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Privacy-Preserving Human-Machine Co-Existence on Smart Factory Shop Floors*

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Abstract. Smart factories are characterized by the presence of both human actors and *Automated Guided Vehicles (AGVs)* for the transport of materials. To avoid collisions between workers and AGVs, the latter must be aware of the workers' location on the shop floor. Wearable devices like smart watches are a viable solution to determine and wirelessly transmit workers' current location. However, when these locations are sent at regular intervals, workers' locations and trajectories can be tracked, thus potentially reducing the acceptance of these devices by workers and staff councils. Deliberately obfuscating location information (*spatial cloaking*) is a widely applied solution to minimize the resulting location privacy implications. However, a number of configuration parameters need to be determined for the safe, yet privacy-preserving, operation of spatial cloaking. We comprehensively analyze the parameter space and derive suitable settings to make smart factories safe and cater to an adequate privacy protection workers.

Keywords: Smart Factory · Spatial Cloaking · Privacy Protection.

1 Introduction

The digital revolution has reached industry shop floors around the globe. Besides leading to an optimization of manufacturing processes, it also fundamentally changes the way the employees work. Companies are increasingly relying on the support of industrial robots for assisting in manufacturing processes and goods transport. Autonomous robots have particularly emerged as viable solutions for material transport between storage areas and workplaces. These autonomous robots, also referred to as AGVs, facilitate the autonomous supply of workplaces with materials from warehouses, without the need for human interaction. Sales forecasts for AGVs show an increasing trend for companies to use more AGVs

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for transport processes in the future [20]. This inevitably leads to an increasing co-existence between humans and robots on the shop floors of smart factories.

The digitalization of manufacturing processes is also changing the way workers work on shop floors. Companies optimize their processes by increasingly promoting the use of wearable computing devices [23] to increase workers' productivity [21,24,27], health [11,12,18], and safety [6]. Wearable devices like smart watches, smart vests, or smart glasses [1,30] already support workers by instructing them or providing them with additional process-related information [21,24]. Moreover, they can contribute to workers' health and safety through their built-in sensors because their data allow for the recognition of user activities, such as walking, standing, sitting, and even the workers' position on the shop floor [2,17].

Connected wearable devices, worn by workers, can inform AGVs about their current locations. This knowledge of the workers' locations prevents AGVs from colliding with humans. There is, however, a downside to a frequent reporting of location information, namely the ensuing threats to the workers' location privacy. Such threats can lead to a reduced acceptance of smart wearables by workers. We therefore investigate the applicability of a location privacy protection techniques in a smart factory scenario. More precisely, we present an extensive simulation study to assess existing trade-offs between AGVs' routing and workers' privacy protection. The rest of the paper is structured as follows. In Section 2, we briefly revisit our definition of smart factories and elaborate on the co-existence of workers and AGVs on the shop floors in industrial environments. Section 3 discusses the resulting privacy implications and existing location privacy preserving techniques. We introduce simulation parameters, objectives, and methodology of our study in Section 4, before discussing the corresponding results in Section 5. At last, Section 6 concludes this paper.

2 The Smart Factory

Smart factories are characterized by the presence of AGVs and other robots that contribute to industrial processes [13]. For the AGVs' coordination, a large volume of information is collected and exchanged between participating devices. This enables seamless, safe, and secure interactions between humans, machines, material, and systems [19,22,29]. Human workers still take an important role in smart factories, because of their in-depth understanding of dependencies between process steps and their capability to adequately react to unexpected situations. We thus anticipate that human-machine interactions will continue to exist on shop floors for many years to come.

In this scenario, problems can occur due to the limited space available on the shop floor, though. Often, workers and AGVs need to share the available space (see Fig. 1 for an example). On smart factory shop floors, AGVs are expected to transport materials between machines and workplaces. Their autonomy allows them to collect and deliver items when and where they are needed. Since AGVs move independently between different places, it is of particular importance that AGVs know the positions of the human workers sharing the shop floor, in or-

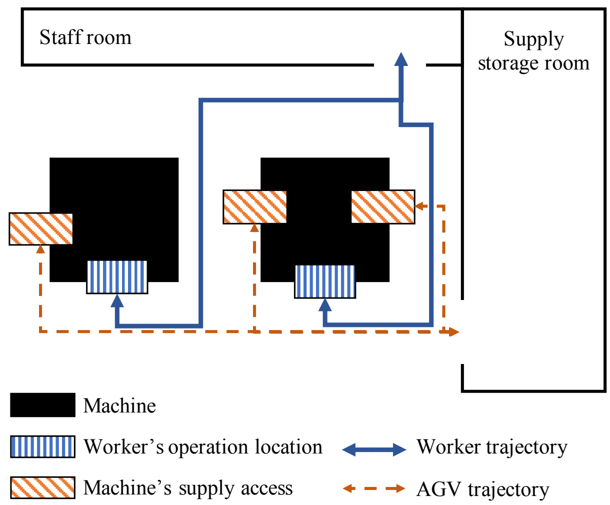
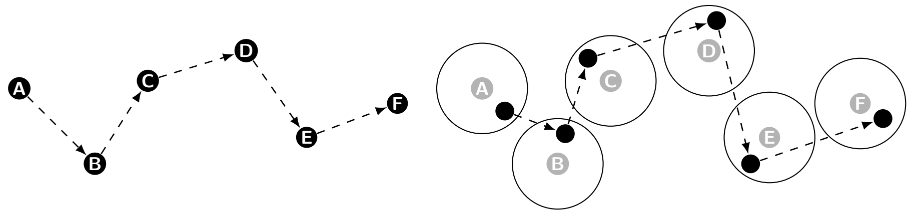


Fig. 1: Sample layout of a shop floor in a smart factory.

