Article

On Ad-Hoc Communication in Industrial Environments (non-reviewed preprint)

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Abstract: In this work ad-hoc communication in the industrial environment is examined. The examined use case is peer-to-peer communication between mobile robots. Nodal Encounter Patterns (NEP) are the chosen tool for examining the characteristics of these networks. A protocol to record these patterns is proposed and compared to existing methods for extracting NEPs from network traces. NEPs were recorded in a running production facility. The protocol implementation and the recorded NEPs are made available. Using this newly developed method, this work offers insights on the characteristics of industrial ad-hoc communication channels. Based on the observed channel characteristics, multi-hop multi-route routing algorithms are recommended for the examined industrial use case.

Keywords: Mobile Ad-Hoc Networks; Industrial Application; Nodal Encounter Pattern; Communication Characteristics

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1. Introduction

Trends like Industry 4.0 are shaping the factory of the future. Flexibility and mobility are central requirements for future production facilities. Wireless communication is a central part in enabling mobility and facilitating flexibility. Automated Guided Vehicles (AGVs) for example depend on wireless communication systems. Researchers are investigating the possibility to utilize ad-hoc communication (e.g. Mesh [1] or DTN [2]) for the communication of the AGVs. The research and implementation of wireless infrastructure and ad-hoc communication would benefit from a more thorough understanding of wireless channel characteristics in industrial environments.

The goal of this work is to offer a more holistic insight into wireless channel characteristics in the industrial environment. In the context of Industry 4.0 a heterogeneous set of new communication technologies is introduced. The developed methods enable researchers and engineers to examine the channel characteristics of newly introduced networks and communication technologies. An engineer can for example use the proposed method to evaluate an existing factory and verify the applicability of a planned Wireless Sensor Network (WSN). Additionally a researcher could use the presented and published recordings to optimize the routing algorithm for an industrial Mobile Ad-hoc NETwork (MANET).

$$C(T,R,t) = \begin{cases} 1, & \text{if } T = R \\ 1, & \text{if T can transmit data to R at time t} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

An encounter is a continuous time frame T in which a transmitter S can send data to a receiver R. A Nodal Encounter Pattern (NEP) is a recording of the encounters in a specific scenario using a specific communication technology. And formalized as $C(S, R, T)$ in Equation 1. The NEP denotes the time variant topology of the network. Properties of the NEP can therefore be used to determine channel characteristics of the used communication technologies in the examined scenario. This work contains a new method for recording NEPs, and the analysis of NEPs, that were recorded in a running production facility. The NEPs are additionally published to the research community to be used for further analysis and as a basis for the simulation of industrial ad-hoc networks.

Hsu et.al. [3] used NEPs for the characterization of ad-hoc networks and their potential. The presented work differs from [3] in regards to the examined scenario, but also in regards to used metrics and method of NEP acquisition. Previously, NEPs have been extracted from network traces of infrastructure networks, which are the recordings of network traffic. Encounters were extracted with the assumption, that two mobile nodes registered at the same access point in a infrastructure network is equivalent with two mobile nodes encountering each other in an ad-hoc network. This assumption hinges on specific scenario parameters and is often not applicable. The differences of the proposed recording method and the extraction from network traces is mathematically analyzed.

Thus, the contribution of this work is therefore four-fold:

1. Two methods for the acquisition of NEPs are compared.
2. A custom protocol for recording NEPs is described and published. This includes the methods for processing the acquired data.
3. NEPs of industrial ad-hoc networks are recorded and published for the use by other researchers for further examinations and industrial peer-to-peer network simulation.
4. The acquired NEPs are analyzed. Channel characteristics are extracted from these NEPs and recommendations for suitable ad-hoc networking solutions are given.

Wireless communication in the industrial context and related work regarding traces and encounter patterns are surveyed in Section 2. In Section 3 the two different methods for NEP acquisition are compared. Section 4 introduces the proposed and utilized tracing protocol and the process of encounter pattern generation from the recordings. The performed measurements and examined network characteristics are described in Section 5. Afterwards Section 6 concludes this work with a discussion on methods and presented observations.

2. Related Work

Wireless communication is not new in the industrial context but it continuously gains importance [4,5]The industrial environment is particularly challenging for the application of wireless communication. On the one hand high requirements in terms of latency, throughput and especially reliability are applied. On the other hand dynamic environments including fading, mobility in transmitter and receiver and the permanent presence of interference are inevitable.

Fellan et.al and Zhang et.al [6,7] analyzes the challenging requirements for the communication systems of mobile robots in the industry 4.0 context. The requirements for different industrial use cases are compared and the applicability of several communication technologies examined.

Relevant communication technologies for the industrial AGV use case include LTE [8], 5G [9,10], WiFi [7,11], ZigBee [12] and specialized solutions like Visible Light Communication and Radar[13]. These technologies have different advantages and strengths and must be chosen based on the application specific requirements. [4,6,12] and [13] compare these strengths to the requirements of emerging industrial trends.

[14–16] and [17] performed measurements in different industrial environments and provide valuable insight on the expected channel characteristics of varying communication technologies. The observed variability of the link over time is a strong indicator for the dynamic nature of the propagation properties within an industrial environment. The measurements were executed with static transmitter and receiver. Spatial variability is an additional factor in scenarios, where transmitter and/or receiver are mobile [11]. [18] illustrates the lack of measurements in industrial applications. No previous work specifically characterizes the peer-to-peer communication channels in a mobile industrial network.

Ad-hoc communications technologies are an emerging trend in the use case of factory automation and industry in general. Wireless Sensor Networks (WSN) are possibly the best established use case for this technology [19,20]. These sensor networks are utilized to monitor machines, environmental conditions and more. Software-Definded WSN (SDWSN) are a particular variant of these networks, surveyed by [21].

