting relay-AGVs. This threshold must be chosen according to the application. For the following simulations a threshold of 85 %. This percentage was chosen based on experience and previous observations.

5.1 Selecting relay positions

The selection of the relay-AGV positions must also be done in a decentralized fashion. In the proposed scheme the AGV which needs assistance determines the target positions for this assistance.

In contrast to many comparable systems (see Section 7) the relays can not be freely positioned. Their movement is limited to defined paths within the factory, while the relay position is limited to a group of parking positions P_{park}. For this set of positions it is guaranteed, that a prolonged presence of an AGV in this position does not block or hinder any other processes in the factory. From this set a sub-set (relay route) R' must be selected, which connects the positions P_{AP} and P_{TD}, where P_{TD} is the task destination and P_{AP} is the position of the Access Point (AP), which is closest to P_{TD}.

For the determination of the relay positions a maximum distance d_{max} is selected. It is assumed, that for any distance smaller than d_{max} a connection is possible. Such a static assumption might not hold true in the dynamic and heterogeneous industrial environment. In this case d_{max} must be lowered or the algorithm enhanced.

In the following "*route*" is used as a term for the collection of positions at which relays must be positioned in order to connect P_{AP} and P_{TD}. Determining this route starts with calculating a distance of each point $P_p \in P_{park}$ to the direct connection of P_{AP} and P_{TD}, defined as:

$$\Delta_p = (|P_p - P_{AP}| + |P_p - P_{TD}|) - |P_{AP} - P_{TD}| \tag{2}$$

Where $|p_1 - p_2|$ is the euclidean distance between p_1 and p_2. All distances are part of $\Delta \ni \Delta_p$, which is sorted in an ascending order.

For each route at least n_{min} relay-AGVs are required, with:

$$n_{min} = \left\lceil \frac{|P_{AP} - P_{TD}|}{d_{max}} \right\rceil \tag{3}$$

The route search process starts with a route consisting of the $n_{min} + s$ nodes with the smallest Δ_p. s is a safety, which enables us to use more nodes than required, but the process begins with $s = 0$.

The following three operations can be done with the route:

- **Sort route**
  The elements of the route are sorted according to their distance from P_{AP}.
- **Check route**
  The distance from P_{AP} to the first route element, between sequential route elements and from the last route element to P_{TD} is compared to d_{max}. The route is valid, if all distances are $\leq d_{max}$.
- **Expand route**
  s is increased by 1. Effectively adding more elements to the route.
- **Optimize route**
  All elements of the route p_i are checked. An elements p_i is removed, if $|p_{i-1} - p_{i+1}| \leq d_{max}$

Based on the defined operations, the following algorithm can be executed:

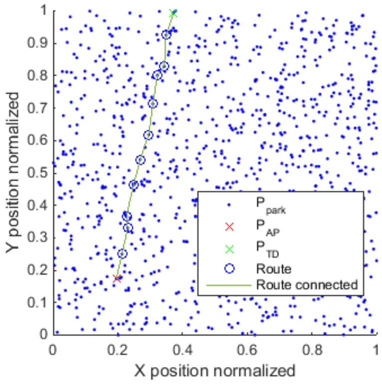

Figure 5: Finding relay positions in irregular abstract scenario.

```
  if(Check route):
      Optimize route
      Return route
  else:
      if(n_min + s < |P_park|):
          Expand route
      else:
          Optimize route
          Check route?
          if(Check route):
              Return route
          else:
              No route found
```

In this process it is possible, that no valid relay route can be identified. But it must be noted, that during simulations $\geq 10^5$ relay routes were determined, and this case did not occur. In future work the probability of this event must be checked in real industrial applications or a simulation developed that suits the examination of this rare event.

In Figures 5 and 6 found relay routes are presented. Figure 5 shows the routes in a irregular abstract scenarios, with a random distribution of P_{park} and Figure 6 a found route in a regular grid of P_{park} is presented. Figure 7 presents multiple routes found in the simulated procedurally generated factory environment.

Once the positions for the relay-AGVs are determined, it must be determined, which of the AGVs shall act as relays.

