Challenges in Realizing Ad-Hoc Networks based on Wireless LAN with Mobile Robots

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***Abstract*—Modern applications of mobile robot teams or robot teleoperation often demand wireless any-to-any communication in combination with highly dynamical network topologies to accomplish more and more complex tasks. Nowadays, often WLAN is used to provide wireless communication for prototype system, for research testbeds, and also for commercial and industrial applications. The application of WLAN ad-hoc networks for teams of mobile-robots and human offers a lot of potential to fulfill the demands of such systems for a flexible, dynamic and efficient communication network. On the other hands new challenges rise when using ad-hoc networks. This contribution gives an overview about scenarios where these ad-hoc networks are advantageous and why it is an promising approach. This overview includes the available and implemented technologies which can be applied and how this technologies can be analyzed and evaluated. For the special case of mobile robot teleoperation a brief presentation of the behavior of different ad-hoc routing protocols is given and important aspects are discussed exemplarily.**

I. Introduction

Meanwhile, mobile robots are planned to be used or even already used in many civil applications like surveillance and security or search and rescue to support and relieve the humans in place. For all of these commercially available systems, the teleoperation of the mobile robot is the key feature. Recently, more and more mobile robots are developed which are capable to operate in impassable or hazardous environments with little or no communication infrastructure which makes the use of easy on-demand deployable networks inevitable. Several approaches are using wireless ad-hoc networks in many different areas of robot teleoperation and for distributing and sharing information between the humans and robots in the team. This includes the transmissions of e.g. sensor data from the robots, observations from the humans, commands, and plans to the different team entities from the human coordinators.

During the last years, several teams achieved remarkable results in this research area. In 2007, Rooker and Birk presented multi-robot exploration with robots using wireless networks [1]. The University of Pennsylvania presented a mobile robot team connected via wireless network which performed localization and control tasks [2] in 2002. [3] [4] placed relay nodes on demand to setup the required telecommunication infrastructure and in [5] [6] mobile robots are used as relay nodes where each mobile node not only works as host but also as router for data packets of other nodes. In [7] a live audio and video data transmission via a multi-hop wireless network is demonstrated. In addition, several systems of rovers with autonomous functionalities [8], groups of unmanned aerial vehicles [9], as well as heterogeneous multi robot systems were proposed. For ground based systems Chung [10] presented a testbed for a network of mobile robots. In the field of rescue robotics [11], or for integrating UAVs into IP based ground networks [12], the use of wireless networks is quite common nowadays. With respect to unmanned aerial vehicles (UAVs), [13] presented a system using an access point running in WLAN infrastructure mode onboard the UAV. [14] presented a system for communication between a ground station and a UAV using WLAN in combination with a high-gain antenna and radio modem. These wireless ad-hoc networks offer a lot of advantages in contrast to static wireless network configurations, but also raise a lot of new challenges in the system design. Wireless communication always implies unpredictable communication delays, packet loss, or in worst case the loss of the link which makes the provision of the required quality for teleoperation or control tasks rather complex [15].

Many of these approaches use IEEE 802.11 wireless LAN as underlying technology for the wireless network interconnecting the team. The ease of use, the affordable prize, small weight, and appropriate power consumption makes WLAN often a reasonable choice to set up dynamic topologies providing direct and indirect any-to-any communication of each network node. In addition, also benefits like redundant communication links in larger networks, no central administration, and a distribution of the traffic load in large networks are present. Of course, these advantages can only be used with rather complex and special routing protocols providing each node the necessary information of the network topology. The nodes itself are working as routers and must store the routing information of the complete network locally. In the field of wireless telecommunication, more than 80 different approaches for ad-hoc routing mechanisms of different types (classes) were developed. Well known classes of these protocols are pro-active, reactive, or hybrid (pro-active and reactive) protocols but also flow oriented, power aware, multicast, position based, or situation aware approaches are available. The number of

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implemented protocols which have reached the status to be used in lab-environments is much smaller [16] and if an appropriate real world scenario with mobile robots is considered, the alternatives are quite small. Some simulations for performance evaluations for larger scale telecommunication networks were done in the past [17] [18] [19] and based on [20] [21] [22] [23] recently AODV, DSR, OLSR, and BATMAN was analyzed with respect to mobile robot teleoperation [24] [25].