der to reduce their speed or even completely stop in the case of an impending collision. Diverse options exist to proactively prevent collisions between AGVs and workers. Most often, this collision prevention is realized through equipping the autonomous robots with detectors for the human presence, and stopping their operation while a human is present in their immediate environment. Diverse technologies can support human detection. On the one hand, AGVs can be equipped with infrared sensors to detect body heat, radar sensors or laser rangefinders to recognize the shape of human bodies, or cameras to locate humans and anticipate their movements [15]. Particularly, laser rangefinders are often used to detect obstacles on shop floors [10]. However, in that case, the AGVs would not be able to optimize their trajectories in advance. On the other hand, workers can be equipped with wearable devices that periodically broadcast their current position on the shop floor, and thus allow nearby AGVs to stop if they come too close. A strong advantage of the latter type of solutions is their capability to detect workers even when they are not within the camera's field of view. Additionally, such wearable devices can also bring benefits for the workers, such as displaying additional information to accelerate the execution of their tasks [21,24]. The increasing number of smart wearables in companies [23] suggests that companies may want to benefit from the advantages offered by these products in the future. Thus, we follow the latter option, and assume that smart wearables (e.g., smart watches) are worn by the workers in this paper. We further assume that the smart wearables know the workers' location information and can broadcast it wirelessly in order to make it known to the AGVs.



(a) Positions without spatial cloaking. (b) Positions obfuscated by spatial cloaking.

Fig. 2: Application of spatial cloaking to user position information.

3 Privacy Implications of Wearables in Smart Factories

The regular transmission of location information has strong implications on user privacy. Transmitted information enables the employer to closely monitor workers' routines (e.g., their breaks or work efficiency), categorize them, and eventually even draw inferences about a worker's performance. Even if no unique user identifiers are transmitted, the AGVs receiving the workers' positions and movements can be tracked based on the constant stream of location information. If the AGVs collude with each other by exchanging their own positions and the times when encountering human workers, they can potentially infer users' movements, routes, and identities. This cannot only reduce the acceptance of such solution, but also impacts their compliance with privacy legislation. Consequently, suitable solutions to protect users' privacy must be implemented.

This can be accomplished with a range of different location privacy-preserving techniques. One option is to report multiple "false locations" in addition to the user's actual position [7,8,16]. Thus, the user's location is hidden within the group of fake locations. However, this approach leads to a highly inefficient operation of AGVs because they cannot move within any of the reported areas. Another option is to apply "spatial cloaking" [14], i.e., the intentional reporting of inaccurate data, which we adopt in this work and evaluate its impact when applied in a smart factory setting. Spatial cloaking works as follows: A user's precise location is replaced by a representation of coarser spatial resolution. By way of example, let us look at the diagrams in Fig. 2. When users are required to report their exact positions in regular intervals (as shown in Fig. 2a), their trajectories can be easily traced. In contrast, when spatial cloaking is applied, falsified location points within a definable radius around the users' actual locations are being reported. This is visualized by means of the black markers in Fig. 2b. While these intentional deviations reduce the resolution at which a person can be tracked, they still appear as valid locations and often correctly describe a valid worker trajectory.

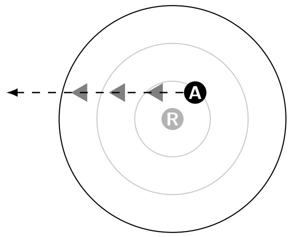
Spatial cloaking relies on two key parameters to determine the efficacy of its privacy protection: The radius of the reported area (depicted as a circle in Fig. 2) and the frequency at which reports are being sent. Frequent reporting rates and small reported radii lead to an accurate tracking of human workers, such that the likeliness of collisions with AGVs is greatly reduced. However, the attained degree of privacy protection is similarly low. Conversely, both larger reported radii and a reduced transmission frequency can be used to reduce the precision of the transmitted location information. The latter aspect, i.e., sending reports less frequently, also preserves the energy budgets of the smart wearables better.

However, a change of the reporting transmission frequency has a direct impact on workers' safety, as their actual positions are randomly distributed inside the reported area and unrelated to their heading direction. The risk ensues that workers leave the reported area in-between two successive transmissions, as the reported workers' location information remains the same until the next transmission. Thus, their protection against colliding with AGVs is no longer guaranteed. Fig. 3 illustrates three typical cases of reported locations (visualized by the light gray markers) with a radius of three. The worker's actual location is represented by the black markers, while the triangles illustrate the number of steps a worker can take without leaving the reported area and until the location have to be updated to ensure worker's safety. If we assume that the worker's actual location is close to the center of the reported area, the worker can take three steps in the given direction before he/she is leaving the reported area (see Fig. 3a). As the worker is unprotected after leaving the reported area, the location should be updated to ensure the worker's safety. If this is not the case, the worker is considered as unprotected until the next location transmission. In comparison, Fig. 3b illustrates the case when the workers' actual location is close to the perimeter of the reported area and the worker moves inwards. Here, the worker is protected for five steps before the worker leaves the reported area. Within the same transmission frequency as before, the worker is protected for a longer duration (i.e., more steps) in this case due to the actual location and the direction in which he/she moves. In contrast, the worker's actual location is also at an area border in Fig. 3c, but the worker is moving outwards. The worker can only take one step within the same transmission frequency, in which he/she is protected by the reported area. Thus, changing the transmission frequency has an impact on the workers' safety depending on the worker's actual location and the direction he/she wants to move.

