R5-COP

Reconfigurable ROS-based Resilient Reasoning Robotic Cooperating Systems

Converged infrastructure for autonomous robots (D43.50)

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Project	R5-COP	**Grant agreement no.**	621447
Deliverable	D43.50	**Date**	31/8/2016
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Document History			
Ver.	**Date**	**Changes**	**Author**
0.1	29/04/2016	Draft version created	Juha Zidbeck (VTT)
0.2	04/06/2016	Input from LTU and SSC	C. Kanellakis (LTU), G. Nikolakopoulos (LTU), J. Wikström (SSC)
0.3	07/07/2016	ToC updated, input to chapter 2 added	Matti Laukkanen (VTT)
0.4	25/08/2016	Input from VTT to chapters 2 and 3	Matti Laukkanen (VTT)
0.5	29/08/2016	Updates from LTU and SSC	C. Kanellakis (LTU), G. Nikolakopoulos (LTU), J. Wikström (SSC)
1.0	02/09/2016	Small improvement, formatting	Matti Laukkanen (VTT)

Note: Filename should be

“R5-COP_D##_#.doc”, e.g. „R5-COP_D91.1_v0.1_TUBS.doc“

Fields are defined as follow

1. Deliverable number	***.***
2. Revision number:	
draft version	**v**
approved	**a**
version sequence (two digits)	***.***
3. Company identification (Partner acronym)	*****

Content

List of Acronyms

ABBREV	Explanation
QoS	Quality of Service
WP	Work Package
UGV	Unmanned Ground Vehicle
RF	Radio Frequency
ROS	Robotic Operating System

1 Introduction

1.1 Summary (abstract)

The ability of the communications network to perform much of the setting up and reconfiguration seamlessly and automatically without manual intervention is critical for making connectivity available and sustainable in the farm robot scenario. Energy-aware routing is prerequisite to re-route the robot's traffic intelligently through the mesh when the mesh nodes' energy supply status changes. QoS and access control are prerequisite to re-route the robot's traffic via an alternative network route when a link / mesh node becomes unavailable / breaks down while maintaining QoS demands. Last but not least, the communications infrastructure must be easy to deploy and maintain.

1.2 Purpose of document

This deliverable will present the developed energy-efficient, robust, reliable and affordable wide area heterogeneous wireless mesh networks to provide connectivity for robots navigating in very challenging and remote environments.

1.3 Partners involved

Partners and Contribution	
Short Name	**Contribution**
VTT	Deliverable coordinator
LTU	Input on 3.2 Section
IMCS	Input on 3.3 Section
SSC	Input on 3.2 Section
PRO	Input on 3.1 Section
TTS	

2 Heterogeneous wireless networks for robot systems

A wireless mesh network (WMN) is a communication network which consists of radio nodes organized in a mesh topology. Wireless mesh networks have several benefits: first, they are less expensive and easier to deploy than installing wires; second, the network is extremely adaptable and expandable, because nodes can be easily added; and finally, reliability of the network is increased with redundancy. If one node for some reason cannot operate, traffic can still be routed through other nodes. An illustration of a mesh network routing principle is presented in Figure x.

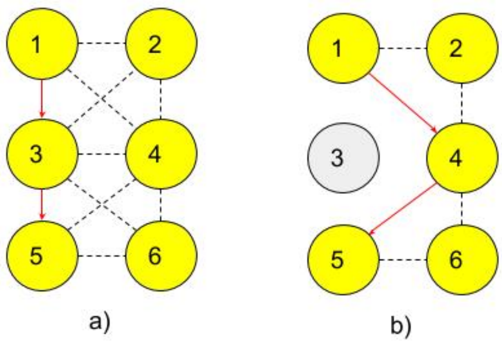

Figure 1. A mesh network with six nodes. In the case a) all nodes are connected to each other. In the case b) the node number 3 breaks down and traffic is routed to an alternative path.

A heterogeneous wireless network (HWN), on the other hand, consists of devices utilizing different radio access technologies (RAT). In contrast to a traditional homogeneous wireless network, a HWN provides several benefits including improved reliability and increased coverage. Reliability is increased because if one RAT fails, the connection can be maintained by a different RAT within the HWN. Because the radio technologies operating on different frequencies offer many operating ranges varying from few meters to dozens of kilometers, HWN can significantly increase the coverage. In addition, using different bands can help reduce interference between devices. For instance, the unlicensed 2.4 GHz band can be very congested in some locations, as a wide range of devices are using the frequency band.

