To Mesh or not to Mesh: Flexible Wireless Indoor Communication among Mobile Robots in Industrial Environments

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Abstract. Mobile robots such as automated guided vehicles become increasingly important in industry as they can greatly increase efficiency. For their operation such robots must rely on wireless communication, typically realized by connecting them to an existing enterprise network. In this paper we motivate that such an approach is not always economically viable or might result in performance issues. Therefore we propose a flexible and configurable mixed architecture that leverages on mesh capabilities whenever appropriate. Through experiments on a wireless testbed for a variety of scenarios, we analyse the impact of roaming, mobility and traffic separation and demonstrate the potential of our approach.

1 Introduction

Industry is continuously looking for ways to further automate processes, improve efficiency, reduce energy consumption, increase economic benefits etc. This ongoing evolution is often referred to as Industry 4.0 [1], where everything becomes connected to a network (e.g., the Internet or a private factory network) by means of communication infrastructure. This not only involves field devices or machines, but also involves mobile robots such as Automated Guided Vehicles (AGVs) [2]. Automated Guided Vehicles (AGVs) facilitate transporting various types of goods automatically and handling materials in automated manufacturing systems. The earliest AGVs were essentially line following mobile robots, but more recent solutions consist of autonomously guided robots that act based on information about where they are and which destinations to reach.

A key technology enabling such autonomously operating robot systems is wireless communication. Wireless communication between robots or between robots and a controller system is crucial for their operation, but challenging at the same time. As robots may move around quite fast through the network area, communication paths may change frequently. On top of this, some of the communication pertains to the real-time coordination of robots and requires sufficiently low latency. Further, radio wave propagation in industrial environments is generally vulnerable and may result in communication in industrial environments is challenging and may result in network coverage problems or packet loss.

Within this challenging context, robust and reliable wireless communication must be realized. In practice, such robots are very often foreseen to become part of the enterprise wireless network, a network consisting of multiple access points that aims to provide coverage on the entire production or warehouse floor. In this paper, we discuss the potential problems that might arise in such a wireless setting, taking the requirements from a real-life use case. We motivate the potential benefit of adding mesh capabilities to the mobile robots. The resulting mixed architecture aims to provide maximal flexibility and configurability in order to be able to meet the performance and quality requirements for a wide range of scenarios.

The outline of the paper is as follows. Section 2 further details the potential problems that might arise when solely relying on the presence of a wireless infrastructure network and motivates our decision of adding meshing capabilities. Section 3 discusses related work in this domain, whereas Section 4 presents our resulting node and network architecture. In Section 5, we illustrate through experiments using a wireless testbed the potential performance issues in infrastructure networks and show how our combined solution can deliver improved performance and flexibility. Finally in Section 6 conclusions are formulated together with potential improvements and future work.

2 Problem statement

It is no surprise that the communication solution used by mobile robots such as AGVs to communicate with each other and with other actors in their environment must be a wireless one. In today's deployments, IEEE 802.11 is typically used as the underlying communication technology as it is widely adopted, is able to offer sufficient throughput and allows connecting to an enterprise infrastructure already present. However, a number of particular challenges arise when relying solely on already available wireless infrastructure, i.e. a network consisting of multiple access points providing coverage on the entire floor.

First of all it is very reasonable to assume that in some situations no wireless infrastructure is present at the factory floor or in a warehouse. This implies that the solution provider that delivers the mobile robots must enforce its customers to make significant investments in order to rollout a wireless network that provides decent coverage across the entire floor. Even if wireless infrastructure is in place, it might not be allowed to make use of it in order not to interfere with ongoing processes that already make use of this infrastructure, in particular when the mobile robot communication heavily relies on broadcast traffic. If wireless infrastructure is present and can be used, another problem may arise. In many situations coverage will not be perfect because of the challenging wireless environment with a lot of metal, reflections, etc. These coverage holes may lead to malfunctioning of the system, e.g. in case mobile robots require permanent connectivity to the wireless network and, in lack of connectivity, stop moving as safety cannot be guaranteed.