Mobile Ad-hoc NETworks (MANET) are not yet present in many industrial facilities. But they are being investigated by researchers in the context of mobile robots (e.g. AGVs) [1]. In this use case MANETs and other other ad-hoc technologies, like Delay Tolerant Networks (DTNs) [2] offer enhanced flexibility, reliability and independence from network infrastructure. The applicability of existing communication and routing solutions to an industrial MANET have not been researched at this point in time.

NEPs have previously been used to examine mobile ad-hoc networks [3]. Hsu et.al used NEP to examine the properties and applicability of ad-hoc data dissemination schemes to campus networks. They acquire NEP using network traces [22,23] from the campus networks of several universities. These traces contain the complete communication within the examined infrastructure network, including the registration of mobile devices at certain access points. With the assumption, that two nodes, that are registered at the same access point can also directly communicate with each other, NEPs can be extracted from the network traces. The resulting NEPs are examined in terms of clustering coefficient, disconnected ratio, average path length and node behavior [24].

No previous work has analyzed the ad-hoc communication channel of mobile clients in an industrial environment. With on-going trends like Industry 4.0 the importance of mobile clients and wireless communication will rise. Therefore this investigation is highly relevant. Additionally this work uses the established tool NEP to examine the ad-hoc channel and proposes and publishes a new method to record these NEPs, which can be applied with other communication technologies in industrial scenarios, but also in non-industrial applications.

3. Comparing methods for the extraction of NEPs

It is hypothesised, that the necessary base assumption for the NEP extraction from network traces is not applicable to the industrial scenario. In this section differences between the indirect generation of NEPs by means of network traces and the direct recording of NEPs by means of a custom protocol are shown. Two primary metrics are examined.

The average number of simultaneous encounter per node $N_{\varnothing}$ and the average duration of these encounters $D_{\varnothing}$ is examined. Both metrics can be directly calculated from a NEP. Both metrics are important, when analysing the characteristics of the ad-hoc communication channels. The first is an indicator for the number of reachable destinations from any node, while the second indicates the duration for which these destinations are reachable.

The first NEP acquisition method is the acquisition by means of a custom protocol, further denoted as trace protocol. The protocol is described in Section 4. The second is the acquisition by means of network traces [3]. This second methods is based on the assumption, that any two nodes encounter each other, if they are registered at the same access point. Both approaches have different strengths and weaknesses.

In this section the fundamental behavioral differences of encounters acquired by both methods are observed. The goal is to analyse the behavior of the average number of simultaneous encounters in regards to the number on nodes N and number of access points N_{AP}. Additionally the average encounter duration in regards to the communication range r of the nodes and their speed v is analyzed. The communication range r results in a node coverage area $A_r = \pi r^2$.

In the following subsections the behavior of the average number of simultaneous encounter per node $N_{\varnothing}^{XX}(N, N_{AP})$ and the average duration of these encounters $D_{\varnothing}^{XX}(r, v)$ is explored. XX describes the type of examined acquisition method. TP is the recording of encounters by means of a Tracing Protocol and NT is the acquisition by means of Network Traces. Models are proposed to emulate the behavior of the different metrics, when observed by the different methods. The goal of these models is not a precise prediction of network performance, but of the impact of certain parameters on the observed metrics.

3.1. Average number of simultaneous encounter per node

With the assumption of equally randomly placed access points and randomly moving nodes on area A, $N_{\varnothing}^{XX}(N, N_{AP})$ can be determined for both acquisition methods. For the observation by trace protocol the number of nodes, that a specific node might encounter, are calculated. It is expected, that the $N-1$ other nodes are randomly distributed on A. The number of simultaneously encountered nodes is therefore expected to be the fraction of $N-1$ that are present in A_r. It follows, that:

$$N_{\varnothing}^{TP}(N, N_{AP}) = \frac{A_r}{A}(N-1) \tag{2}$$

For the acquisition by means of network traces NT two different cases must be considered. The first case is, that the area A is not completely covered by access points. This case is defined by $N_{AP}A_r \leqslant A$. This means, that the combined covered area by all access point is smaller than A. Overlap of access point communication ranges is rare, due to the assumed equal distribution of the access points. If the area is not completely covered, the average number of simultaneous encounters is equal to the average number of nodes, within range of an access point minus the source node ($\frac{A_r}{A}(N-1)$) times the probability, to be within the range of an access point ($\frac{N_{AP}A_r}{A}$). When assuming complete coverage of the area this probability is 1. Once the area is completely covered the covered area per access point decreases, because the nodes will tend to register at the closest access point[1]. This decline can be formalized with $A_{AP} = \frac{A}{N_{AP}}$ where $A_r \geqslant A_{AP}$. It simplifies to:

$$N_{\varnothing}^{NT}(N, N_{AP}) = \begin{cases} \left(\frac{A_r}{A}(N-1)\right) \cdot \frac{N_{AP}A_r}{A}, & \text{if } N_{AP}A_r \leqslant A \\ \\ \frac{N}{N_{AP}} - 1, & \text{otherwise} \end{cases} \tag{3}$$

The models for the acquisition via trace protocol is therefore equal to the model for the acquisition via network trace only for the case $N_{AP}A_r = A$ and a perfect 1:1 coverage of the application area by the access points. Later results show differences even in this case.

3.2. Average duration of encounters

The average duration of encounters $D_{\varnothing}^{XX}(r, v)$ is mostly dependent on the mobility of the nodes. Hsu et.al [3] assumed nodes, that stay within the range of an access point for a prolonged duration. This assumption minimizes the influence of mobility on the encounter pattern, which is a valid assumption for the examined network traces. In the examined campus networks students listen to lectures or visit libraries and similar locations for a duration of $\geqslant 1\,\mathrm{h}$. This assumption however is not transferable to the examined use case of AGVs in an industrial environment, therefore the effect of mobility on the two observation methods must be considered.