5.2 Selecting relay nodes

In this work a decentralized approach for selecting the best suited AGV is proposed. The system is designed like a decentralized auction with the following steps:

1. The assistance requesting AGV broadcasts info about the positions, at which relay-AGVs are required
2. Receivers of this broadcast send info about their state (status, position, battery state, communication devices)

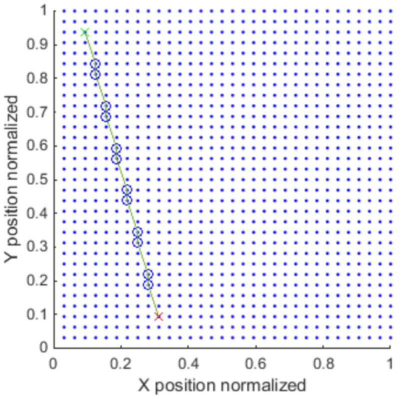

Figure 6: Finding relay positions in regular abstract scenario.

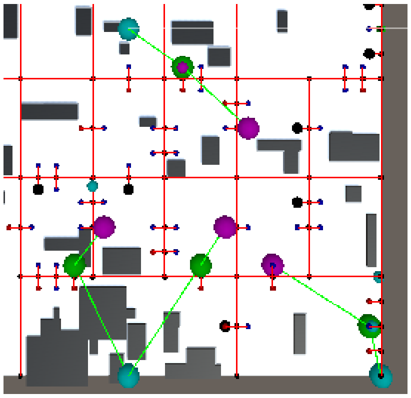

Figure 7: Finding relay positions in simulated factory. APs in cyan, task destinations in magenta and relay-AGV positions in green.

1. (3) The assistance requesting AGV, chooses the best suited AGV and sends the assistance task to it. The requesting AGV itself drives to the task destination.
2. (4) The assisting relay-AGV drives to the destination of the assistance task.

In this approach different parameters of the AGV can be checked in order to determine the best relay-AGV. Firstly, the most important parameter is the transport status. An AGV can only assist, if it has no active transport task. Secondly, it is risky to use an AGV with a drained battery, as it might not be able to charge at the destination of the assistance task. On the other hand it might be advantageous to use an AGV, with a nearly drained battery, if charging is available at the target position. The availability of different communication technologies to the AGV might also be important in the decision. All of these information must be available to each AGV, if they are part of the AGV selection algorithm.

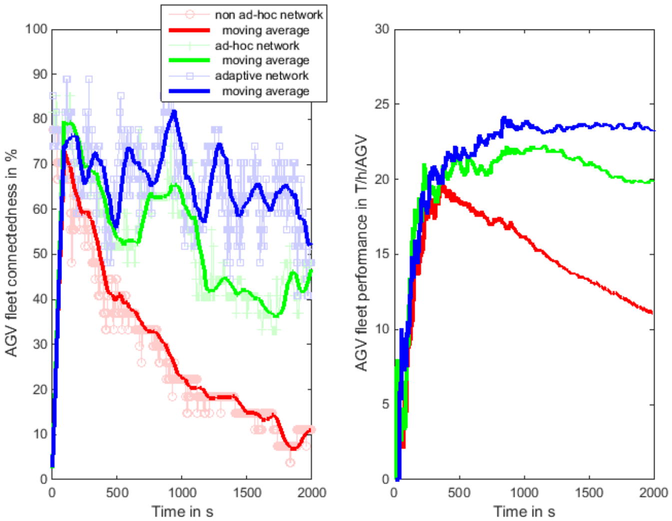

Figure 8: Plot of different AGV fleet parameters over time for different network types in the same factory.

6 TESTING COVERAGE OPTIMIZATION METHODS

In the following section the effectiveness of the proposed system is examined. Two different scenarios are examined. Firstly, factories with non complete network coverage by APs are examined. The environment does not change in this scenario, it is further described as the static scenario. The second scenario, the dynamic scenario, in contrast the environmental conditions change. In the beginning the APs offer full coverage to the factory in these scenarios, but at a specified point in the simulation, some of the APs stop working and some of the obstacles change position.

The following observation is expected: The adaptive network should outperform the ad-hoc network, which should perform better than the non ad-hoc network. In the dynamic scenario it is expected, that the networks perform identically for the first half of the simulation, but that the ad-hoc network and adaptive network are not as impacted by the fault of the APs. After some learning time the adaptive network should perform better than the ad-hoc network.