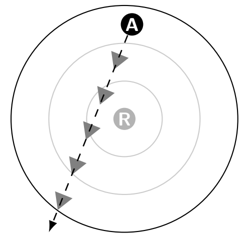
4 Simulation Settings

The efficacy of spatial cloaking relies on the choice of its parameters. In order to assist in the choice of these parameters for the safe and efficient operation of workers and AGVs, we conduct an in-depth analysis of the parameter space. More specifically, we analyze how the following factors affect the accuracy of detection workers on a shop floor, and also assess the extent to which workers' privacy is preserved:

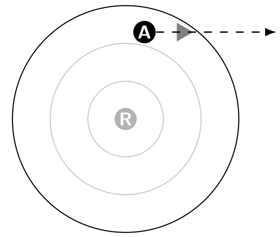
1. The maximum allowed deviation between actual and reported location, i.e., the *spatial cloaking radius*.



(a) Location reported close to the center of the area.



(b) Location reported at area border, moving inwards.



(c) Location reported at area border, moving outwards.

Fig. 3: Typical cases of location reporting for a cloaking radius of three; A is the worker's actual location and R the reported location. Triangles show the number of steps the worker can take without leaving the reported area.

2. The location information transmission rate, i.e., the *spatial cloaking reporting frequency*.
3. The *transmission success rate* to take into account potential communication loss due to, e.g., channel contention or packet collisions.

For our analysis, we adopt the simulation environment described in Section 4.1. We further assume the behavior for both workers and AGVs as detailed in Sections 4.2 and 4.3, respectively. All simulation results show the average values of three runs with different random seeds.

4.1 Simulation Environment

To evaluate the different parameters, we have created a virtual simulation environment in NetLogo, an agent-based-social framework [25,28]. In the simulation environment, our smart factory has a size of 128×64 meters (a square meter corresponds to a patch, which is the surface unit in NetLogo). Since factories are usually unique in size and organization [3,9], we have chosen this particular setting to be able to get the first insights. An analysis of the impact of the factory organization on the results is foreseen in future work. In this factory illustrated in Fig. 4, both workers and AGVs move between different areas. While workers visit both their workplaces and the staff room, AGVs roam between workplace storage units and the main storage room. This setting is applied to simulate a manufacturing setting, in which AGVs regularly deliver new materials to the workplaces and move completed items to the main storage. We set the number of workplaces to ten. By doing so, our simulated smart factory can accommodate multiple workers and AGVs with a meaningful degree of activity. During the initialization phase, workplaces are configured to have a pre-defined minimum distance to each other, such that both workers and AGVs are able to move between them easily. Additionally, this means that the trajectories of both AGVs

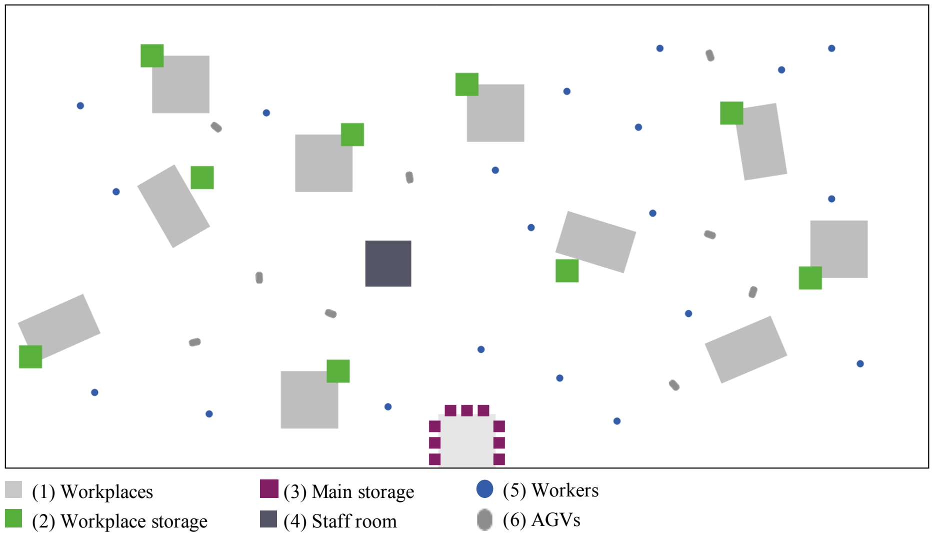
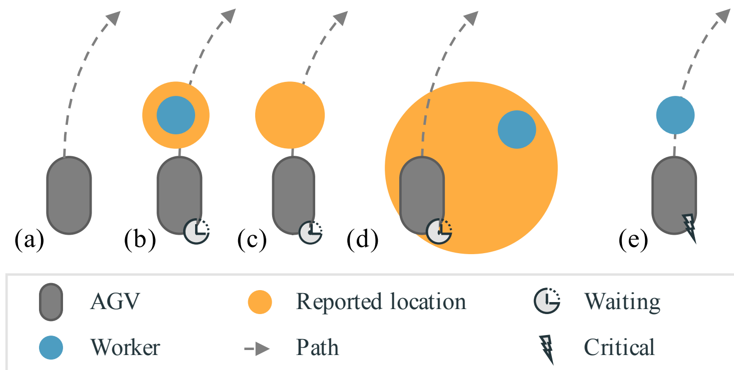


Fig. 4: Sample arrangement of the smart factory used in our evaluation.

and workers cross in different areas of the smart factory. We set the number of workers to 20 and the number of AGVs to nine. This ensures that each workplace storage is regularly visited by an AGV, and thus the AGVs are almost constantly in motion on the shop floor. Our simulations terminate when one of the following events occur: (1) when all workers had a near miss with AGVs, which arise when an AGV's and a worker's trajectories cross on the same patch at the same time or (2) when reaching the maximal duration of 36 000 seconds. All simulation settings are summarized in Table 1.