The proposed models reduce the dependencies of the encounter duration of two nodes to the speed v of the nodes and the communication range r. On average a moving node passes the static communication range of an access point along a path of length $\frac{\pi}{2}r$ (see Appendix B) and therefore for a time of $D_{AP} = \frac{\pi}{2}\frac{r}{v}$. This average only accounts for a node passing an AP range. If the destination of the node is within the AP range, the average travelled distance within communication range[2] changes to

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[1] In reality the chosen access point depends on the applied roaming scheme. Most are based on received signal strength.

[2] Average destination is at the AP position. Distance to reach the AP and subsequently leave range is $2r$.

$2r$. It is assumed, that $\sqrt{A} \gg r$, therefore this special case is subsequently not considered. An encounter between any two nodes persists as long as both are in range of the access point. At the point in time at which any node enters the range, every other node that already is connected to the AP will leave the range after $\delta t \in]0, D_{AP}[$. Therefore on average the encounter duration of two nodes can be reduced to $\frac{D_{AP}}{2}$:

$$D_{\varnothing}^{NT}(r,v) = \begin{cases} \frac{\pi}{4}\frac{r}{v}, & \text{if } N_{AP}A_r \leqslant A \\ \frac{\pi}{4}\frac{r_{AP}}{v}, & \text{otherwise} \end{cases} \quad \text{with } r_{AP} = \sqrt{\frac{A}{\pi N_{AP}}} \tag{4}$$

Analogous to the model of $N_{\varnothing}^{NT}$, the case of complete coverage has to be considered, when calculating the duration. This is done with the scaled access point communication radius r_{AP}.

Determining the encounter duration of two mobile nodes is very challenging. Therefore an approximate for the average encounter duration was determined via a fit to data from extensive simulation:

$$D_{\varnothing}^{TP}(r,v) = \frac{r^{\lambda}}{v} \tag{5}$$

For typical values of A the best fit was generated with $\lambda = 1.11$.

Both models are highly simplified. For the model of NEP acquisition via network trace a dependence to N_{AP} is present, which would not be present in reality.

3.3. Numerical comparison

The proposed models for $N_{\varnothing}^{NT}$,$N_{\varnothing}^{TP}$,$D_{\varnothing}^{NT}$ and $D_{\varnothing}^{TP}$ were compared to a numerical simulation. In this simulation the nodes use the Random WayPoint Model to move within the confined area. The results of the proposed models and the numerical simulation are presented in Appendix A.

The numeric simulation confirms the behavior expected from the presented models. Models and simulation show the same behavior in regards to parameters and similar network performance. The table A1 also shows the differences of the two methodologies TP and NT. The two acquisition types show clear behavioral differences, which are examined in detail in the following subsection. Only for specific configurations of N, N_{AP}, v and r similar results in terms of $N_{\varnothing}$ and $D_{\varnothing}$ can be obtained from both acquisition methods. All these observations were done under assumption of random node mobility and random access point placement. More complex distributions of nodes and APs will lead to even more complex relations between all of these parameters and metrics and even more pronounced differences between both acquisition methods.

3.4. Behavioral differences

The average number of simultaneous encounters $N_{\varnothing}^{XX}$ and the average encounter duration $D_{\varnothing}^{XX}$ are two metrics, that change their behavior in regards to the applied acquisition method.

The direct acquisition by means of a tracing protocol enables the more precise examination of a network. Using this method both metrics behave as expected. The number of encounters rises linearly with the number of mobile nodes. The duration of the encounters is constant, when the communication range and node speed are not changed. Both, extensive simulation and proposed model, confirm this intuitively expected behavior.

The indirect acquisition by means of network traces, shows a different behavior. The number of access points is important, when observing the behavior with this method. The duration of encounters is lower, than expected and further declines, when the density of access points is increased. A higher density of access points is beneficial, when observing the number of encounters. The best fit to the direct observation is, at the point of full coverage ($N_{AP}A_r = A$). At higher access point density the number of encounters decreases. In both metrics the decrease is caused by the higher probability for overlapping of the communication ranges of the access points.

The direct acquisition by means of a tracing protocol is therefore recommended. Even if the number of access points is known a correction of these metrics is hardly possible, due to the complex spatial distribution of nodes and access points in real networks [25].

Using a tracing protocol for the acquisition of NEPs also has the advantage, that encounters can be directional. This means that node A can send data to node B, while node B cannot send data to node A. This directionality in encounters can not be extracted, when a network trace is the basis of the NEP. But this is of major importance, when evaluating the applicability of certain routing protocols.

4. Tracing Protocol

NEPs describe encounters between nodes of a wireless network [3]. The patterns can be used two-fold. Firstly, they can be analyzed independently to determine specific network or channel characteristics, like bidirectionality, encounter duration and more. Secondly they can replace mobility model, signal propagation model and the lowest layers of the network model in a network simulation. A NEP has the advantage of being extracted from the examined environment, therefore no complex validation of models is necessary.

The goal of this section is to introduce a protocol, that can be executed on mobile nodes (e.g. AGVs in a production facility) and generate a NEP. The protocol and the required processing is described and a simple implementation based on the Click-Router [26] is published [27]. The tracing protocol has the advantage, that the real NEP can be directly recorded but the protocol must be implemented and running on all observed nodes.

4.1. Protocol Description

The basic idea of the protocol is to use beacons to indicate the possibility of data exchange between a transmitter T and a receiver R. A number of nodes is placed in the examined environment. All nodes send beacons with a certain frequency $\frac{1}{dt}$. If any beacon is received by any receiver, it is logged to a log-file. After the recording is completed the log-files of all nodes are processed and a NEP is created.