The remainder of this work is structured as follows. In Section II, important scenarios of multi-hop networks for mobile robots are presented. Section III briefly discusses some technological aspects of WLAN being used as underlying technology for ad-hoc networks of mobile robotics and its applications. In Section IV four implementations of well known ad-hoc routing protocols which are already used within mobile robot networks are described. Section V presents several teleoperation approaches of mobile robots, as well as future prospects on control tasks via wireless multi-hop networks. In Section VI, a brief insight to results of using AODV, DSR, OLSR, and BATMAN for mobile robot teleoperation, as well as some evaluation approaches are described. A conclusion is given in Section VII.

II. Scenarios

One special and very challenging application scenario for mobile robots is search and rescue. This scenario has very high demands on almost all aspects related to the fields of mobile robots, multi-robot teams, and human-robot teams. Besides for instance mobility, localization and human-robot interaction one of the most important elements in this scenario is communication on all levels. After a disaster, the search and rescue team in most cases cannot (or only partially) rely on existing pre-installed communication infrastructure. Often the environment is very unstructured and cable communication systems are only applicable for short distances. Therefore, these scenarios require a wireless communication which can adapt to the current needs and constraints in a reasonable time. One idea to support this is to equip all the heterogeneous team entities (humans and robots) communication devices. These team members are now available for the other team members as communication relays by implementing ad-hoc routing protocols which allows redundant communication links and higher communication distances. Another interesting chance for the application of ad-hoc networks is the use of the heterogeneity of mobile robots. On the one hand, it is possible that team entities with limited communication capabilities can use any team entity with better communication in its limited communication range to reach the rest of the team. On the other hand the ad-hoc network offers the possibility to build subteams and to use nodes only if they are really necessary to communicate with the target. In [26], several of these scenarios were analyzed in a simulation study comparing the performance of several ad-hoc routing protocols. Figure 1 shows how such a typical heterogeneous team might look like. These ideas can also be easily transfered to other scenarios like e.g. autonomous transportation systems in industry.

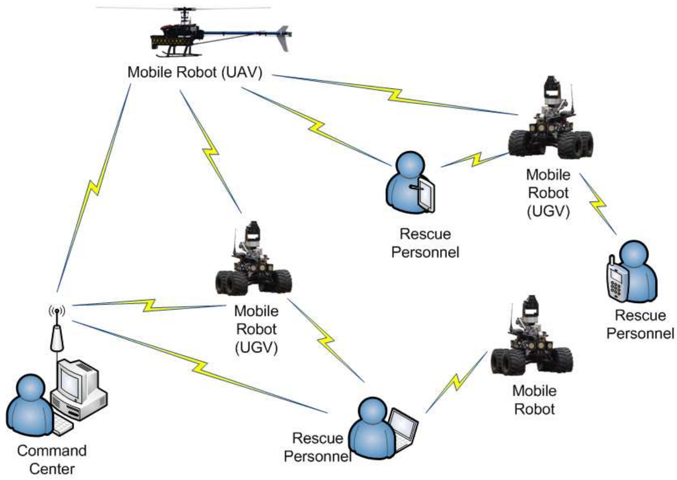

Fig. 1. Heterogeneous network of mobile robots and human personnel without stationary communication infrastructure.

The dual use of mobile nodes (e.g. robots) for their own communication and as communication relay for other nodes opens the possibility to extend the communication range between a control station and a teleoperated machine [5] [3] [6] [4] or to set up a communication infrastructure in an environment containing several obstacles [12]. Figure 2 shows a mobile robot being teleoperated and several nodes – which could be stationary or mobile – are used to keep up the communication link. In the presented scenario a chain of nodes is established which can be considered as a kind of worst case scenario as the grade of meshing is very low (only minimum number of neighbors in range) and no redundant routes between robot and operator are available. These topological constraints have a large effect on the behavior of the used protocols and the corresponding parameter settings which was demonstrated in [27] and [24].