Thirdly, mobile robots can drive at reasonably fast speeds (0-2m/s). Considering a challenging wireless environment that requires a multitude of access points to provide decent coverage, this will result in very frequent handovers. Such handovers significantly contribute to the communication latency. For the particular real-life use case we consider here, frequent time-critical broadcast exchanges between mobile robots are required for their distributed coordination, next to less time-critical, but reliable unicast traffic to and from controllers. More specifically, broadcast packets have a strict upper bound to the latency of 20ms in order to arrive in time at nearby mobile robots. Every handover involves a series of packet exchanges, which consumes valuable time. Hence, frequent handovers may have a detrimental impact on the required performance, as we will show in Section 5. Finally, as requirements to the mobile robot system may change over time, e.g. when scaling up the network, it must be possible to dynamically adapt the communication behavior.

Table 1. Functional requirements for our mobile robot system

RQ1. Function in the absence of fixed wireless infrastructure (network of APs)
RQ2. Exploit the presence of available fixed infrastructure
RQ3. Deal with occasional/sudden coverage holes in wireless infrastructure
RQ4. Reliably deliver unicast traffic
RQ5. Timely deliver frequent broadcast traffic (<20ms)
RQ6. Deal with mobility (0-2m/s)
RQ7. Adapt to future needs

The above observations and performance requirements, lead to a challenging set of functional requirements for our mobile robot system, which we have summarized in **Table 1**. Based on the above requirements, it is clear that we need to target a design that is capable of connecting either to existing enterprise networks (RQ2), to create its own mesh network (RQ1) or to do both (RQ3). This requires the incorporation of two wireless network interfaces in every mobile robot. Next to this, also the other requirements have to be fulfilled, requiring sufficient intelligence and flexibility in order for the system to be deployed in a variety of scenarios, with minimal configuration, having sufficient performance and with the possibility of future extensions.

These requirements have resulted in a modular and configurable communication system for mobile robots, consisting of 2 wireless interfaces that can either operate in ad hoc or infrastructure mode and offering the possibility to control in a fine-grained way how traffic is being handled. As such the system can support a variety of different networking architectures, potentially combining both infrastructure communication and mesh communication and supporting the separation or duplication of different traffic streams according to configuration settings. From an application point of view, no changes need to be made as everything is handled in a transparent way. The design of the system and the supported network architectures are discussed in more detail in Section 4, whereas the advantages of our architecture for our particular use case at hand are experimentally evaluated in Section 5.

3 Related work

Systems consisting of multiple mobile robots form an interesting research domain that is gaining importance in manufacturing in order to improve performance and increase automation. An survey of mobile robots in manufacturing is given in [3], highlighting localization problems, coverage problems up to communication technologies and environment hardships in manufacturing environments as important open research issues. In [4] a survey is presented regarding the coordination in multi-robot systems, including here also the communication technologies. The authors highlight the importance of explicit communication, i.e. direct message exchanges between robots, to ensure accuracy of the information, opposed to implicit communication by perceiving a change in the environment through the use of sensors.

During the last years, mobile robot communication experienced an evolution in their application as well as in protocol used. Many works put forward ad-hoc or mesh communication as a promising solution for realizing inter-robot communication. For instance, [5] gives an overview of network and MAC layer protocols for ad-hoc robot wireless networks. They motivate the use of ad-hoc networking for mobile robot communication due to the fact that most of the robots most likely are equipped with wireless transceivers that do not allow them to communicate directly with the data collection point. This is true even in industrial environments, but for another reason, namely due to coverage problems from access points. For instance, [6] illustrates how an infrastructure network can be extended with multi-hop relaying functionality. We also recognize this as one of the key requirements for our communication solution, but we also consider direct ad-hoc or mesh communication between all mobile robots. So far, most research into multi robot communication has focused on ad hoc networking. For instance, in [7] four different routing protocols for ad-hoc networks are compared for realizing mobile robot teleoperation. Many other works studied how ad hoc routing protocols could be used and optimized for ad-hoc robot communication. A hybrid communication solution that is capable of combining both mesh and infrastructure communication and offering flexibility to distribute traffic has not been considered so far for such systems.