Combining the best parts from WMN and HWN concepts plays a key role when building a flexible and reliable network for autonomous mobile robot use cases. However, there are also several disadvantages and trade-offs that should be considered. In this section, requirements for a wireless network are discussed from a robot's point of view, and trade-offs are analysed. Finally, different wireless technologies suitable for a heterogeneous wireless mesh network are briefly presented.

2.1 Requirements

A robot operating in rural areas poses several challenges for the network. Reliable network connectivity is a critical requirement for a number of reasons, such as need to communicate with other robots, or teleoperation. The environment also sets some limitations, as there might be limited infrastructure for wireless technologies and power availability, and conditions can be harsh. Therefore, the network should be self-healing and tolerant against disruptions.

Range and coverage

The range of a wireless technology is proportional to the RF sensitivity of a receiver and the power of a transmitter, but also many other factors affect. For example, frequency of carrier wave, antenna radiation pattern, propagation path obstructions, and signal encoding schemes have significant impact on range. Moreover, longer range usually decreases data rate or increases power consumption, which should be taken into account when designing the network.

Bandwidth and throughput

Bandwidth and throughput are indicators of network performance, the former one meaning theoretical maximum of achievable data rate, while the latter indicates the rate of successful delivery in practice. The value of throughput is usually less than bandwidth and is affected by various factors, such as packet overhead, noise, and network congestion.

The required bandwidth is highly dependent on the use case. For example, sending a video stream to a remote operator requires more bandwidth than occasionally sending a small amount of data. As robots usually have limited computational capacity, some of the data processing might be more reasonable to be performed on a remote machine. However, both transmitting and processing data consume energy, so it is balancing between these two. Safety functions should always be executed locally, since the robot must survive even without network connection.

In a wireless mesh network, when the packets traverse through multiple nodes, called “hopping”, the throughput decreases and the latency increases up to 50% on each hop. Therefore it is very important to optimize the routing of the packets. Bandwidth degradation problem between hops can be overcome at some extent by using multi-radio nodes that employ different radio channels for downstream and upstream traffic.

Latency

The time delay between sending and receiving the data packet is also critical for an autonomous robot. For example, teleoperation or real-time monitoring of the robot quickly becomes unusable, if the latency increases excessively.

Latency increases proportionally to the link range and the number of hops in a mesh network. Latency strongly affects to throughput of the network, as only a limited amount of data can be transmitted at a time, and the complete packet has to be received before it can be forwarded to a next node. Packet loss quickly increases the latency, because the retransmission of a packet has to be executed in each node. Therefore the routing has to be balanced between shortest possible path and using least congested channels.

Power consumption

Robots usually have limited battery capacity, so the power management is an important concern. Moreover, in remote areas that are sometimes difficult to reach, providing a reliable power source for the nodes of the network is not necessarily trivial.

Limiting the transmission power of the radio comes at the expense of the link range and bandwidth. Increasing the complexity of the mesh network emphasizes the need of energy-aware routing, as each intermediate node adds power consumption. Certain radio technologies provide features for power reduction, such as turning off the device when the links are idle.

Robustness

Robustness can be understood in various ways, therefore a definition is required. In a heterogeneous wireless mesh network, robustness could be determined as an ability to tolerate disruptions, and to maintain its connectivity. Network has to be self-healing so that if a node in the mesh suddenly becomes unavailable, the network should be able to autonomously re-route the traffic effectively via alternative path, or the connection should be maintained by switching to a different RAT. Prompt detection of the faults within the mesh network and seamless handovers between different wireless technologies are a key in maintaining sufficient level of throughput and QoS.

2.2 Suitable wireless technologies

2.2.1 IEEE 802.11 (Wi-Fi)

IEEE 802.11 is a set of specifications for implementing wireless local area networks (WLANs) [1]. The standard, also known as Wi-Fi, was originally released in 1997 as a wireless counterpart to wired LANs using Ethernet technology. Since then, several amendments have been developed and new technologies and capabilities have been added to the specification. Today the Wi-Fi standard is available virtually everywhere and IEEE 802.11 compliant radios are found in a wide range of devices, including computers and mobile phones.

Most IEEE 802.11 standards operate in unlicenced 2.4 and 5 GHz frequency bands, which are sub-divided into smaller channels. Depending on the country, there are some regulations applied to the channels; e.g. some channels in the 5 GHz band are restricted to indoor use only, and maximum transmission power levels are limited. Several other frequency bands have are also: the IEEE 802.11ad amendment (also known as WiGig) specifies high-speed Wi-fi networks operating in the 60 GHz millimeter wave spectrum [2], whereas IEEE 802.11af specifies operation in TV white space spectrum between 54 and 790 MHz [3].