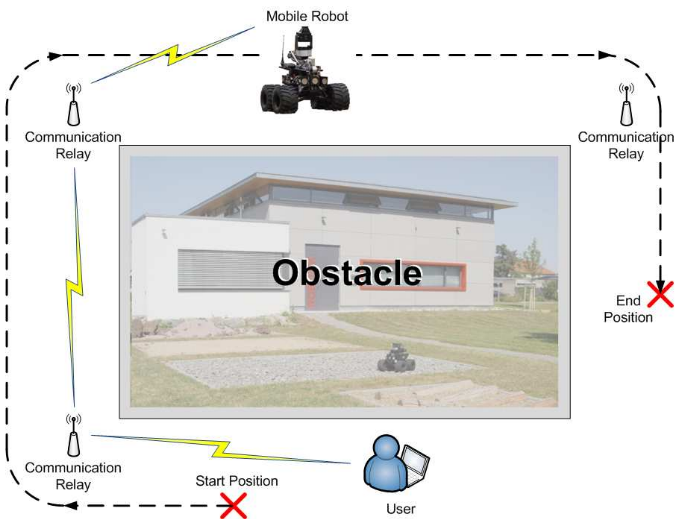

Fig. 2. Communication relay to increase the range for teleoperation of a mobile robot.

The dynamic characteristic of ad-hoc networks allows the

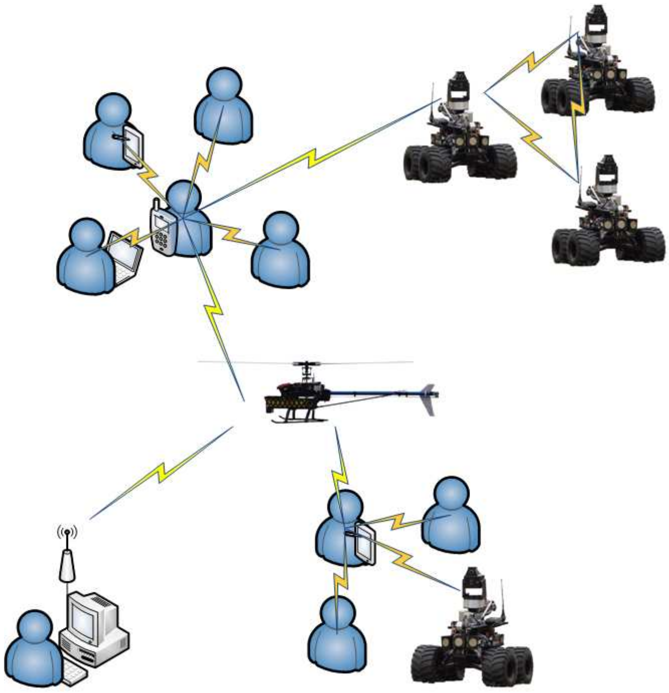

Fig. 3. Communication inside and between teams.

very flexible and efficient adaptation to the current communication needs. It is possible that nodes spatially co-located can communicate directly without involving any other node. As there is no special central node present for coordinating and forwarding the traffic, the probability of this node being a bottleneck while a larger number of nodes transfers large amounts of data (e.g. video streams) is reduced (cf. Figure 3). Therefore, ad-hoc networks also very much support a distributed, decentralized communication architecture on the higher communication levels. This characteristic also supports the establishment of smaller communication subgroups on a logical or spatial level inside the whole group of nodes. The possibility to adapt the ad-hoc network to current needs for communication allows an intelligent solution to use the different wireless links more efficiently. If there are heterogeneous nodes in the ad-hoc network where some of the nodes have better communication capabilities (e.g. higher transmit power), a mobile node with only short range communication can use any of the the nodes with long-distance communication which is currently in its own communication range to transmit information to any other node in the network.

III. Wireless LAN as underlying Technology

The previous Sections referred to many scenarios and multi robot systems which are based on 802.11 wireless LAN. Setting up a testbed or a prototype of a multi robot system is quite easy, but nevertheless, several technical aspects which are discussed in this section must be considered to prevent unstable communication links or not suitable packet round trip times.

A. Security Issues

1) Operational Security: Often, the operation of a mobile robot like an unmanned aerial vehicle (e.g. a helicopter) or an unmanned ground vehicle holds a risk in terms of endangering or injuring persons or damaging the environment. As soon as a wireless link is incorporated into the teleoperation or control, the potential loss of the communication link must be considered. Several approaches exist to prevent the robots from being a risk for the living or non-living environment. Two of these approaches are described in Section V.