In addition, in industrial settings, it is also important to be able to meet the performance and latency requirements as we have indicated in Section 2. For meeting real-time requirements a routing algorithm should not provide just the next neighbor to forward the packet but has to provide also the additional QoS requirements, such as guaranteed bandwidth and end-to-end latency. In [8] a routing algorithm for mesh networks is presented for use in industrial applications. They use a QoS manager which, after a calibration phase, manages QoS flows based on the requests from stations on specific QoS flow requirements, Packet Data Unit (PDU) size and destination. The calibration phase makes the solution more difficult to be deployed in highly dynamic environments. Again, the possible use of an available infrastructure network and separation of traffic according to the requirements is not considered. Finally, [9] describes a solution for wireless mesh network infrastructure with extended mechanisms to foster QoS support for industrial applications. Like in [8] they propose a mesh network with a central admission unit to decide for the communication flows requested by different applications. They could offer with their solution streams with RTT less then 100ms. Again, the mechanisms are only applied to a mesh case, whereas we believe that a mixed solution such as the one we propose can offer additional benefits, especially when further extended with more advanced QoS mechanisms.

4 Communication system and network architecture

In the following subsections we will describe the designed mobile robot communication system and potential network architectures that can be realized.

4.1 Mobile robot communication system architecture

In section 2 we motivated our decision to design a communication solution that makes use of 2 wireless communication interfaces. Each of these interfaces can either operate in ad hoc mode for establishing mesh communication or in infrastructure mode in order to connect to an existing enterprise network. From an application point of view it should not matter which interface is being used for transmitting packets or how this interface has been configured. Similarly, external components, such as a controller, that want to communicate with a particular mobile robot, should also not be bothered with underlying communication details. To this end, we have designed an abstraction layer that transparently manages and dynamically configures the underlying network interfaces on the mobile robot. Towards the local applications running on the robot, a single virtual interface with one IP is being offered. This way, all communication to and from the mobile robots makes use of a single IP independent of whether the resulting traffic will flow via a mesh network or an infrastructure network.

The latter also implies that additional logic for routing and traffic management is needed that is able to take into account the specifics of the underlying physical interfaces. Unicast and broadcast routing over a mesh network is completely different from routing over an infrastructure network. Unicast mesh routing requires a routing protocol that can establish forwarding paths over multiple hops, together with neighbor discovery and link break detection mechanisms in order to deal with mobility and trigger route recovery. Broadcasting requires appropriate mechanisms in order to stop the propagation of the broadcasts inside the network. Regarding traffic management, the node design foresees a number of traffic classification components that can be dynamically configured. According to their configuration, unicast and broadcast traffic streams can be separated and directed to different interfaces or traffic can be even duplicated for redundancy purpose.

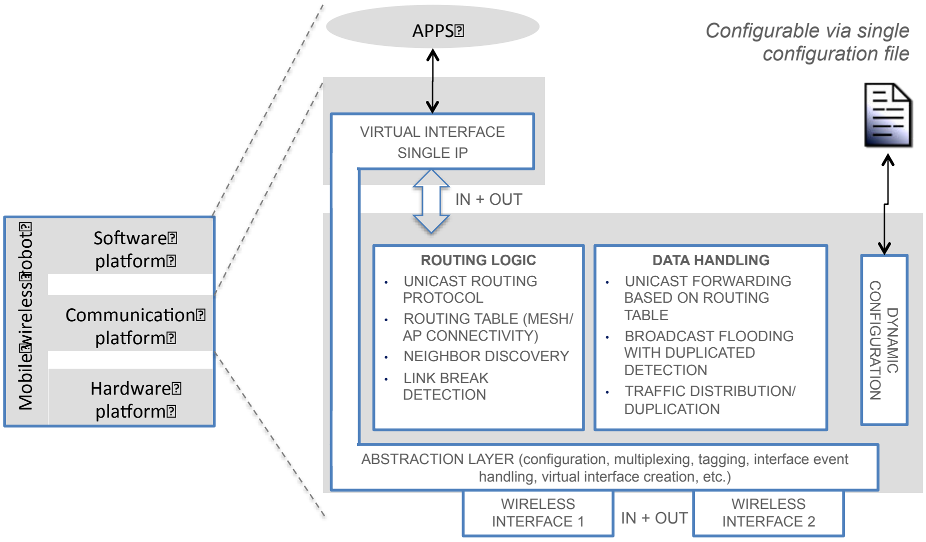
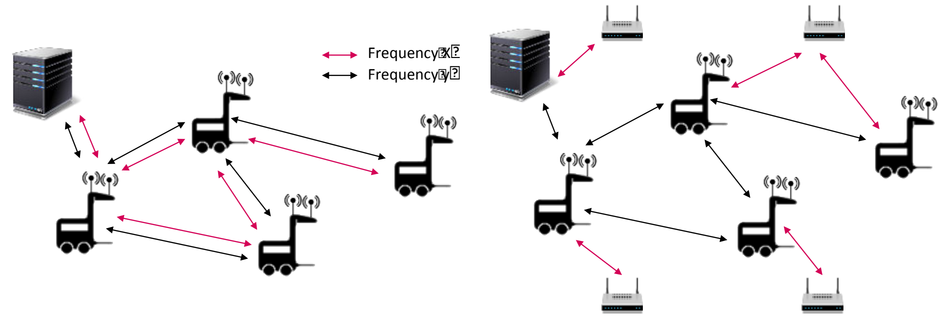