In Figure 8 the two performance parameters of an AGV fleet, fleet connectedness and fleet transport performance, are presented. It can be seen, that the connectedness varies widely. The transport performance in contrast increases sharply in the beginning and afterwards closes in to a final value. If the connectedness is not steady, then the transport performance also is not steady (compare non ad-hoc performance). It can be seen that the ad-hoc network again performs better than the non ad-hoc solution, while the adaptive system further improves upon the ad-hoc network.

It must be noted, that the adaptive system can improve the connectedness of the AGV fleet, but at some cost. The AGVs that are used for relaying are not available to transport goods, while assisting other AGVs. It was expected, that measures must be taken to prevent an over-utilization of AGV resources by the adaptive

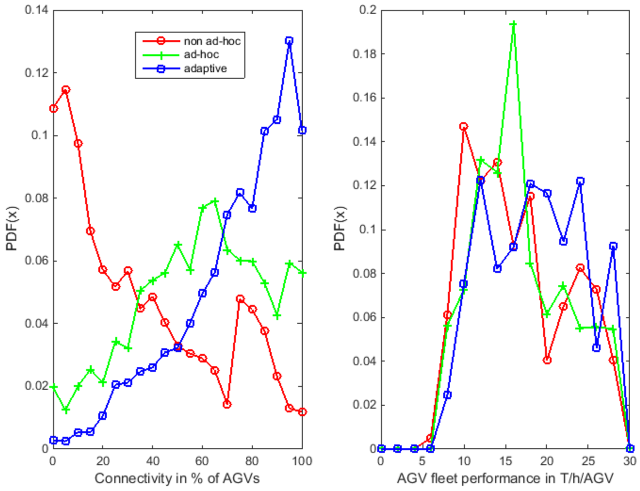

Figure 9: Probability distribution function of connectedness and performance for different network types.

positioning system. However, observation shows, that this is not necessary. In general, requested relay routes often only use 1 or 2 relay-AGVs. The percentage of AGVs that operate as relay-AGVs is therefore relatively low. The number or type of relay-AGVs can be restricted using auctioning schemes. Design patterns and an examination of the effectiveness of such restrictions is outside the scope of this work and can be completed in future work.

6.1 Static scenario

For the static scenario over 360 different factories were simulated with the three network types, non ad-hoc, ad-hoc and adaptive. During the simulation the AGV fleet connectedness and fleet transport performance was logged. In Figure 9 the Probability Density Functions (PDFs) for these two metrics are presented.

The plot of the network connectedness shows, that all three network types can vary in connectedness between 0 % and 100 %. However, the non ad-hoc network is the network type, that occurs most often with a network connectedness between 0 % and 43 %. The ad-hoc network in contrast is dominant between the range of 43 % and 68 %, while the adaptive network has the highest probability to exhibit a network connectedness over 68 %. This observation is in line with the previously described expectations. Therefore, from the network perspective the adaptive network is an useful improvement of the ad-hoc network. But this improvement comes at a price. AGVs are used to improve the connectivity, therefore these AGVs are not available to transport goods, while they assist other AGVs to stay connected.

The AGV fleet transport performance is examined next, in order to determine, if the adaptive network does not only improve the connectedness, but also the transport capabilities. In the PDF it can be seen, that the differences between the networks are not as pronounced as in the connectedness PDF. In terms of performance the non ad-hoc network with an average performance of 16"89 T/h/AGV performs slightly worse than the ad-hoc network with an average transport performance of 17"35 T/h/AGV. When examining the empirical distributions of both mean values constructed by moving block bootstrapping it is evident that the performance of these two cases is only lightly deviate from one another. The adaptive network achieves an average performance of 18"69 T/h/AGV. This is an improvement of 7"7 % compared to the ad-hoc network and above the statistical significance of the simulation.

In general it can be said, that the performance of an AGV fleet can be improved by employing an adaptive ad-hoc network, if the AGVs operate in an environment with non-complete coverage by APs.

6.2 Dynamic scenario

Modern factories are often planned and build with wireless communication in mind. Typically, network coverage is a set requirement. However, it was observed, that even in these modern production facilities connectivity can not be guaranteed. Causes for this are, for example, that the requirement fulfillment was not sufficiently tested, that the environment changed, technical faults and more. In this work the dynamic scenario is used to simulate such a use case. In this scenario initially the factory has complete network coverage. At 1500 s, the mid-point of the 3000 s simulation, the environment is changed and some of the APs stop operating. This scenario was simulated with about 380 different factories.