2) Data Security: Besides these aspects of operational security, also security aspects with respect to data security, user management, prevention of misuse or intrusions, and encryption of connections should be possible. Often, research prototypes or testbeds are not including these aspects but with respect to industrial applications the presence data security is inevitable. Nowadays, many proprietary solutions exist but governmental organizations (e.g. BSI[1]) supports the standardization and recommend the use of IEEE 802.11i / 802.1x in industrial and commercial solutions.

B. Integration into existing Computer Networks

Besides the above mentioned security issue, the mobile robots should be integrated into existing IP based networks to enhance interoperability and increase their data distribution capabilities. In current research projects, several network topologies – starting form wireless LANs using infrastructure mode and several access points up to wireless ad-hoc networks using different ad-hoc routing protocols – were used [10], [13], [14], [28], [29]. Often, these networks uses standard IP based communication together with WLAN. An advantage of WLAN is the availability of a relatively high bandwidth and the high flexibility in integrating new protocols or extending features of available protocol implementations. As currently the cooperation of several vehicles is very important, challenging problems like nodes acting autonomously as communication relay, a highly dynamic and variable network topology (some network nodes may leave or join the network at any time), routing problems, and several data streams and sources with different bandwidth requirements have to be solved. Often, ad-hoc capabilities must be present.

IV. Common Ad-Hoc Routing Protocols

This section briefly summarizes four popular ad-hoc routing protocols AODV, DSR, OLSR, and BATMAN. For all of these protocols, implementations for real world use are existing as a stable running version.

A. Ad-hoc On-demand Distance Vector (AODV)

The AODV routing protocol [22] [23] is a reactive routing protocol and searches for a route on-demand. In case a certain node is part of an active route, Hello messages are used to obtain the route status. These Hello messages are broadcasted periodically to all neighbors. If a neighbor does

[1]Bundesamt fuer Sicherheit in der Informationstechnik in Germany

not send a Hello message within a specified time a link loss is detected and the node is deleted from the routing table. In addition, a Route Error message (RRER) is generated. To discover a route to an unknown destination, a Route Request (RREQ) message is broadcasted. Each intermediate node which is not the destination and without a route to the destination receiving a RREQ broadcasts this RREQ further. In case the RREQ is received more than once, only the first reception will result in a broadcast. To avoid uncontrolled dissemination of RREQ messages, each RREQ has a certain time to live (TTL) after which it is discarded. When the destination receives a RREQ message, a Route Reply (RREP) message is generated and sent back to the source in unicast hop by hop fashion along the route which was determined by the RREQ message. After generating a RREP message, the RREQ message is discarded at this node. As the RREP propagates, each intermediate node creates a route to the destination. After the source receives the RREP, it records the route to the destination and begins sending data. In case the source receives multiple RREPs, the route with the shortest hop count is chosen. The status of each route is maintained in the local routing table and timers are used to determine link failures which will result in the creation of Route Error messages (RERR). More detailed information on AODV is given in [22]. In the referred test scenarios, AODV-UU version 0.9.5 from Uppsala University (Sweden) is used [2].

B. Dynamic Source Routing (DSR)

DSR is also a reactive ad-hoc routing protocol which works similar to AODV without using Hello messages for route maintenance. However, it uses source routing [30]. DSR allows the network to be completely self-organizing and self-configuring, without the need of any existing network infrastructure or administration. DSR does not use any periodic routing advertisement, link status sensing, or neighbor detection packets, and does not rely on these functions from any underlying protocols in the network. DSR is composed of two main mechanisms that work together to allow the discovery and maintenance of source routes in the ad-hoc network. In case source node (S) wants to send data to an unknown destination host (D), S initiates the Route Discovery mechanism. S broadcasts a Route Request message which identifies the source and destination of the Route Discovery to all neighbors. A Route Request also contains a record listing the address of each intermediate node which was forwarding this particular copy of the Route Request. A node which receives this Route Request without being the destination looks up for a source route to the requested destination in its route cache. Without any source route present in its own route cache, the node appends its own address to the route record and broadcasts the Route Request message. In case this request message was received more than once, it is simply discarded. As soon as the Route Request message arrives at the desired destination D, a Route Reply message to S is created which contains an accumulated route record of the Route Request. After S receives this Route Reply, it caches the corresponding route in its route cache and S is ready to transmit data. Of course, there exist mechanisms to omit flooding of the network with Route Requests. A hop limit was introduced and every time a Route Request is forwarded, the hop limit is decremented by one. As soon as it reaches zero, the request is discarded. Also mechanisms for avoiding infinite recursion of Route Discoveries are implemented. A more detailed description of this protocol is given in [20] [31]. The referred work uses DSR-UU version 0.2 from Uppsala Univeristy (Sweden) [3].