The nodes are all identical in function. The protocol defines a time step dt. This is the time resolution of the resulting NEP. A smaller dt leads to a higher resolution in the NEP and to a higher bandwidth usage by the protocol. It must be assumed, that the examined channels are non-changing within dt. An address A_n is assigned to every node and a counter $I_n(t)$ is incremented every time the node sends a beacon. Beacons are send every dt. The beacon contains the address of the transmitter A_T and the current index of the tramsitter I_T.

This beacon is send by the wireless interface (e.g. WiFi IEEE802.11 b/g/n) of the node. Any receiver (A_r) logs this beacon as an encounter tuple, with r being the receiver and s the transmitter. All recorded encounter tuples can be concatenated to form an encounter recording R_R, which is a set of encounter tuples recorded by node R.

$$C = \begin{pmatrix} A_R & T_R = I_R \cdot dt & A_T & T_T = I_T \cdot dt \end{pmatrix} \in R_r \tag{6}$$

Any entry in the recording describes the start or persistence of an encounter of the nodes T and R. It is important to note, that these encounters are directional. The entry only indicates a connection from S to R, not vise versa. A second entry must indicate the reverse encounter. With $t = I \cdot dt$ the indices can be converted to time values. All connections have two time values. This is necessary to compensate for time offset and drift between the internal clocks of the nodes.

The encounter recordings of all nodes can be concatenated to form R_Δ.

The clock offset is compensated by choosing a reference node N_R for every other node an offset $O_n(t)$ has to be determined. For every non-reference node n a time pair is extracted from R_Δ, where t_R is the record time of the receiver, while t_T is the send time recorded at the transmitter. The discrete offset function $O_n(t_n) = t_R - t_T$ can be made continues by assuming for example no or linear drift between the clocks of node N_R and n. The offset is subsequently compensated by the following conversion:

$$C_n = \begin{pmatrix} R & t_R & T & t_T \end{pmatrix} \rightarrow \begin{pmatrix} t_R + O_R(t_R) & T & R \end{pmatrix} = \begin{pmatrix} t & T & R \end{pmatrix} \in R \tag{7}$$

A offset compensated encounter list R is the result, when applying this offset to all entries.

The NEP is subsequently a function of the transmitter T, the receiver R and the time t. It is defined as:

$$C(T,R,t) = \begin{cases} 1, & \text{if } T = R \\ 1, & \text{if } \begin{pmatrix} t & T & R \end{pmatrix} \in R \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

For computational purposes this function is represented as a 3d-matrix of the dimension $N \times N \times \frac{t}{dt}$. With N being the number of nodes, that were used for the recording and the last dimension offering one entry per dt time step for the complete measurement time t.

5. Examination of the industrial ad-hoc channels

Measurements with the proposed tracing protocol were performed in different environments and under varying conditions. The goal of the measurements and the analysis is the characterisation of the industrial environment in terms of effects on ad-hoc communication channels. Knowing the characteristics of a communication channel allows for a more effective selection and configuration of applied routing solutions. The networks examined by Hsu et.al [3] is fundamentally different from the network examined in this work. The number of clients is the most important difference in regards to network characterization. Different metrics for these networks characterization are therefore applied in this work.

Bai et.al [28] shows, that after sufficient time all nodes of a network encounter each other, if they move randomly on the same area. AGVs do not move randomly, but for the examined small networks the same behavior was observed. It is expected, that in bigger AGV systems it may not be true, that all AGV encounter all other AGVs. Certain AGVs could for example exclusively transport goods within specified disjoint areas.

5.1. Performed Tests

In order to evaluate the channel characteristics of industrial ad-hoc channels, tests in different environments and with different setups were conducted. The goal is to differentiate between the influence of environment and mobility on the ad-hoc communication.

A **reference test** was performed to check the general functionality of the protocol and to deliver a reference for the examined network characteristics. It was performed in an office environment with static nodes.

A **static industry test** describes the measurement with nodes in an industrial environment. In this test all nodes collectively moved in an industrial environment, hence did not experience any relative movement. They therefore moved as one group. The goal of this test is to characterize the effect of interference in the industry, while mitigating the effects of mobility and variable signal propagation. The absolute movement of the node group enabled the observation of the spatial variation in the interference.

Lastly a **mobile industry test** was conducted by utilizing AGVs in a accessible production facility to implement mobility. The nodes were mounted on the AGVs in an unosdructed way. Therefore two signal attenuation effects influenced the existence of encounters in the resulting NEP. Firstly, large scale fading causes path loss between transmitter and receiver due to the distance between them. Secondly,

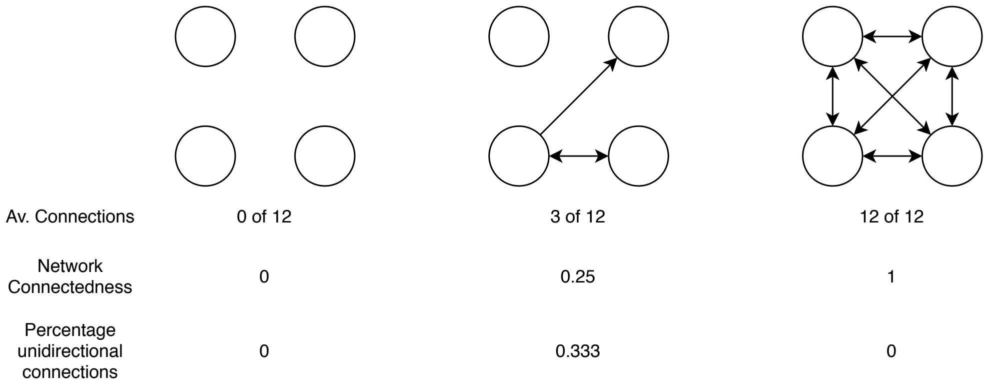

Figure 1. Illustration of network connectedness and probability for unidirectional channels with three example networks.

small scale fading caused by reflection, refraction and scattering can be caused by obstacles on the primary propagation path.