At first the changes of the AGV fleet transport performance over time are observed. In Figure 10 the performance of the AGV fleets over time are plotted, sorted by the type of utilized network. In the first plot the median transport performance of the different network types are aggregated and compared. In the following three plots the median performance as well as the performance range of the three networks (non ad-hoc, ad-hoc and adaptive) are presented. The last three plots show, that any type of network is more or less affected by the change in the environment. Some networks perform just as well as before the change, while other networks lose all connectivity and can no longer operate. In this case the) / / +-value drops in a specific curve, since more and more time elapses, but no more tasks are completed.

In the first plot the different network types can be compared. It can be seen, that the three types of network performance identically for the first 1500 s of the simulation. After 1500 s the performance of all three network types drops significantly. The non ad-hoc network is slightly more affected, compared to the ad-hoc network and the adaptive network. For the first 200 s to 300 s ad-hoc network and adaptive network perform nearly identically. After about 250 s the learning effects of the adaptive network manifest. The performance of the adaptive network is slightly above the performance of the ad-hoc network after this point.

The impact of the environmental change on the transport performance can be better observed with PDFs. For each type of network two PDFs are created. The "before faults"-PDF compiles the data of the time range from 1000 s to 1500 s. Respectively the "after faults"-PDF contains the performance data from time points ≥2500 s.

The PDFs confirm, that the performance of the non ad-hoc, ad-hoc and adaptive network are nearly identical before the faults

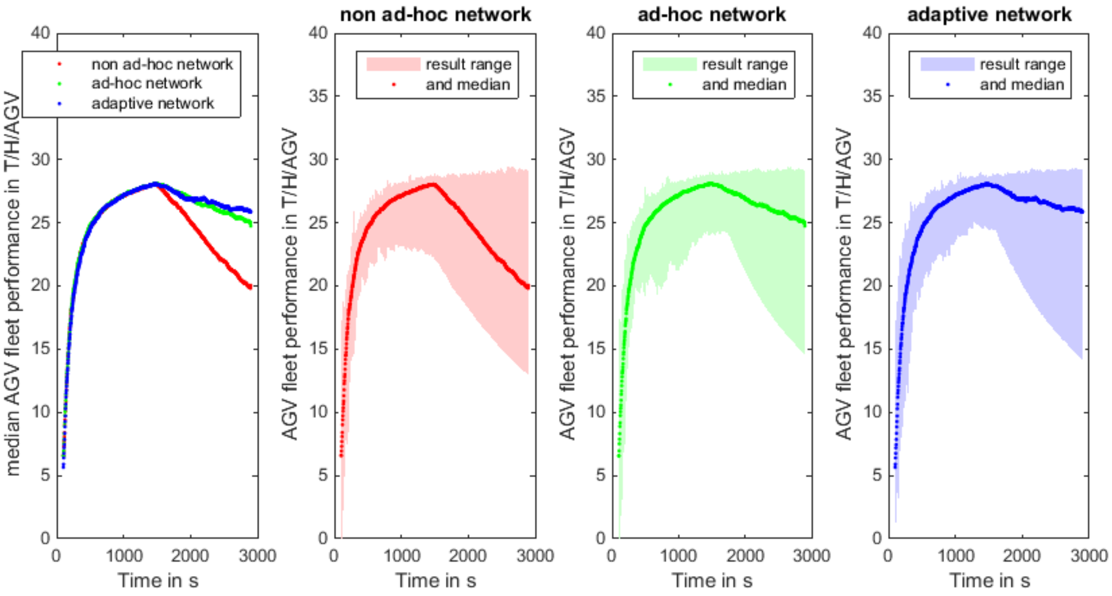

Figure 10: Change of performance over time in different networks.