C. Optimized Link State routing (OLSR)

OLSR is a table-driven, pro-active routing protocol for mobile ad-hoc networks. It uses hop-by-hop routing – each node uses its local information to route packets. OLSR minimizes the overhead from flooding of control traffic by using only selected nodes – called Multipoint Relays (MPR) – to retransmit control messages. Each node in the network selects a set of nodes in its neighborhood, which may retransmit its messages. This set of selected neighbor nodes is called the MPR set of that node. The neighbors of node N which are not in its MPR set, receive and process broadcast messages but will not retransmit broadcast messages received from node N. The MPR set is selected such that it covers all 2-hop nodes. That means every node in the 2-hop neighborhood of N must have a link to the MPRs of N. OLSR continuously maintains routes to all destinations in the network. Therefore, it is suitable for a large set of nodes communicating with each other.

To distribute link and neighborhood information, Hello messages are exchanged periodically. These messages are also used for link sensing and for checking the connectivity. Thus, the network topology is discovered and disseminated through the network, which allows the route calculation. More details on OLSR are given in [32]. The referred scenarios of the present work are performed with OLSR version 0.5.3 [4].

D. BATMAN

BATMAN (Better approach to mobile ad-hoc networking) is a new approach to ad-hoc routing. Unlike other algorithms that exist right now, BATMAN does not calculate routes. It continuously detects and maintains the routes by receiving and broadcasting packets from other nodes. Instead of discovering the complete route to a destination node, BATMAN only identifies the best single-hop neighbor and sends a message to this neighbor. These messages contain the source address, a sequence number, and a time-to-live (TTL) value that is decremented by 1 every time before the packet is broadcasted. A message with a TTL value of zero is dropped. The sequence

[2] http://core.it.uu.se/core/index.php/AODV-UU

[3] http://core.it.uu.se/core/index.php/DSR-UU

[4] http://www.olsr.org/index.cgi?action=download

number of these messages is of particular importance for the BATMAN algorithm. As a source numbers its messages, each node knows whether a message is received the first time or repeatedly. More details on BATMAN are given in [33]. In the test scenarios referred in is work, BATMAN version 0.2 is used [5].

V. Teleoperation and Control

A. Teleoperation with Local Autonomy

As previously mentioned, the design of teleoperation mechanisms via wireless communication links must always be able to cope with packet loss, high jitter, or even a communication drop out. One possibility to allow teleoperation via lossy communication links is a combination of local autonomy which takes over the control of the most critical and necessary subsystems of the mobile robot in case communication is lost and a teleoperation interface which allows the user an appropriate command of the robot while communication is available.

One example using this approach is the helicopter of the University of Wuerzburg [34]. Onboard the helicopter, a state machine is taking care of the modes of operation and it is interacting with the status of the communication link (cf. Figure 4). While receiving commands, the helicopter is in normal operation modes and can directly be operated by the user. In case a communication link failure is detected, the state machine switches to a safe mode of operation - a stationary hovering without changing position and orientation. After reestablishing the communication link, the status of the helicopter and the control PC must be synchronized to provide valid data to the user. The helicopter control protocol presented in [27] is used in an environment which allows any to any communication between all network nodes like mobile robots, UAVs, or humans with a PC or PDA. Therefore, a WLAN running in ad-hoc mode is used. Each robot and UAV is equipped with a PC architecture and a standard TCP/IP and UDP/IP protocol stack. A seamless interaction of this robust mechanism within WLAN based multi-hop networks was shown in [27].