The tests are characterized by a number of varying parameters. When comparing the presented results of the measurements variations in these parameters have to be taken into account. Table 1 compiles and describes the different parameters and their values for the performed experiments.

Parameter name	Unit	Reference test	Static industry test	Mobile industry test	Description
dt	s	0.2 s	0.2 s	0.2 s	Send period of beacons by the trace protocol and therefore time resolution of the nodal encounter pattern
T	s	>11 800 s	>8800 s	>10 400 s	Total run time o the measurement
N		6	7	8	Number of nodes, further divided into N_m and N_s with $N = N_m + N_s$
N_m		0	0	8	Number of mobile nodes
N_s		6	7	0	Number of static nodes
Mobility	Type	None	Group	AGV	Defined when $N_m > 0$. Descibes the type of mobility
Environment	Type	Office	Industry	Industry	Type of environment

Table 1. Measurement parameter description and values for measurements

Some parameters are restricted by external requirements. The send period dt of the trace protocol for example had to be adjusted, as a minimal band-width impact of the measurement was required. Table 1 compares the measurement parameters of the three measurements.

All tests were performed with IEEE802.11 b/g/n communication interfaces at 20 dbm send power. The protocol was implemented with the Click modular router [26] on a battery-powered single-board computer. The implementation and the resulting NEPs are published at [27]

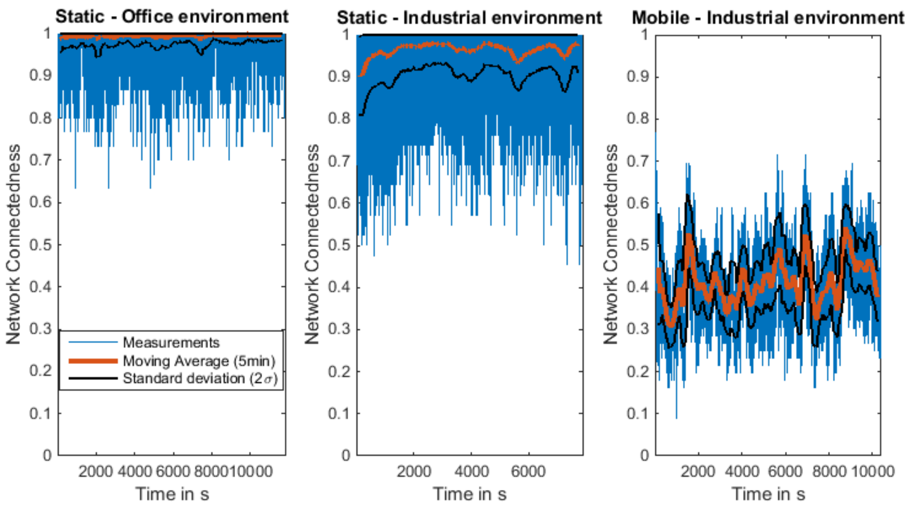

Figure 2. Network connectedness in different scenarios as extracted from NEP.

5.2. Network Connectedness

The network connectedness is the average percentile of neighbouring[3] nodes [25]. Which describes the number of connections that any node in the network has at a certain point in time as a percentile of the total number of possible connections.

A connection can be established if an encounter is registered. It is assumed, that two nodes can communicate for the time of 1 dt after an encounter was registered. Within a network of n nodes $n-1$ connections are simultaneously possible for any node. Hence, nodes cannot connect to themselves. The network connectedness of the network at time t is then defined as:

$$N(t) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{n-1}\left(\sum_{j=1}^{n} C(i,j,t)\right) - 1 \tag{9}$$

When de-normalized and averaged over the time of the recording the network connectedness is equal to the previously used metric $N_{\varnothing}$:

$$\frac{1}{T}\int_0^T nN(t)dt = N_{\varnothing}^{TP} \tag{10}$$

Figure 1 illustrates the meaning of different network connectedness values. A network connectedness $C_N = 0$ describes a network, where no nodes are connected. The network connectedness rises once connections are available. If all nodes can reach all other nodes the network connectedness reaches 1.

The network connectedness of the three examined measurement configuration are displayed in Figure 2. On average the network in the reference measurement is fully connected. This means all nodes can communicate with all other nodes. Short-lived variations occur due to interference between the nodes and interference with other wireless communication systems within the same spectrum. The second measurement set shows slightly lower connectedness within the network. This indicates, that the industrial environment might contain more sources for interference, than the office environment. The variations in network connectedness indicate spatial correlation. The NEP of mobile nodes in the industrial environment exhibits the lowest network connectedness and even higher variations in

[3] Encountered nodes with which direct data exchange is possible

connectedness as the static measurement in the industrial environment. In Figure 2 it can be seen, that the effect of mobility is far more pronounced, than the one of interference.