For each random seed, the workplaces, workplaces storages, staff room, AGVs, and workers are distributed randomly inside the factory environment. Only the main storage has a fixed location at the center of all simulated scenarios, as visible in Fig. 4. In order to fully explore the parameter space, we consider transmission success rates between 10 % and 100 % in increments of 10 %. Note that we have chosen this range of transmission rates to cover worst case scenarios, in which, e.g., workers' smart watches may be ill-functioning, and measure their impact on the workers' safety. We, however, expect a normal transmission success rate to be about 90 %. Likewise, we vary the size of the reported location between 0 (i.e., no spatial cloaking) and 15 meters around a worker. A further enlargement of the radius would only lead to longer AGV waiting times and thus to a significant reduction in productivity. We also vary the workers' location reporting frequency between 1 second and 20 seconds in increments of 1 second each. A further reduction of the frequency would only lead to an even shorter simulation duration and thus to lower workers' safety due to fewer location updates as explained in Section 3. This corresponds to a 10 h working day and thus approximately 2 h over the average working hours inside industrial



Figs. 5: Possible behaviors of AGVs.

environments. It hence provides a better comparison with real production environments [5,26]. The previously introduced parameters are chosen to provide a good balance between the workers' and AGVs' motions.

4.2 Worker Behavior

We assume that workers move within the shop floor at a speed of 1.38 $\frac{\text{meters}}{\text{second}}$ between the staff room and the workplaces, as the average speed of a pedestrian is approximately 5 $\frac{\text{km}}{\text{h}}$ [4]. The length of stay of the workers at the workplaces and in the staff room is 1 second. This means that the workers are constantly in motion. At the moment a worker reaches the staff room, he/she selects a random free workplace to visit next. Each workplace can accommodate two workers. In this way it can be ensured that all workplaces in the shop floor are served. Thus, we can evaluate whether the workers' safety can be ensured despite the use of spatial cloaking. If an AGV's and a worker's trajectories cross on the same patch at the same time, the worker is considered to be in shock after this near miss with an AGV, so that he/she cannot work anymore until the end of the shift and is therefore not considered in the simulation scenario anymore. Each worker transmits his/her cloaked location via a smart wearable. This reported location depends on the spatial cloaking radius, the spatial cloaking frequency, and the transmission success rate, which are defined in Section 4.1.

4.3 AGV Behavior

We assume that AGVs move within the shop floor at a speed of 2.22 $\frac{\text{meters}}{\text{second}}$ between the main storages and the workplace storages. AGVs stay at their destinations for 1 second before continuing their journeys, so as to be constantly in motion. Fig. 5 illustrates the different AGVs' behaviors on the shop floor. An AGV follows its regular trajectory in absence of any workers' reported locations as shown in the first case, noted (a) in Fig. 5. An AGV immediately stops if it

Table 1: Summary of the used simulation parameters.

Parameter	Value
Dimensions of the simulated scenario	128×64 patches
Number of workers	20
Number of AGVs	9
Number of workstations	10
Number of workstation storages	9
Worker velocity	1.38 $\frac{\text{meters}}{\text{second}}$
AGV velocity	2.22 $\frac{\text{meters}}{\text{second}}$
Maximum simulation duration	36 000 seconds
Transmission success probability	[0.1, ..., 1.0]
Spatial cloaking radius	[0, ..., 15] meters
Location transmission frequency	every [1, ..., 20]$^{\text{th}}$ second
Equivalent real-world distance per patch	1 m
Equivalent real-world time per interval	1 s

is about to enter a workers' reported location as depicted in cases (b) and (c). In (b), the worker is still located in his/her reported location, while the worker already left the reported location in (c). The latter case can happen when the workers reduce their spatial cloaking reporting frequency. Otherwise, it is also possible that an AGV immediately stops, even if the worker does not cross their path as shown in case (d). When an AGV stops when entering a workers' reported location, it needs to wait until it is able to continue its trajectory. As a result, its productivity decreases. In the absence of workers' reported locations, the AGV continues its work even if a worker crosses its trajectory as seen in case (e). In this case, the AGV performs an emergency braking. We consider that this avoided collision may still fright the worker and impact his/her capacity to work. We hence consider that he/she is unable to work for the remaining of the shift. As a result, this worker is not considered in this simulation run anymore. Please note that this assumption is adopted to allow for an evaluation of the different parameters, and serves as the termination criterion for the evaluation.

5 Simulation Results

We explore the sensitivity of spatial cloaking to the selected simulation settings summarized in Table 1. Across all evaluations, we use both the workers' safety and the AGVs' productivity as metrics. Since the simulation stops as soon as all workers have crossed the path of an AGV, we consider the simulation time as an indicator of the reached workers' safety: The longer the total simulation time, the better for the overall workers' safety. Likewise, the shorter the aggregated time during which AGVs are stopped, the higher the productivity.