With respect to UGVs, the Outdoor MERLIN of University of Wuerzburg follows an approach which is similar in some aspects [35]. The MERLIN robot carries several different sensors for obstacle detection which allows a more powerful local autonomy. Thus, in case of a bad or lost communication, MERLIN can still perform some of its tasks [36].

B. Generated Traffic

Usually, the traffic transmitted via a multi-hop network of mobile robots has a broad spectrum in its characteristics. The network might be used for exchanging packets for control loops, commands, different kinds of sensor data, or in heterogeneous teams even voice. The traffic usually generated by controllers consists in rather small packets which are sent with a high sampling rate (e.g.> 100Hz). Commands sent by users often are transmitted with a much smaller frequency. With respect to sensor data feedback, the generated packet stream depends on the kind of sensor which are used. The range lasts from only a few bytes (e.g. a single value for representing a measured velocity) up to large streams with a bandwidth of more than 3 Mbit/sec (e.g. video data). Besides the required bandwidth of the corresponding data flow, also the sampling rates of data affects the overall performance of the 802.11 link. In case of packets for control mechanisms or video transmissions a rather constant packet inter-arrival time with a small jitter (variance of inter-arrival time) is desired. Figure 5 shows an example of a video stream which is recorded by a mobile robot and transmitted via a wireless ad-hoc network based on IEEE 802.11. The x-axis represents the test time and the left y-axes displays packet inter arrival time and the right y-axes shows the corresponding jitter. In the beginning, only the video stream is transmitted, but as soon as the link load exceeds a certain level (cf. at 60 seconds in Figure 5), the packet inter arrival time and the jitter increases such that the video cannot be used for teleoperation anymore. More details on this and a mechanism to adapt the video in order to allow teleoperation also in environments with limited resources are given in [25]. These aspects also apply for the traffic which is generated by control loops and requires a certain quality in terms of delay, packet loss, and packet inter-arrival time.

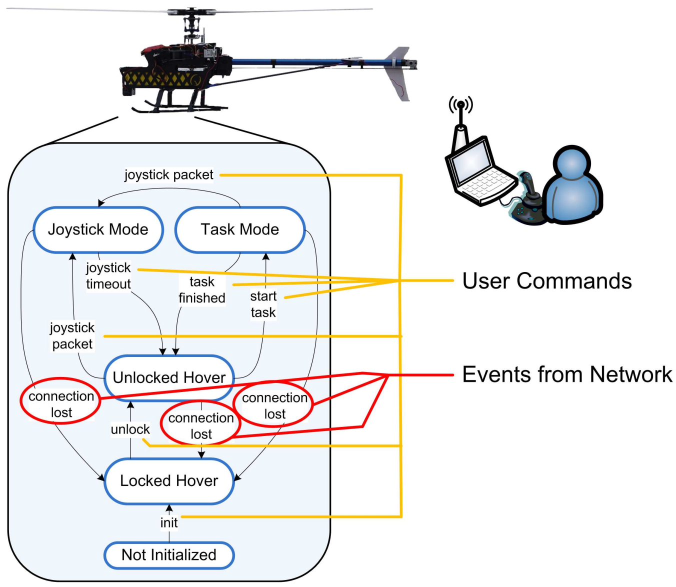

Fig. 4. State machine of the helicopter interacting with the communication link.

C. Video for Teleoperation

Video streams still play a major role in all applications where a mobile robot is controlled by humans. Hereby it makes no large difference which level of teleoperation is applied – supervisory control, direct teleoperation or anything in between. The video often is the most important element to reach and maintain situational awareness and common ground between human and robots. Depending on the task of the