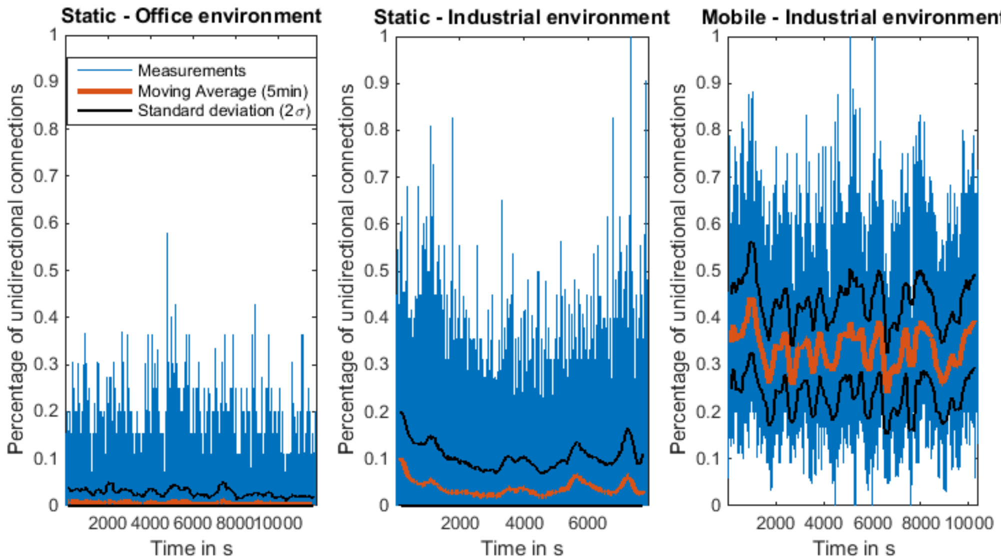

Figure 3. Percentage of unidirectional connections in scenarios.

5.3. Directional Channel Probability

Consider a transmitter A sent a message to receiver B at time T_{AB}. In this work a channel is classified as unidirectional if a transmission at time $T_{BA} \in]T_{AB} - dt, T_{AB} + dt]$ from B was not received at A. If the transmission is received, the channel is classified as bidirectional. Possible reasons for unidirectional channels are changes in the propagation path within dt or interference with other communication networks. The office reference test shows, that interference within the tracing protocol are very unlikely.

Many common routing protocols (e.g. DSR [29], AODV [30]) expect bidirectional connections. Routing protocols can be enhanced to work in the presence of unidirectional channels at the cost of higher overhead [31]. The percentage of unidirectional connection is therefore highly relevant in the evaluation of the applicability of ad-hoc routing protocols to the industrial environment. We assume that such protocols need at least about 200 ms for route search and establishment, therefore the chosen 0.2 s NEP time resolution is sufficient for the examined application.

NEPs, that were extracted from the proposed trace protocol, can be used to determine this probability of a channel being unidirectional. It is defined by equation 11.

$$P_u(t) = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |C(i,j,t) - C(j,i,t)|}{2 \cdot \left(\sum_{i=1}^{n} \sum_{j=1}^{n} C(i,j,t) - n \right)} \tag{11}$$

Previously shown Figure 1 illustrated examples for the probability of a channel being unidirectional. In the central graph three connections exist. One of these connections has no reverse connection. There for $\frac{1}{3}$ of all connections are unidirectional.

As seen in Figure 3 the percentage of unidirectional connections is much higher in mobile industrial scenarios, than in the reference use case. In the static reference measurement unidirectional connection are very rare and only of short duration. On average only 0.52 % of all connections are unidirectional. In contrast about 33.6 % of all connections are unidirectional in the mobile industrial scenario. In the static industrial scenario on average about 3.8 % of all connections are unidirectional. The results therefore support the previous observations, that node mobility has a higher impact on the wireless channel, than the industrial environment.

Overall such channel characteristics have to be taken into account when selecting or designing a routing protocol for the industrial use case. Another important aspect for this task is the route life time.

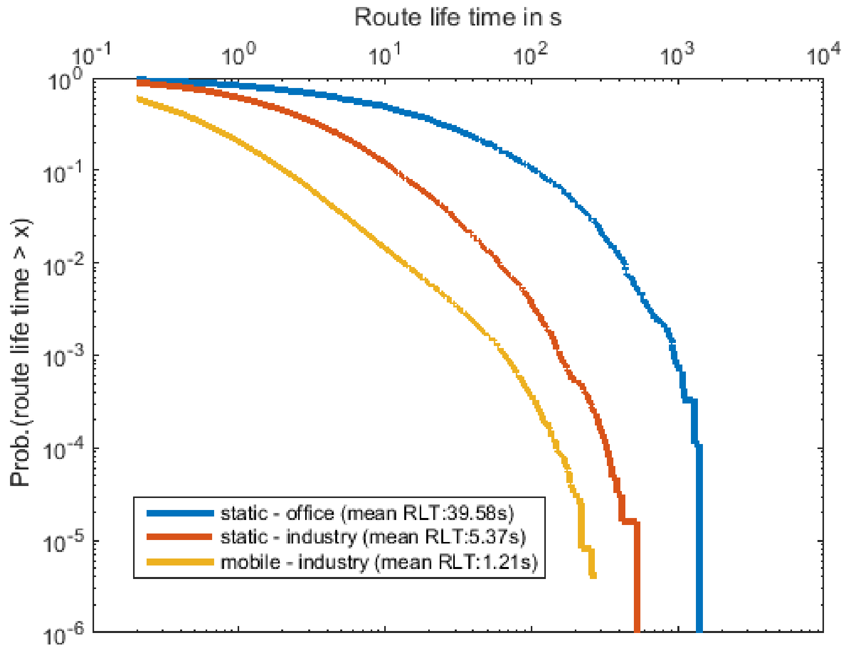

Figure 4. CCDF of route life time in different scenarios.

5.4. Route Life Time

The route life time describes how long a connection between two nodes persists before the ability to transmit data is lost. This is an important parameter in the analysis of applicability for certain network technologies. A low route life time would for example lead to more route failures and therefore more overhead in a Manet routing protocol. The average route life time is equivalent to the previously used parameter $D_{\varnothing}$.