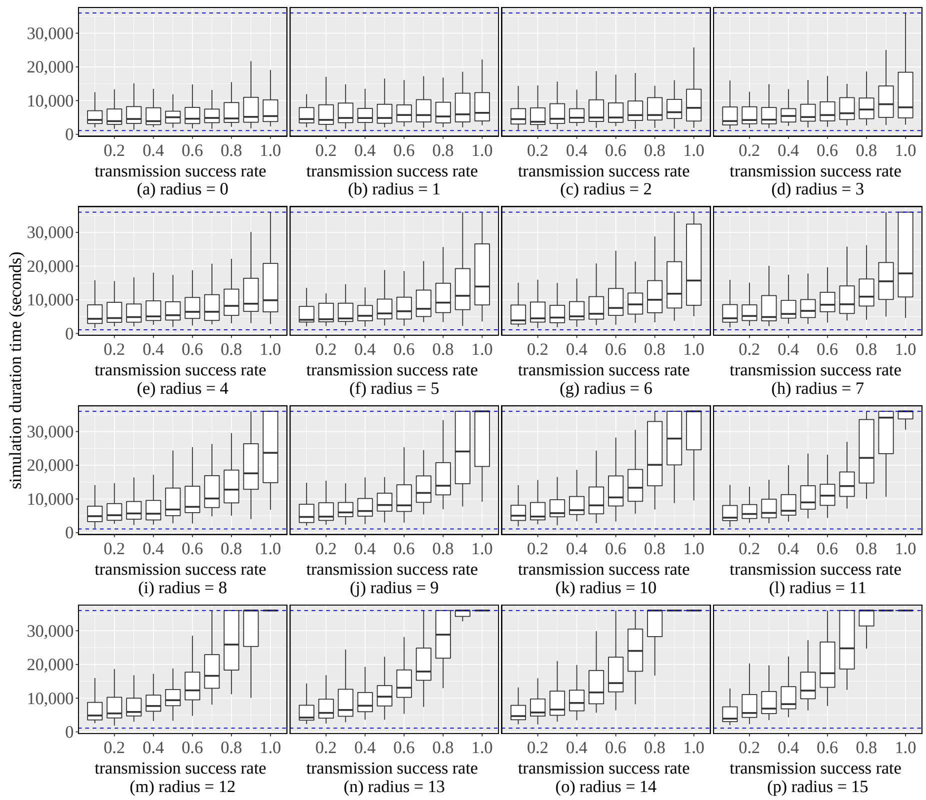


Fig. 6: Influence of spatial cloaking radius on the workers' safety.

5.1 Impact of the Spatial Cloaking Radius

In our first evaluation, we investigate the influence of the spatial cloaking radius on both workers' safety and the AGVs' productivity. Intuitively, a larger radius leads to an increased location privacy protection for the workers and fewer near misses can happen between the AGVs and workers. However, this may decrease the AGVs' productivity.

Fig. 6 illustrates the results obtained when varying the spatial cloaking radius from 0 to 15 meters. A radius setting of 0 corresponds to reporting the exact workers' location, i.e., the baseline performance without spatial cloaking. In contrast, a radius of 15 corresponds to the most inaccurate location data reporting in our evaluation. The simulation duration is depicted along the y-axes of all box plots, with its upper limit of 36 000 seconds, as per Table 1. On the x-axis, different transmission success rate values are plotted. Boxes show upper and lower quartiles as well as the median value obtained for different values of the spatial cloaking radii. As expected, we observe that greater radii lead to better worker protection, which expresses itself through longer durations of the

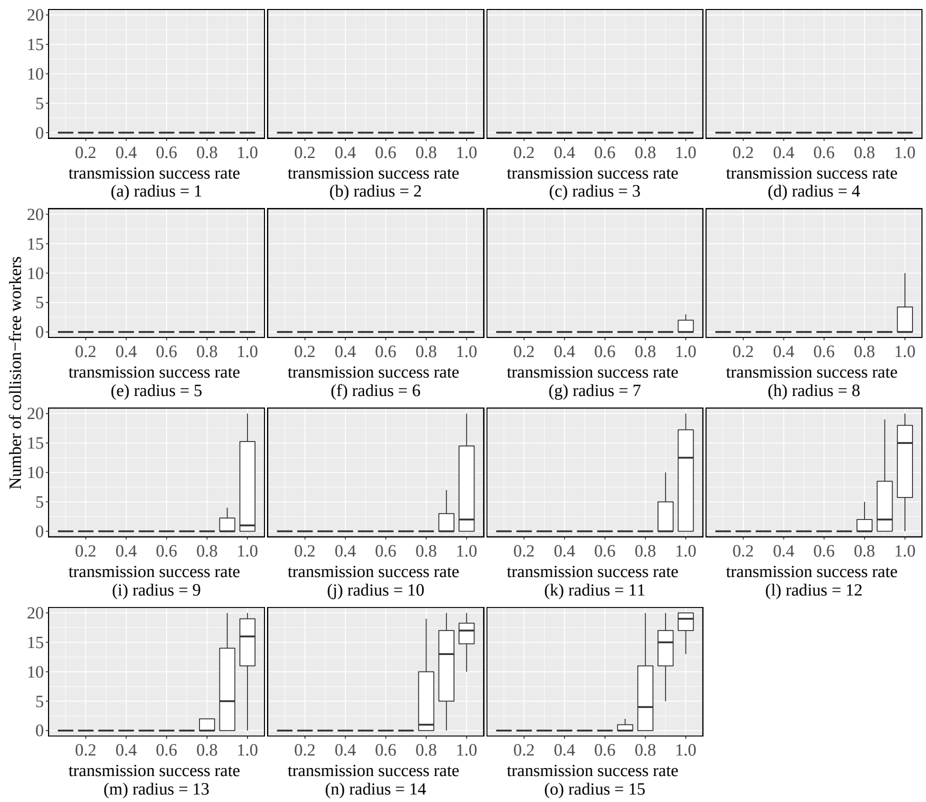


Fig. 7: Influence of spatial cloaking radius on the number of collision-free workers.

simulated settings, because each location report will stop all AGVs within the radius and near misses will thus be are avoided.

A closer look reveals that the results for small radii show almost constant median values for the simulation duration regardless of the transmission success rate. This indicates that spatial cloaking with small radii leads to many near-misses between workers and AGVs. In contrast, increasing the spatial cloaking radius improves the workers' safety. From a radius of 9 meters, the median simulation duration is 36 000 seconds, i.e., the full simulation duration. As expected, the simulations confirm that transmission success rate has an impact on the workers' safety. For the same radius of 9 meters, packet losses of just 10 % lead to a 17 % decrease of the simulation duration. Moreover, the medians reveal that the last four radii in the highest transmission success rate reached the full simulation duration. Likewise, the last two radii reached the full simulation duration, also with a 90 % transmission success rate. It becomes apparent that the simulation results are sensitive to the transmission success rate. Four more workers remain active (i.e., have not experience near misses with an AGV) when a transmission success rate of 100 % is assumed instead of 90 %, for a radius