[5]https://www.open-mesh.net/batman

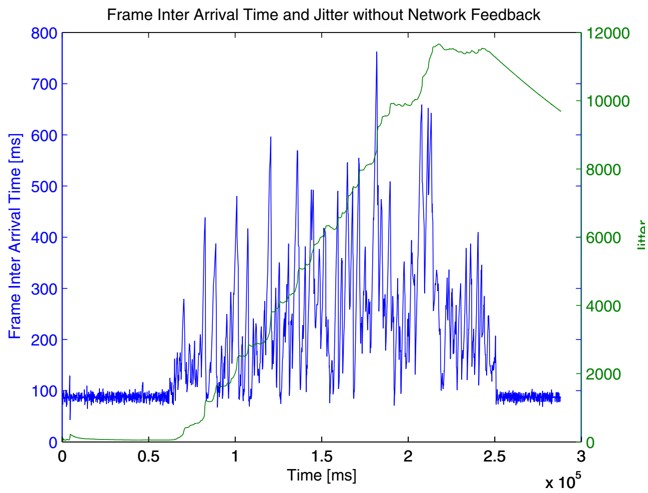

Fig. 5. Packet inter-arrival time and jitter of a video stream using a WLAN in an environment with limited bandwidth and a high network load.

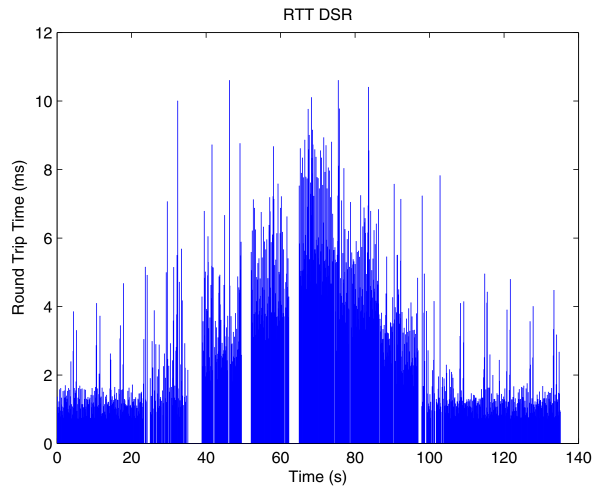

Fig. 6. Round Trip Times for DSR.

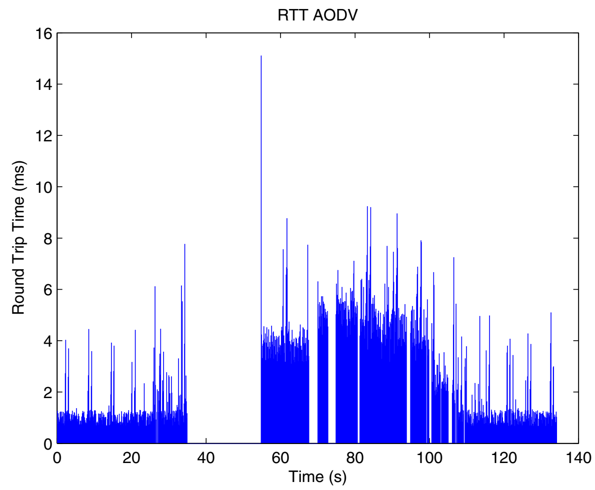

Fig. 7. Round Trip Times for AODV.

human different parameters of the video stream are important. For humans monitoring the robot or searching objects with the help of the robot, the resolution is one of the most important parameters. For direct teleoperation (possibly with assistance systems) the resolution is not the major performance criteria. High frame rates, a constant frame inter-arrival time and small constant delays are much more important for the performance of the human operating the machine remotely. E.g. if the video gets stuck while a human is steering a mobile robot, in most cases the human will stop the robot until the frame rate recovers. Another example is that the human can adapt to a certain delay of the feedback from the robot while steering the robot. But if this delay is varying (changing inter-arrival times of the video) the operator is not able to compensate this anymore, which will lead in most cases to wrong and imprecise steering commands. Dependent on the specific tasks, it has to be ensured that the parameters for the video stream are still at the required or possible level when the teleoperation is realized over an ad-hoc network.

VI. Evaluation and Analysis Tools

A. *Evaluation of Routing Protocols*

In [27] and [24], AODV, DSR, OLSR, and BATMAN are analyzed in teleoperation scenarios of mobile robots. The results of this work have shown that the existing implementations of the evaluated protocols AODV, OLSR, and BATMAN are not suitable for mobile robot teleoperation with the standard parameter setting and even DSR is only usable with limitations (cf. Table I). Also the behavior of different protocols e.g. DSR (cf. Figure 6) or AODV (cf. Figure 7) is very different considering the rerouting time or the packet loss (cf. Table I). It was shown that parameter tuning can improve the performance of some protocols such that at least minimum requirements in performance can be reached. For more details please refer to [27] and [24]. But still, there is more potential for improvements and future research in this area.