Fig. 1. Mobile robot communication architecture

Fig. 1 gives an overview of the high-level architecture we designed for the communication system of the mobile robot. The modular Click router framework [10,11] in addition with our own proprietary extension for event handling and dynamic interface management was used for the communication system. In terms of implementation, all components have been realized as separate modules in order to support future extensions or the replacement of existing modules with more advanced versions or different implementations (*RQ7*). Finally, the whole system can be configured dynamically, enabling administrators to define the behavior in a single configuration file (e.g. configuration of interface, how traffic must be distributed, timing values, etc.).
At this moment, a basic implementation of the DYMO routing protocol is being used for unicast mesh routing together with blind flooding for broadcast traffic. Next to this, two different neighbor discovery methods are being considered in order to recognize the occurrence of link breaks within the mesh network. The first one relies on the generation of beacons every N_{ms} seconds, the second one also takes into account the generated traffic as beacons in order to suppress real beaconing traffic. Given the fact that our particular use case heavily relies on broadcast messages, this might reduce the network load in case the same wireless interface is being used for unicast traffic as well.

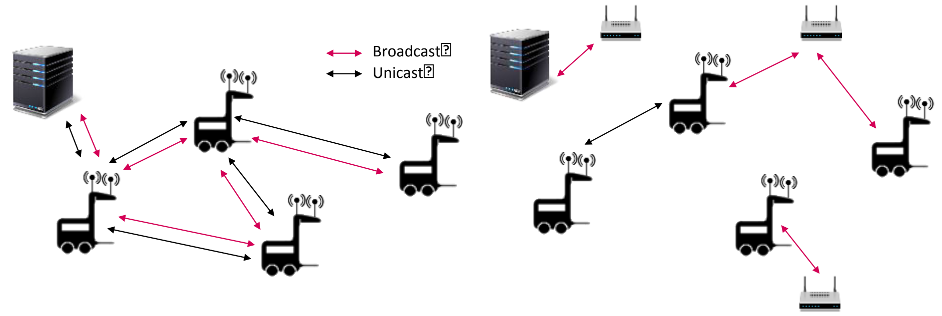
4.2 Network architecture

Depending on the particular configuration of the mobile robot communication architecture, several resulting networking architectures can be realized. This way, the solution is able to deal with the wide variety of contexts the mobile robots might have to operate in. In this subsection, we discuss a number of potential network architectures that can be easily realized by the proposed design through simple parameter reconfigurations and which are shown in **Fig. 2**.



a) Multi-interface mesh network in the absence of fixed infrastructure or in case fixed infrastructure cannot be used

b) Mixed mesh (single-interface) and infrastructure network



c) Multi-interface mesh with traffic separation

d) Infrastructure network with mesh support for handling coverage problems

Fig. 2. Potential network architectures that can be realized by reconfiguring the designed mobile robot communication system