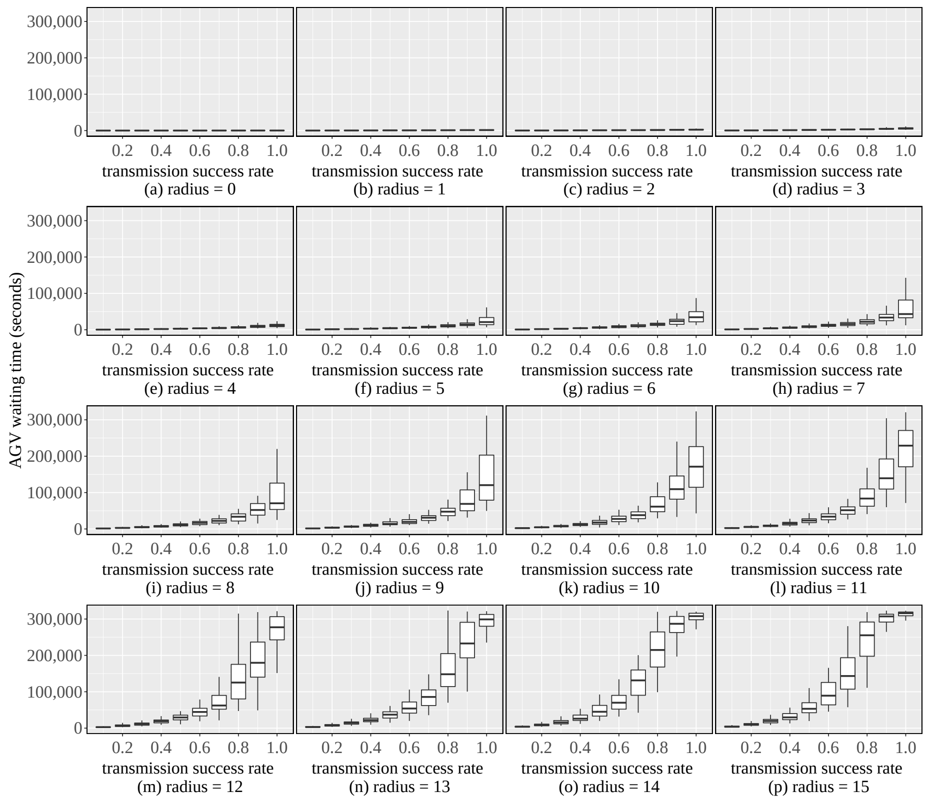


Fig. 8: Influence of the spatial cloaking radius on the AGVs' productivity.

of 15 meters. When using smaller radii, an even greater number of workers remains collision-free until the end of the simulation duration (11 for a radius of 13 meters, 8 for a radius of 14 meters) when assuming a transmission success rate of 100 %.

Fig. 8 illustrates the influence of the spatial cloaking radius on the AGVs' aggregated waiting time for different transmission success rates. As expected, smaller radii especially for higher transmission success rates lead to higher AGVs' productivity, as the AGVs wait significantly less time. For example, assuming no packet losses, the nine AGVs only need to wait for a total of 3 min for a spatial cloaking radius of 0 meters. This time drastically increases to 28 h 21 min when using a radius of 9 meters, and 78 h 54 min for 15 meters in total. For a very lossy link with an assumed transmission success rate of only 10 %, the AGVs' waiting time increase by 61 % when the spatial cloaking radius increases from 9 meters to 15 meters, so that the AGVs seem to stand still almost continuously for larger radii. This confirms the expected trade-off between the size of the spatial cloaking radius for the worker's safety and the AGV's productivity.

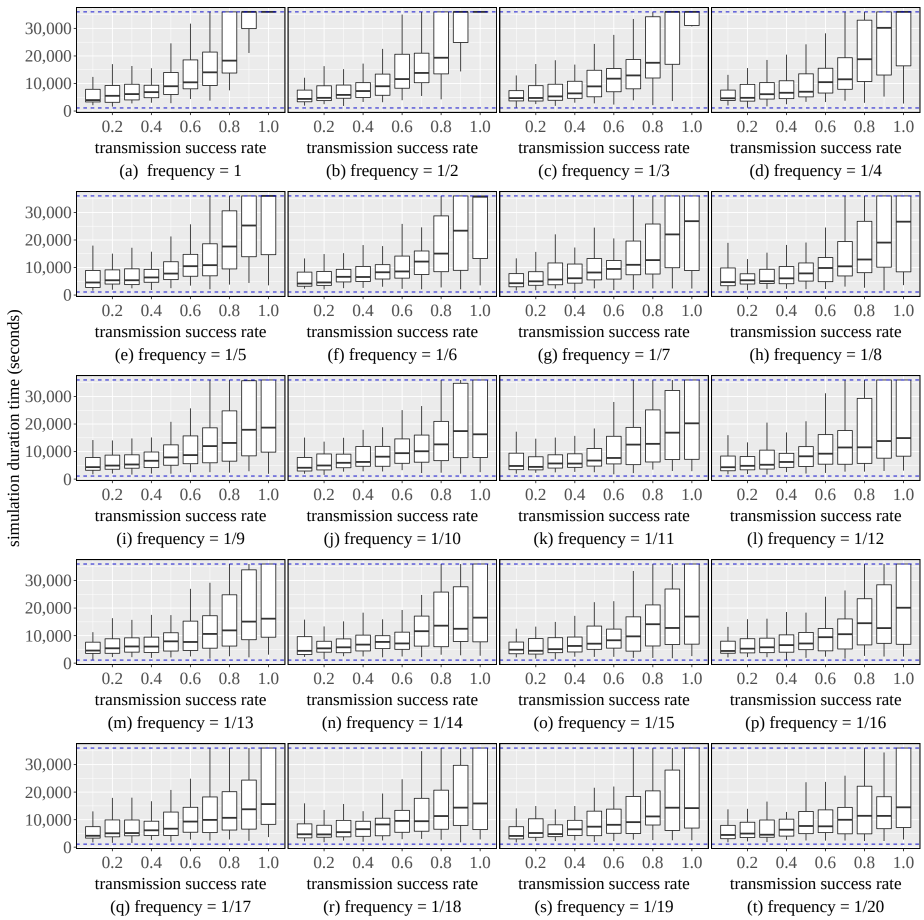


Fig. 9: Influence of spatial cloaking frequency on the workers' safety.