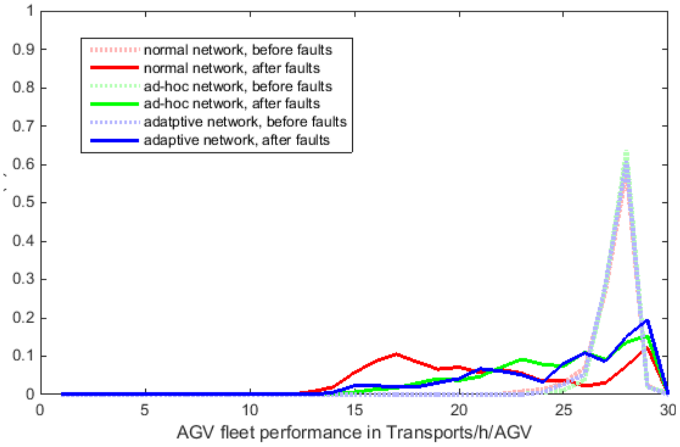

Figure 11: Distribution functions of performance before and after environmental change.

Table 2: Performance of networks in dynamic environment

Network type	Pre-Change performance in) / / +	Post-change performance in) / / +	Change
Non ad-hoc	27”67	20”52	−25”8 %
Ad-hoc	27”73	25”41	−8”6 %
Adaptive	27”68	25”93	−6”3 %

occur.After the faults, the non ad-hoc network decreases in performance the most, followed by the ad-hoc network. The time-frames of the PDFs were chosen in a way, that the adaptive network had time to learn the new connectivity and therefore the adaptive network is least impacted by the faults. The median performance of the different networks are compared in table 2.

7 RELATED WORK

By examining related work the presented work is motivated and the proposed systems characteristics are compared to the state-of-the-art. This comparison to other system from the same field is part of the first subsection. In the second subsection related work to the methods used in this paper is discussed.

Add relation to own work.

7.1 Communication System

It is well known, that incomplete network coverage in industrial application has strong negative impact on the effectiveness of wireless communication solution in the industrial environment. Invanov et al. [3, 2] introduced systems to the industrial application, which enabled the planning of network coverage in industrial applications. This also includes the utilization of mesh networks to achieve fault-tolerance [2]. Recently, the interest in mesh networks for industrial applications and their ability to detect and tolerate faults has resurfaced [14].

Even in the context of AGVs, ad-hoc networks have previously been discussed [14, 5]. The previous works envisioned, that these networks and their flexibility will benefit the AGV use case. In this work it was possible to show that this is true. Ad-hoc networks were generally able to benefit the AGV fleet not only in terms of connectedness, but also in terms of transport capabilities.

There are several characteristics, that differentiate the proposed system from previous work [15, 16, 17]. Firstly, the application demands a flexible system, in which any of the AGVs can request assistance and also act as assistance. Additionally, multiple relay assistance tasks can be active within one factory at the same time. The positioning of the relay-AGVs can also respect the restrictions on the movement of the AGVs and on the positions at which relay-AGVs are placed. This is required, since the system must not impact or impede any other process on the factory floor. Lastly, the system was implemented to learn about the connectivity on the factory floor over time. This is required since the industrial environment is highly dynamic and signal propagation characteristics change regularly.

7.2 Methods

As previously described Arnold et al. [12] was an important inspiration for the methods found in this work.

To the best of our knowledge this work proposes the first system to procedurally generate industrial environments. Such applications are not mentioned by the survey done by Smelik et al. [18]. The systems itself in similar to the rule-based generation of indoor environments proposed by Tutenel et at. [19].

8 CONCLUSION

The goal of this work was to optimize the connectivity of mobile devices in industrial applications. In particular the connectedness in an industrial MANET, consisting of AGVs, had to be improved. The concept was, that the movement of position of some of the AGVs is controlled to supply connections to the other AGVs.

In the process of implementing and testing this system, new methods were developed to examine such systems. A simulation tool, which procedurally generates industrial environments and tests the networking solution in these environments. The results from hundreds of different factory floors are combined in order so determine, if a systems is beneficial without depending on the specific scenario.

With this method it was possible to show, that ad-hoc networks are generally beneficial to AGV fleets, and that the increased network connectedness also increases the achieved AGV fleet transport performance. In short: A well connected AGV fleet is able to transport more goods. The method also showed, that the adaptive control of AGV movement further improves the connectedness and performance of the AGV fleet.

For future work it is envisioned to improve the control system. It would be beneficial to have the system react faster to changes in the environment or to use actual machine learning to learn about the characteristics of the network during its operation. Additionally, the search for relay positions does not regard signal blocking by obstacles right now, further improvements might be possible by including this.

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