Fig. 2a shows a first architecture that can be realized in case no fixed wireless infrastructure is present or when fixed wireless infrastructure cannot be used (*RQ1*). Both wireless interfaces can then operate in ad-hoc mode, forming a mesh network with parallel links that operate on different frequencies. In case wireless infrastructure is present and can be used, a mixed network can be established as shown in **Fig. 2b** (*RQ2*). One of the interfaces is used to connect to the existing network, whereas the other interface is used to form a mesh network. Depending on additional configuration settings, it can be further decided how traffic is distributed over the different interfaces. This is shown in **Fig. 2c** for the case of a multi-mesh configuration, where one of the interfaces is used for unicast traffic and the other interface is used for broadcast traffic. Finally, **Fig. 2d** shows how the communication can be configured in order to tackle coverage problems by making use of mesh functionality in the specific area that experiences these coverage problems (*RQ3*).

5 Performance analysis

It is clear that the proposed communication system enables several networking topologies. Combined with the flexibility on how to distribute the traffic it is interesting to investigate how this flexibility can be exploited in order to deal with the other requirements that are specific for our targeted use case (*RQ4-6*). For this, we conducted a set of experiments on the w.iLab.t wireless testbed [11], which are now discussed in the following subsections. Hostapd and wpa-supplicant are used as user space daemon to run access point and client, respectively. The mobile robots have on top of them Zotac nodes which are running Linux and our Click Router implementation presented in Section 4. The access points are static Zotac nodes running Linux. The Wi-Fi cards of all devices have Atheros AR93 chips.

5.1 Wireless infrastructure network only

In this scenario, we assume the presence of fixed access points and do not make use of any meshing capabilities. Every mobile robot is connected to an access point and selection of the most suitable access point is based on signal strength. Mobile robots move around the environment covered by access points and get attached and detached to/from access points. As mobile robots can drive at relatively high speeds, such handovers may take place frequently and will affect the communication performance. To quantify this effect on the performance of unicast and broadcast traffic, we set up an experiment in the w.iLab.t testbed as shown in **Fig. 3**.

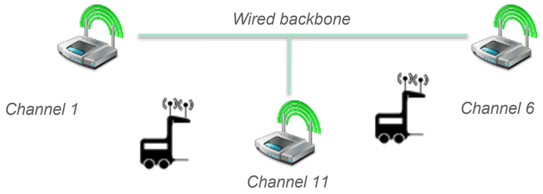


Fig. 3. Experimental setup to assess the impact of handovers on the communication performance. Three APs and two mobile robots are used.

Three non-overlapping channels (1, 6 and 11) in the frequency of 2.4 GHz have been used. To enforce handovers from one access point to another access point, we remotely control the transmit powers of the access points. The mobile robots are limited to scan only over the mentioned channels to prevent time and energy consuming procedure for scanning all available channels. During the experiment, both mobile robots are communicating with each other via the insfrastructure wireless network.

Fig. 4 shows the latency distribution of 10000 unicast packets during a run of 200 seconds. Unicast packets are exchanged every 20ms and the frequency of roaming among access points is configured to be 10, 20 and 30 seconds. As can be seen, in most cases the latency is lower than 4ms, which is close to the median amount. However, it can become as high as 78ms during the roaming procedure. Further, the more frequent roaming happens among the access points, the higher the packet latency can become. The reason behind this is that every time a client performs a handover between access points, it gets dissociated, has to look for stronger signal strength and needs to associate to a new access point. **Table 2** shows the latency statistics plot, presenting the first and third quartile of the results shown in **Fig. 4**.

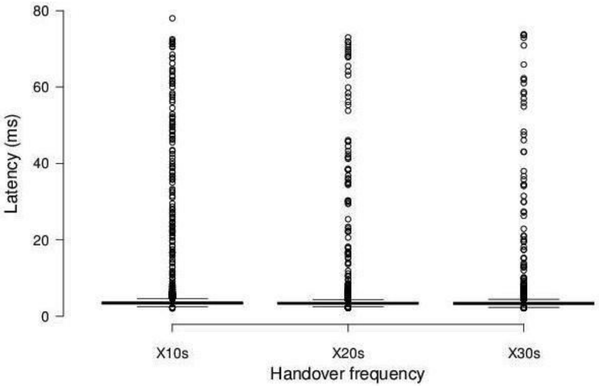


Fig. 4. Latency of unicast traffic for different roaming frequencies

Table 2. Unicast latency statistics plot considering min, max and median (in ms)