5.2 Impact of the Spatial Cloaking Reporting Frequency

We further analyze the effect of the spatial cloaking reporting frequency on both workers' safety and AGVs' productivity. We assume that a more frequent reporting would lead to an increase of the AGVs' productivity. Moreover, it should lead to fewer near misses between AGVs and workers. However, since their cloaked locations are reported more often, it may be easier for an attacker to infer the workers' actual locations from the reported ones. Fig. 9 illustrates the obtained results for spatial cloaking frequency ranging from 1 to 20 seconds. As expected, we observe that higher frequencies lead to a better workplace safety, as expressed through a longer simulation duration and thus to increased workers' safety. In fact, frequent location updates allow the AGVs to avoid collisions. The graphs indicate that the median values in lower transmission success rates are almost

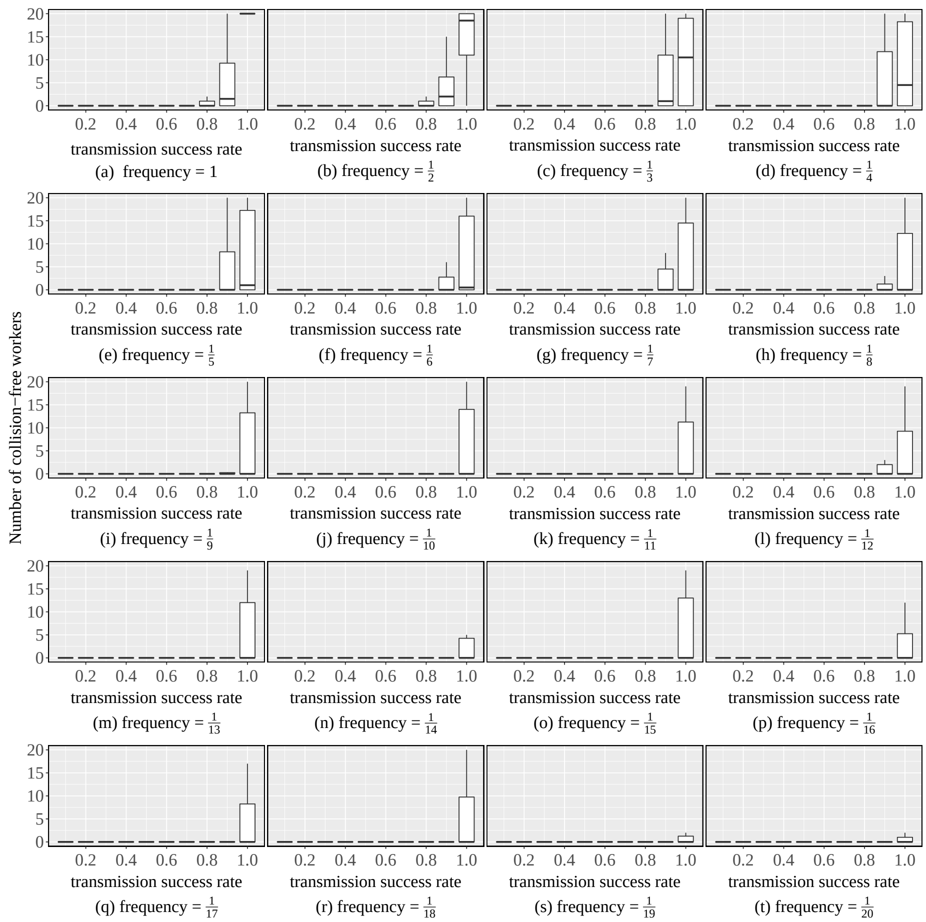


Fig. 10: Influence of spatial cloaking frequency on the number of collision-free workers.

constant. In comparison, for higher transmission success rates and higher reporting frequencies, the simulation duration tend to reach the full simulation duration time of 36 000 seconds. This indicates reporting that spatial cloaking with longer frequencies leads in many cases to unprotected workers, and hence more near misses occur, as the workers take out of their reported locations and are therefore unprotected, until their next location update. From a frequency of 6 seconds, the median simulation duration achieved is equal to the maximum simulation duration on lossless wireless channels. However, the next lower frequency of 7 seconds in-between transmissions leads to a reduction of the median simulation duration time by 34.16 %, and thus to less workers' safety. Moreover, the results of lower frequencies, especially in conjunction with high transmission success rates, indicate a greater variance. The reason for this is due to the ef-