The frequency has a significant impact on the performance of the network. Most commonly used 2.4 GHz protocols are susceptible to radio interference in densely populated areas and inside residential buildings, because many consumer devices as well as other Wi-Fi networks are using the same frequency band. 5 GHz devices are generally less prone to interference, as there are significantly more channels and fewer devices in that frequency band. Higher frequency radio waves have shorter wavelength, thus they are more susceptible for obstructions, such as walls and ceilings. Therefore the range of 5 GHz Wi-Fi network is generally shorter than those using 2.4 GHz. In 60 GHz band the attenuation of radio waves is even bigger problem, and the operating range is short and line-of-sight is required.

As mentioned before the range of Wi-Fi connection is affected by the frequency used, but also by other factors, such as transmission power or type of the antenna. A typical indoor Wi-Fi access point has a range of a few dozens of meters, but when using directional antennas in obstacle-free environment, the link between the devices can be extended to kilometres [4]. The range and coverage of a network can be also expanded by utilizing multi-hop mesh topologies, which are specified in the IEEE 802.11s amendment.

Throughput of Wi-Fi has increased steadily. While the original 802.11 standard in 1997 supported data rate of 2 Mbps, several years later 802.11g standard provided 54 Mbps. Currently, the 2013 released IEEE 802.11ac standard operating in 5 GHz band can achieve data rate up to 1.27 Gbps by using MIMO antennas and wider channel bandwidth [5]. WiGig in 60 GHz band can provide data rate up to 7 Gbps, but as discussed earlier, operating range is limited. These data rates are theoretical maximums, and actual achievable speeds depend on signal strength.

2.2.2 Wireless Sensor Networks

A wireless sensor network (WSN) can be defined as a network of spatially distributed small devices, called sensor nodes, which gather information from their environment and cooperatively communicate through wireless links. The data gathered by different sensors is passed to a sink node, which can be connected to other networks. Depending on the application, the size of a WSN can vary from a few to thousands of nodes and the topology can vary from simple star or tree networks to a complex multi-hop mesh network. Examples of different WSN topologies are presented in Figure 2. In comparison to Wi-Fi, WSN devices are designed specifically for low power and low data rate communication. A node might operate on battery with a lifetime of up to multiple years, or energy harvesting solutions (e.g. solar cells) can be used. Typically WSNs have been used in many applications, such as industrial process monitoring or home automation systems [6].

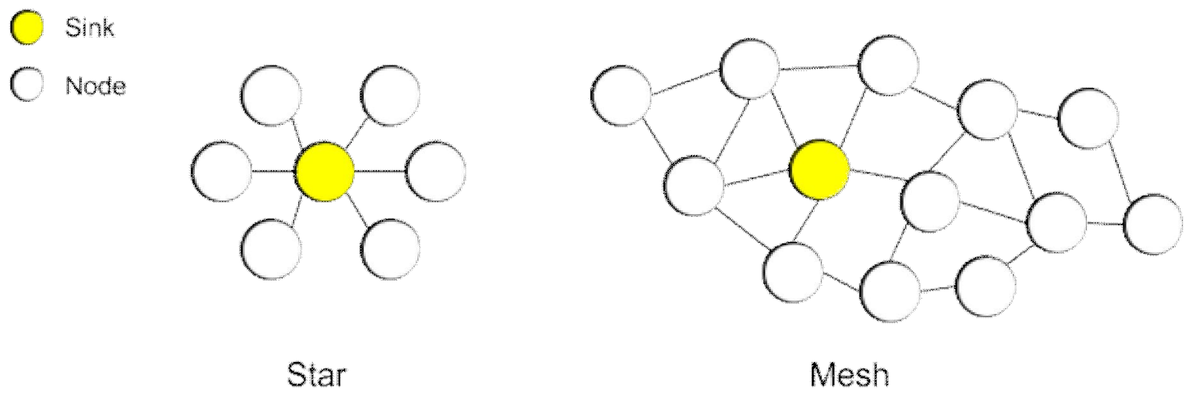

Figure 2. Different topologies of WSN networks.

Several standards and technologies for WSNs coexist. One widely used standard is the IEEE 802.15.4, which specifies the physical layer and medium access control for low power wireless sensor communication [7]. It allows connectivity for up to 65,536 nodes in three specified operating frequencies: 868, 915 and 2450 MHz. The maximum operating range is up to 100 m, but it depends on frequency and transmission power used. Maximum achievable data rate is 250 kbps. Several higher level layer specifications providing IPv6 capabilities are based on the IEEE 802.15.4, including ZigBee [8] and 6LoWPAN [9].