Statistics	10s roaming freq.	20s roaming freq.	30s roaming freq.
Median	3.45	3.42	3.39
1st quartile	3.21	3.18	3.13
Min	2.13	2.12	2.09
Max	78	73	73.8
3rd quartile	3.75	3.66	3.66

Fig. 5 presents the latency of 10000 broadcast packet transmission within the same 200 seconds time period. Again, the roaming procedure happens every 10, 20 and 30 seconds. As it is shown in **Table 3**, in contrast to the unicast latency, the broadcast latency is not mostly around the median number but around the third quartile number. The results also show a much more profound negative impact of handovers on the broadcast latencies, due to the way broadcasts are disseminated through the network. Every broadcast from a mobile robot needs to be rebroadcast to other devices connected to the same access point as well as to all other devices connected to the other access points. This is visible in **Fig. 6** where every time the mobile robots were connected to the same access point the latency was around 5ms while when roaming took place the latency increased up to 100ms. It is clear that even in this simple setup our mobile robot solution will never be able to meet the envisioned latency requirements (<20ms) of broadcast traffic.

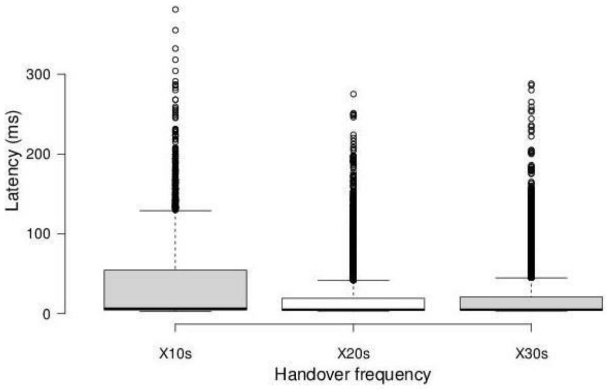


Fig. 5. Latency of broadcast traffic for different roaming frequencies

Table 3. Broadcast latency statistics plot considering min, max and median (in ms)

Statistics	**10s roaming freq.**	**20s roaming freq.**	**30s roaming freq.**
Median	6	4.89	4.97
1st quartile	4.44	4.18	4.46
Min	3.06	3.17	3.26
Max	381	275	288
3rd quartile	54.5	19.2	20.6

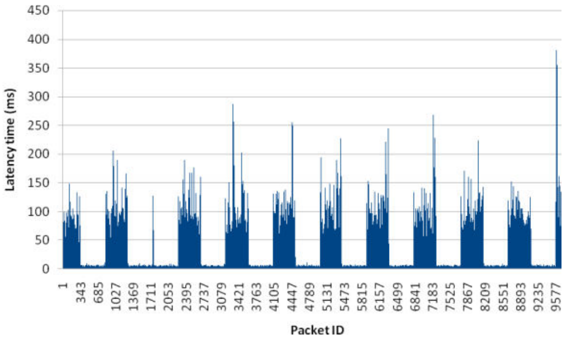


Fig. 6. Latency of broadcast traffic for a roaming frequency of 10s

5.2 Mesh network only

In this scenario, only a mesh network is being used as shown in **Fig. 2a.** As mentioned, unicast traffic uses a simple reactive routing protocol, whereas broadcast traffic uses blind flooding with duplicate detection. Using this setup we again measure the impact of mobility of mobile robots on the latency of packet transmissions. In order to be able to mimic a variety of speeds and thus link breaks, we used a forced mobility approach, where MAC filtering is being used to artificially change the mesh topology as showing in **Fig. 7**. Nodes c1 and c5 are communicating. While communicating, c1 establishes a new link with node c2, c3, c4 and c5 respectively, breaking the old link and gradually changing the number of hops over which the packets need to travel.

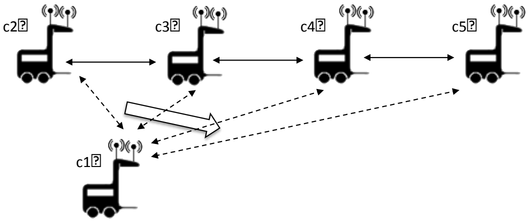


Fig. 7. Fully mesh network among mobile robots.