B. *Tools for Analysis and Evaluation*

The implementations of routing protocols is often available for standard Linux systems or sometimes even for Windows operating systems. Depending on the supported operating system and the implementation techniques, the availabilities for monitoring, logging, and evaluating different ad-hoc routing protocols are different. Unfortunately, there are no off-the-shelf tools for analysis available. Often, also the investigated scenario determines the type of measurement category which must be monitored. This section gives a brief description how it is possible to get an easy access to relevant protocol parameters and measurement categories with respect to the analysis of scenarios with multi-hop networks of mobile robots. Objectives of analysis tools are the reconstruction of the network topology after the test runs, access to the “view on the network” of each single node for a certain time, and logging of measurement categories related to the packet flows (e.g. round trip times, packet loss, ...).

TABLE I
PACKET LOSS & TIMES FOR ROUTE REESTABLISHING.

Protocol	Packet loss during test run	Time for re-routing min.	max.
AODV	29.2%	$2.1s$	$> 30s$
OLSR	14.2%	$10.1s$	$> 30s$
DSR	11.2%	$2.4s$	$2.7s$
BATMAN	conn. lost	–	–

DSR: The tests presented in the previous sections were performed with a Linux operating system. The used DSR implementation creates a network device of a dedicated network supporting DSR ad-hoc routing. Additionally, the standard routing table of the kernel is not used in the standard way. All relevant information like neighbors and route requests of a node, link costs and hop count, and information about the gratuitous route reply can be accessed in the "/proc/net/" directory of the file system during runtime. The kernel routing table does not contain topology information for the DSR-enabled network.
OLSR: This ad-hoc routing protocol uses the existing network devices and updates the kernel routing table with the required information. Furthermore, it supports a visualization plugin providing graph visualization of the network topology (Graphviz format) easily.
BATMAN: The BATMAN daemon also maintains the entries of the kernel routing table. In addition, it can be started in a debug" mode which provides additional information about the network topology (originator router, potential routers, and direct neighbors).
AODV: Besides maintaining the kernel routing table, an additional file is created which contains only AODV related route entries. Here, the destination, next hop, hop count, route status, and expire flags are stored and accessible.
Summary: As no off-the-shelf analyzing software is available, own tools were developed to perform the evaluations in [27], [24], and [25]. Main objective was set on information of the packet stream and measurement categories like packet loss, time for route reestablishing, packet inter-arrival time, and bandwidth. This information can be collected with the help of small scripts or measurement programs. Of course, also the network topology is monitored during the tests to interpret the behavior correctly. Unfortunately, the decentralized design of ad-hoc routing protocols makes the representation of the overall network topology a challenging task. The required temporally synchronization of the log-files of each node can be realized either by time synchronization (e.g. ntp) or synchronization by events. Both mechanisms only provide an accuracy of several 0.01 milliseconds in the beginning, which will additionally degrade while advancing in time. Nevertheless, for most evaluation purposes, this accuracy is good enough to understand the behavior of the network. Future work could be done with respect to faster topology views for the protocols.

VII. CONCLUSION

The presented work gives an overview of relevant scenarios for heterogeneous teams of human and mobile robots which can be used for an application of wireless multi-hop networks based on WLAN. Furthermore, technological aspects, security issues and implementation details with respect to mobile robot teleoperation are discussed. A key issue of the presented approaches is the support of a highly dynamic network topology demanding the use of special ad-hoc routing protocols. Several common ad-hoc routing protocols which are already used in multi robot systems are presented and results of using these protocols in the described scenarios are given. Also different types of traffic which are typically present in mobile robot multi-hop networks are briefly summarized. Finally, the results of a parameter tuning of the above mentioned ad-hoc routing protocols show that multi-hop networks based on WLAN can be used for mobile robot teleoperation. The work concludes with details on evaluation and analysis of wireless multi-hop networks with mobile robots.

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