Figure 4 shows the probabilities for route life times in the three scenarios. This metric also iterates the same trend as the previous: From static office scenario over static industrial scenario to mobile industrial scenario the route life time decreases. In the static office scenario an average route life time of about 39 s was observed. Interference between nodes or with other signal sources is rare. This route life time significantly decreases, when the same setup is observed under industrial conditions. The route life time further decreases when observing mobile nodes. Two AGVs are within communication range for far longer than 1.21 s[4], therefore the further decrease in route life time cannot be explained by the distance between the AGVs and their communication range. Rather effects on the primary line-of-sight path or on secondary propagation paths might be the cause of the increased number of disconnections.

[4] Assuming a communication range $r = 20\,\mathrm{m}$ and an AGV speed $v = 1\,\mathrm{m/s}$. An encounter duration of 20 s follows.

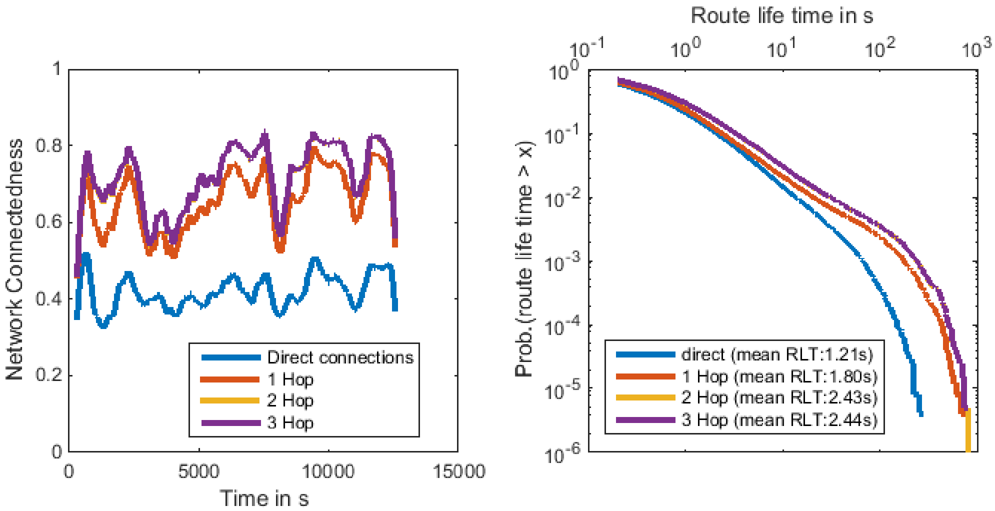

Figure 5. Network connectedness over time and CCDF of route life time in mobile industrial scenario.

5.5. Effects of multi-hop relaying

Mobile Ad-hoc NETworks (MANETs) [1], Delay Tolerant Networks (DTNs) [2] and Wireless Sensor Networks (WSNs) [20] are emerging and developing trends in the industrial context. Ad-hoc network's major advantage over infrastructure networks (e.g. WiFi) is flexibility and redundancy. They are envisioned to mitigate the dependence on network infrastructure and enhance a combined wireless network structure.

In this work the NEP is used to examine the advantage of redundant multi-hop links between mobile nodes in industrial environments. The previously examined route life time is the primary metric for evaluating the improvement. It is envisioned, that the utilization of redundant links increases the route life time. Another expected improvement will be, that multi-hop relaying enhances the network connectedness.

The relevant metrics regarding both expectations were examined and are presented in Figure 5. It can be confirmed, that the utilization of multi-hop connections is beneficial in the mobile industrial context. Firstly, the network connectedness raises, therefore more nodes can be reached, by any other node. Secondly, the average route life time is positively affected. The number of available hops is highly relevant, when examining these benefits. For the examinations it must be assumed, that finding and establishing a route of length h (in hops) is possible within dt. As illustrated in Figure 5 the first hop is the most effective in increasing network connectedness and route life time. It is suspected, that in AGV scenarios with more mobile nodes and/or on a bigger area more hops would be effective in increasing the network connectedness. In the observed scenarios the first and second hop were most effective in enhancing the route life time, while only the first hop enhanced the number of reachable nodes.

6. Discussion and Conclusions

This work examined ad-hoc communication under industrial conditions by means of NEPs. Existing methods for the extraction of these patterns from network traces were examined. It is concluded, that the direct observation of encounters with a custom protocol can more accurately present the behavior of an ad-hoc network. The custom protocol was implemented, tested and used in an industrial environment. The protocol is made available for researchers to analyse the behavior of other ad-hoc network applications. The encounter patterns, that were recorded are also made available. The examined production facility followed the key principles of Industry 4.0. To the best of our knowledge no complete model of the mobile Industry 4.0 communication scenario exists. With these recordings researchers and engineers can, for the first time, analyze, simulate and test industry specific communication solutions for the factory of the future. Additionally the acquired NEPs were analyzed in terms of general network behavior.

The ad-hoc channels in an industrial environment presented some challenging characteristics. The observations of network connectedness (sparse vs. fully-meshed) suggested that interference is impacting the channel availability in the industry. But mobility of the clients has by far higher effects on the availability of channels between nodes. The analysis of the bidirectionality of the available channels suggests that many existing MANET protocols are not applicable to the shop floor. The high percentage of unidirectional connection (30 % to 35 %) highly impacts the search for routes and the resulting routing overhead. The network performance will be further impacted by the low route life time. For the ad-hoc channels between mobile clients in the industrial environment an average route life time of 1.21 s was observed. In regards to route life time interference in the industrial environment has the higher impact, compared to the mobility. Lastly the effects of multi-hop networks on the network connectedness and route life time were observed. Both benefit especially from the inclusion of the first and second relay/hop. This is an interesting observation, when considering the availability of technologies like Side-Link for 5G. Even more hops have an even bigger effect, but the benefit decreases.