Fig. 8 presents the impact of link breaks and the resulting change in topology and hop count on unicast and broadcast packet transmissions with transmissions being generated every second. In this experiment, latency for unicast and broadcast traffic varies between 17.2ms/19.9ms and 2.62ms/3.04ms and is directly related on the number of hops between the sender and receiver, which decreases from 4 to 1.

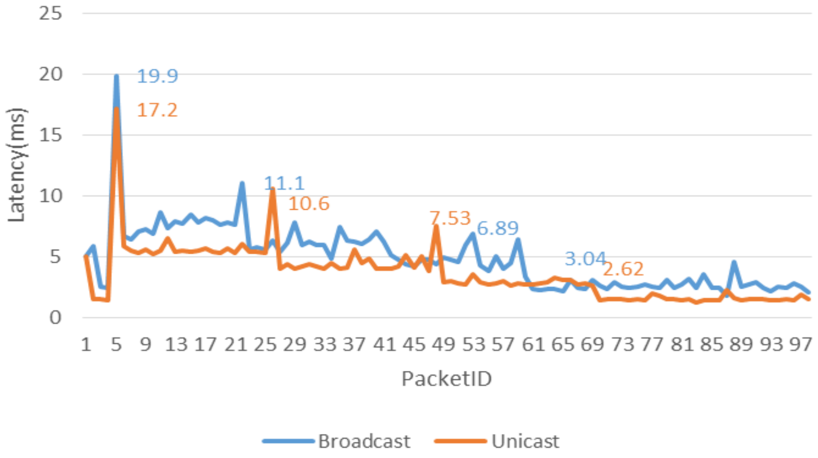


Fig. 8. Latency of broadcast and unicast traffic with link breaks occurring every 20s.

The performance of unicast traffic however, is also strongly affected by the link break detection and routing mechanism. In the scenario shown in **Fig. 8**, the beacon interval was set to a very small value (20 ms), making it possible to very quickly react to link breaks in this small topology. In addition, with traffic only being generated every second, no significant unicast packet losses occurred, illustrating only the impact of hop count on latency in a mesh setting.

In reality the protocol might react slower, traffic generation can happen more frequently or the topology is more complex. These first two aspects are shown in **Fig. 9**, where unicast traffic is being generated every 120ms. Keep-alive beacons are sent less frequently, every 500ms, with the detection of a link break in the absence of beacons after 2500ms. Further, upon the detection of a link break, all traffic for a destination that has become unreachable is being buffered until the route has been established. This has two consequences. First of all, unicast traffic in the presence of link breaks in the mesh network exhibits much higher packet losses than in an infrastructure network, with the amount of lost packets directly related to the efficiency of the underlying link break detection mechanism as shown in **Fig. 9**. Secondly, route recovery takes some time, resulting in higher latencies of the packets that were buffered between the detection of the link break and the moment the route has been recovered. Broadcast traffic does not experience these drawbacks as it can make use of any available link and does not depend on route establishment.

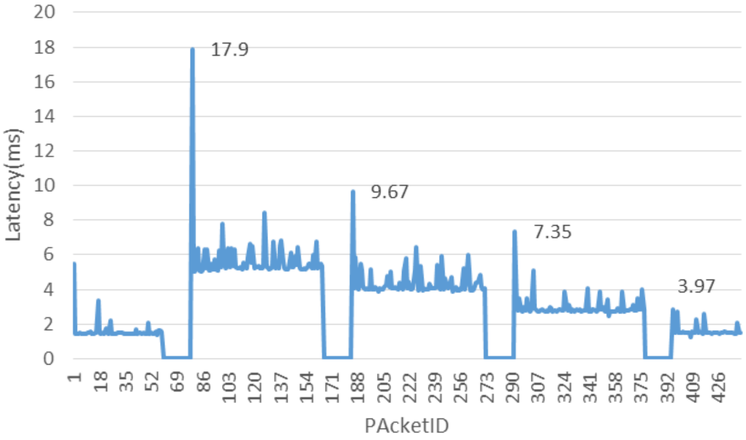
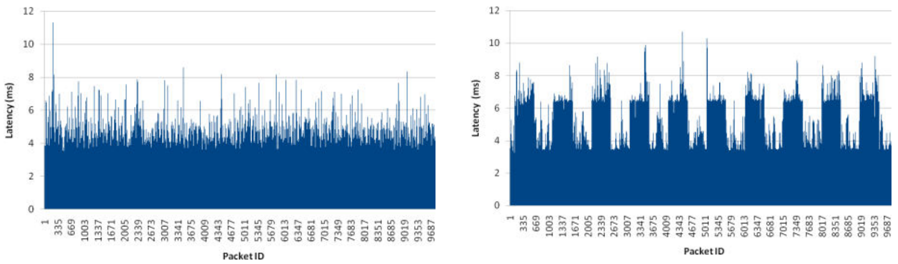