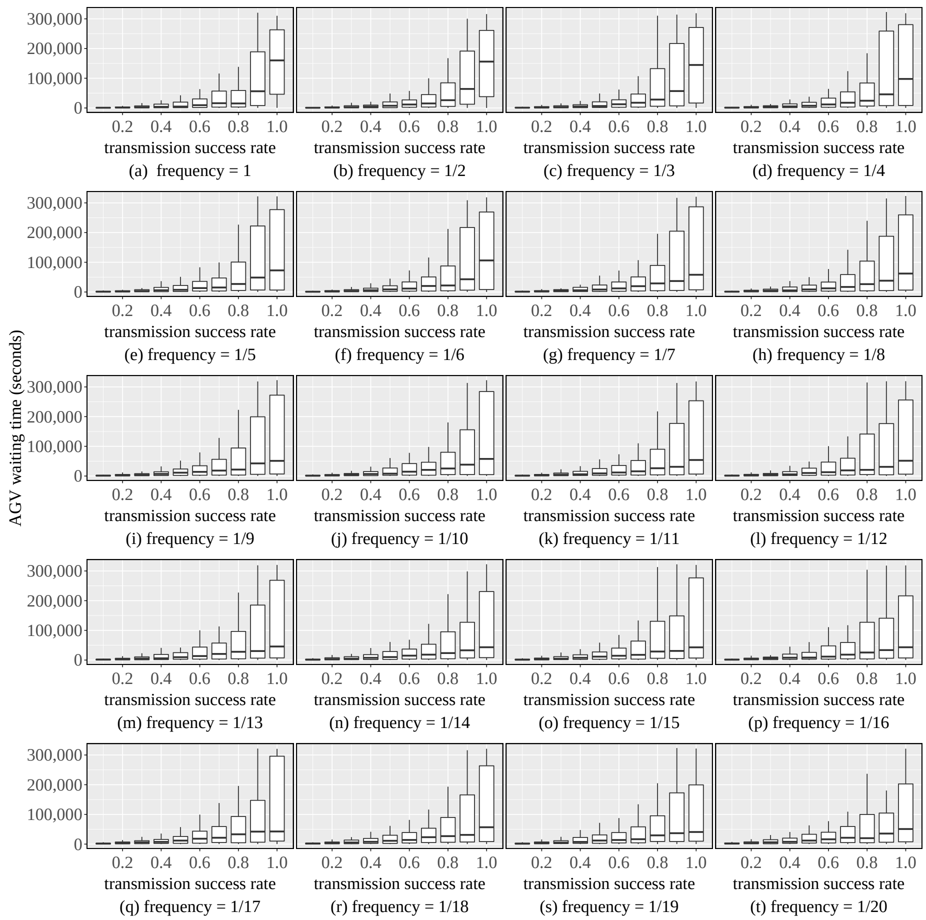


Fig. 11: Influence of spatial cloaking frequency on the AGVs' productivity.

fects of the radius settings, as larger radii increase the workers' safety, especially when using lower reporting frequencies. Workers in small radii leave their protection zones significantly faster, which means that they are unprotected for a certain period of time, as mentioned in Section 3. For example, at a frequency of 5 seconds with a radius of 15 meters, no worker experiences a near miss with an AGV. However, at the same frequency, but with a reduced radius to 10 meters, just 10 workers reached the full simulation duration. While with a further reduction, to a radius of 5 meters, no worker is collision-free anymore. In addition, Fig. 10 demonstrates the influence of spatial cloaking frequency on the number of collision-free workers for different transmission success rates. In particular, the change in-between a frequency of 1 and 3 seconds without any transmission losses lead to 9.5 additional near misses between workers and AGVs in average. Remarkably, even a 10 % signal loss lead also in the transmission frequency of

1 second immediately to worse workers' safety as only 1.5 workers achieved the full simulation duration time.

At last, Fig. 11 illustrates the influence of the spatial cloaking frequency on AGVs' productivity. We observe that the AGVs' waiting times increase slightly when using more frequent location transmissions, especially for higher transmission success rates. The longer AGVs' waiting times can be attributed to the fact that the AGVs have to stop more often when workers' location updates (with randomness added through spatial cloaking) are received more frequently.

5.3 Limitations

This paper aims to gain insights about privacy-preserving human-machine co-existence on smart factory shop floors. Our results have, however, three main limitations described in what follows. Firstly, our results are based on the factory settings we have chosen. Since these settings can highly vary between factories [3], a common factory model to cover all scenarios is almost impossible to establish. As a result, our results cannot be generalized to all factories at this stage. They, however, lay the ground for gaining preliminary insights about the feasibility of our approach and we plan to investigate the impact of the factory layout on the obtained results in future work. Secondly, we assume in our simulations that the AGVs are only able to locate workers based on the location information provided by their smart watches. However, in case of near misses, the AGVs are able to perform emergency brakings, so that workers will not be injured. Therefore, in a real-world scenario, the AGVs would likewise be equipped with additional sensors to cater for redundancy and thus, ensure workers' safety if their devices should stop working or to prevent near misses in advance. The third and last limitation of this paper is that the privacy protection offered by spatial cloaking has not been directly measured in our simulations, as our primary focus is to first determine whether and under what conditions the suggested approach is feasible with regards to workers' safety. A detailed analysis of the privacy protection offered by this approach based on different attacker models is planned in future work, though.

6 Conclusion and Outlook

In this paper, we have considered the co-existence of workers and AGVs on smart factory shop floors. Through smart wearable devices configured to regularly transmit position announcements of the human workers, collisions between workers and AGVs can be avoided. Transmitting workers' location information, however, threatens their privacy. We have therefore applied a privacy-preserving solution and measured its effects on both the AGVs' productivity and the resulting workers' safety by means of simulations. While our results are restricted to our tested scenario, they confirm our expectations and allow to quantify the effects of the tested parameters, i.e., the reporting radius, its frequency, as well as the transmission success rate. The results show that the larger the cloaking radii are selected, the better it is for the workers' safety. However, larger radii imply a significant reduction in the AGVs' productivity, which may not be compatible with a real-world deployment. Furthermore, to enhance workers' safety in real-world industrial environments, the AGVs could use previous workers' locations until a new one has been transmitted. Therefore, our work lays the foundation for future explorations of different privacy-preserving solutions. Preserving privacy may help companies to convince workers and works councils to use smart wearables to exploit this potential. Nevertheless, we believe that future research on other location privacy techniques and attacker models is required to fully realize privacy-preserving smart factory environments.

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