The presented results illustrate the benefits of industrial MANETs, but also the challenges. In the future it is planed to acquire more NEPs from a rich set of industrial and other environments. This dataset will benefit us in the design and testing of industrial MANETs and a unified communication framework for mobile robots in the industry. Additionally, the acquired NEPs shall be used to test different routing protocols, where the results will be validated by experimental MANET implementations in production facilities

389 **Appendix A. Simulation and model results**

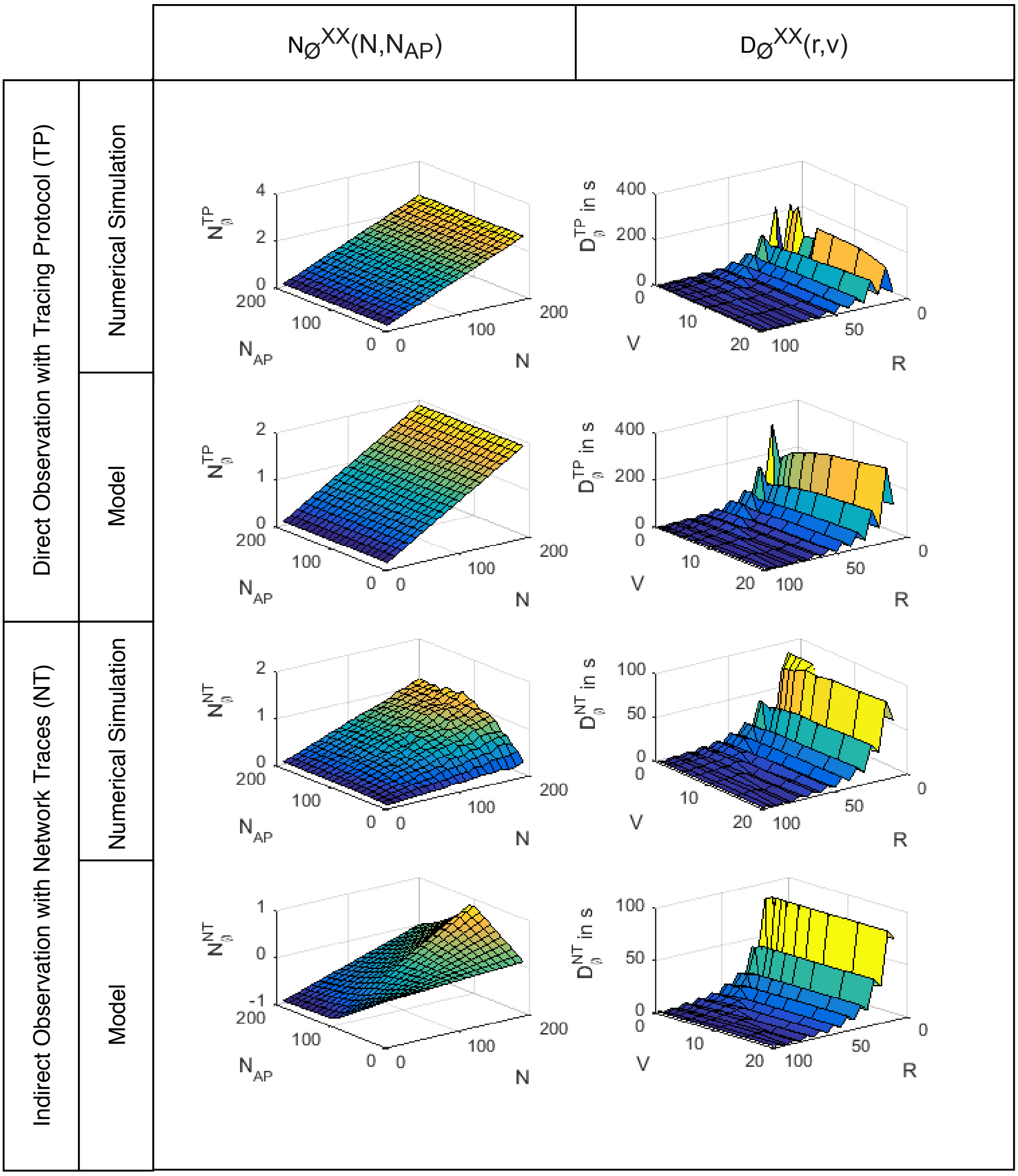

Table A1. Comparison of proposed model and numerical simulation

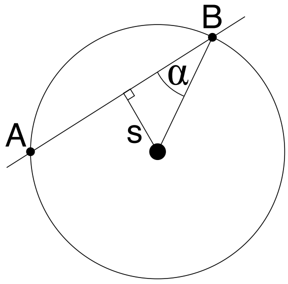

Figure A1. Line intersecting circle.

Appendix B. Theorem of circle intersection length

Theorem A1. *The chord length of a circle intersection depends on the radius r of the circle and the distance s of the chord to the center of the circle. With these two values α can be determined as $\alpha = \arcsin \frac{s}{r}$. The length of the intersection is subsequently defined as $I(s,r) = 2r \cdot \cos \arcsin \frac{s}{r}$. In the scenario of randomly driving nodes through the circle, it is assumed that s is equally distributed over $s \in [0, r[$. With this assumption the intersection length can be averaged over the distribution as follows:*

$$I(r) = \frac{1}{s_{max} - s_{min}} \int_{s_{min}}^{s_{max}} I(s,r) ds = \frac{1}{r-0} \int_0^r 2r \cos \arcsin \frac{s}{r} ds = \frac{1}{r} \frac{\pi r^2}{2} = \frac{\pi}{2} r \tag{A1}$$

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Sample Availability: Nodal encounter patterns (including raw data), protocol implementation and processing scripts are published at: https://github.com/ChrSau/IndustrialAdHoc

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