Fig. 9. Unicast packet transmission latency in the presence of link breaks every 10s

5.3 Combined Network

The third scenario being considered is a hybrid setup, where every mobile robot uses 1 interface to connect to the infrastructure network and one interface to set up a mesh network as shown in **Fig. 2b**. In order not to overload the wired network with broadcast traffic, the communication system is configured to send broadcast traffic over the mesh interfaces. To avoid frequent rerouting inside the mesh network, unicast traffic is configured to run over the other wireless interface. Again, we measure the latency of unicast and broadcast traffic in order to investigate the advantages and feasibility of a hybrid configuration with traffic separation. In this scenario we use three interconnected access points (as in **Fig. 3**) and four mobile robots. Two of them are communicating using unicast traffic via access points while two others are generating broadcast traffic. All of them are connected to one of the access points. One mobile robot is configured to reply to the broadcast packets. Channel 6 is used for communication within the mesh network. The handover and link break frequency in this case are both 10s.



a) Unicast latency *b) Broadcast latency*

Fig. 10. Unicast and broadcast latency in a mixed scenario with traffic separation

Table 4. Latency statistics of unicast and broadcast packet transmission (in ms)

Statistics	**Unicast traffic**	**Broadcast traffic**
Median	3.33	4.9
1st quartile	3.2	3.4
Min	2.26	2.73
Max	7.98	10.7
3rd quartile	3.49	5.3

Fig. 10a shows the latency of 10000 unicast transmissions during 200 seconds, whereas **Fig. 10b** shows the latency of 10000 simultaneous broadcast transmissions. As it is shown in **Table 4**, the mixed scenario that exploits the possibility to separate different traffic streams, combines the best of both worlds. Broadcast traffic can meet the strict latency requirements by using the mesh network, whereas unicast traffic achieves low latency by avoiding the complexity of ad hoc routing.

6 Conclusions

Many existing solutions in industrial settings that make use of mobile robots make use of an available enterprise network. In this paper we discussed the potential drawbacks of such an approach. For our particular use case at hand, a key requirement was the ability to delivery broadcast traffic with very low latencies, a requirement that could not be fulfilled in an enterprise network where handovers take place frequently as shown on our testbed. Other requirements, such as the ability to function in the absence of infrastructure of to tackle coverage holes, made it necessary to design a flexible and modular networking architecture that is able to exploit both the advantages of the presence of an enterprise network and the advantages of a mesh network. In this paper we showed the feasibility and a proof-of-concept implementation of this architecture. The architecture supports a variety of setups and we evaluated three of them, thereby measuring the impact of mobility on unicast and broadcast traffic. The design and evaluation clearly shows the advantages of being able to exploit a mixed architecture.

This paper presented the foundations and feasibility of such an architecture, but at the same time reveals some open issues and possible improvements. More research is needed to see how unicast routing and blind flooding can be improved. One path that will be investigated is the incorporation of position information, distributed using the frequent broadcasts, in order to improve unicast routing performance and to reduce overhead. For this, connectivity will be analyzed in a realistic industrial environment. Next to this, additional modules will be foreseen that are capable to deal with the occurrence of coverage holes. These extensions will make our solution more versatile, able to optimally deal with the variety of contexts in which mobile robots have to operate.

7 References

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