Another potential technology for WSNs is Bluetooth, which is a technology for low-cost and short-range devices. Originally Bluetooth was standardized as IEEE 802.15.1, but the standard is no longer maintained and the technology is currently managed by Bluetooth Special Interest Group. Starting from specification version 4.0, Bluetooth Low Energy (BLE), an ultra-low-power technology was introduced. It operates on the same 2.4 GHz frequency band as Wi-Fi and provides up to 1 MBps data rate on 200m range. According to Bluetooth SIG, upcoming Bluetooth version 5 in 2016-2017 will double the data rate and quadruple the operating range, and mesh networking capabilities will be added [10][11]. One notable advantage of the BLE technology is its wide availability in the consumer markets; nowadays nearly all smartphones are equipped with it and billions of BLE devices have been shipped.

2.2.3 Cellular Networks

Cellular network is a wide area network (WAN) providing seamless coverage for a very wide geographical area, such as a country. Originally cellular networks were voice-centric, but from the second generation (2G) deployed in 1990s and the 3G systems in early 2000s, the technology has evolved to provide high-speed wireless data transport in the fourth generation (4G or LTE). The networks are maintained and developed by 3GPP [12]. Currently the 2G, 3G, and 4G networks are usually deployed in parallel. As of 2015, the coverage of the 2G network is estimated to be 95% of the world population, while the coverages for 3G and 4G networks are 69% and 35% respectively [13]. Especially the adoption of 4G technology has been estimated to increase rapidly in the few next years.

The main radio coverage in cellular networks is provided by base stations that are mounted to buildings and ground-based masts. The range of a cell can be up to tens of kilometers, but is typically several kilometers. In densely populated areas also smaller cells (ranges varying from 10 meters to 1 km) are used to increase network capacity and provide better service. The base stations of a network are owned and controlled by network operators that have a licence to access the radio spectrum, regulated by the government. Several distinct network operators may service simultaneously in the same area.

Several different radio frequency bands are used in cellular networks. While the 2G and 3G networks operate only on a few distinct frequency bands, there are more than 40 possible frequency bands for LTE networks. Moreover, the bands are region specific, so interoperability issues are possible. Modern devices, however, usually support multiple frequency bands simultaneously.

Throughput of the cellular networks has considerably increased recently. Whereas 2G systems provide up to 384 kbps data rates, 4G network can support data rates up to 1 Gbps by using advanced modulation, multiplexing, and link adaptation techniques. As with the data rates, also the latencies have improved with each generation. With 2G networks latency is typically hundreds of milliseconds, whereas 4G networks can achieve latencies as low as 5 ms.

5G, the next generation of cellular networks is currently under development and commercial deployments are suggested to be started around 2020. It will provide higher data rate and lower latency than current 4G technologies. 5G will also have to face challenges of rapidly growing amount of transferred data and massively increasing number of devices, as new use cases are expected[14]. Proposed improvements in 5G include employing new radio frequency bands, using massive MIMO, and moving towards device-to-device (D2D) communication as contrary to infrastructure-centric control in current networks[15].

3 Communication Networks in the WP43 Use Cases

3.1 Farming Robot (VTT, PRO)

In this scenario a mobile robot autonomously navigates in a field, simultaneously executing a specific task, e.g. applying pesticide, or inspecting the health of the crops with a thermal camera. The robot must also be aware of its surroundings and avoid any obstacles along its path. This deliverable presents the demonstrator platform from communication point of view.

3.1.1 Requirements

The robot is equipped with a computer that takes care of controlling the motors and processing sensor data. As the robot should perform autonomously and most of computation is done on board, not that much data necessarily needs to be transferred all the time. However, in some special occasions an efficient and reliable network connection is essential. For example, in an emergency situation the robot may need to be teleoperated, so the latency should not be too high. Moreover, the sensor data, such as video streams and high-resolution point clouds require high throughput. The robot should also be always reachable, so the seamless coverage is mandatory.

3.1.2 Network Architecture

Communication with the robot is handled by using IEEE 802.11 and cellular technologies. The robot is equipped with an ASUS RT-AC68U 802.11ac capable 2.4/5 GHz dual-band Wi-Fi router. The router also supports 3G/LTE modems, which are plugged into USB port. If the Internet connection in the Wi-Fi network is lost, the router can automatically switch to use cellular data connection.

Diagram of the network configuration is presented in Figure 3. The Probot Mobility Modules are connected to the computer with CAN interface, while Microsoft Kinect v2, GPS module, IMU and other sensors are connected to USB ports. The computer and Ethernet cameras are connected to a switch, which is connected to the Wi-Fi router. The router is bridged to a wireless mesh network that is also accessible with VPN connection.

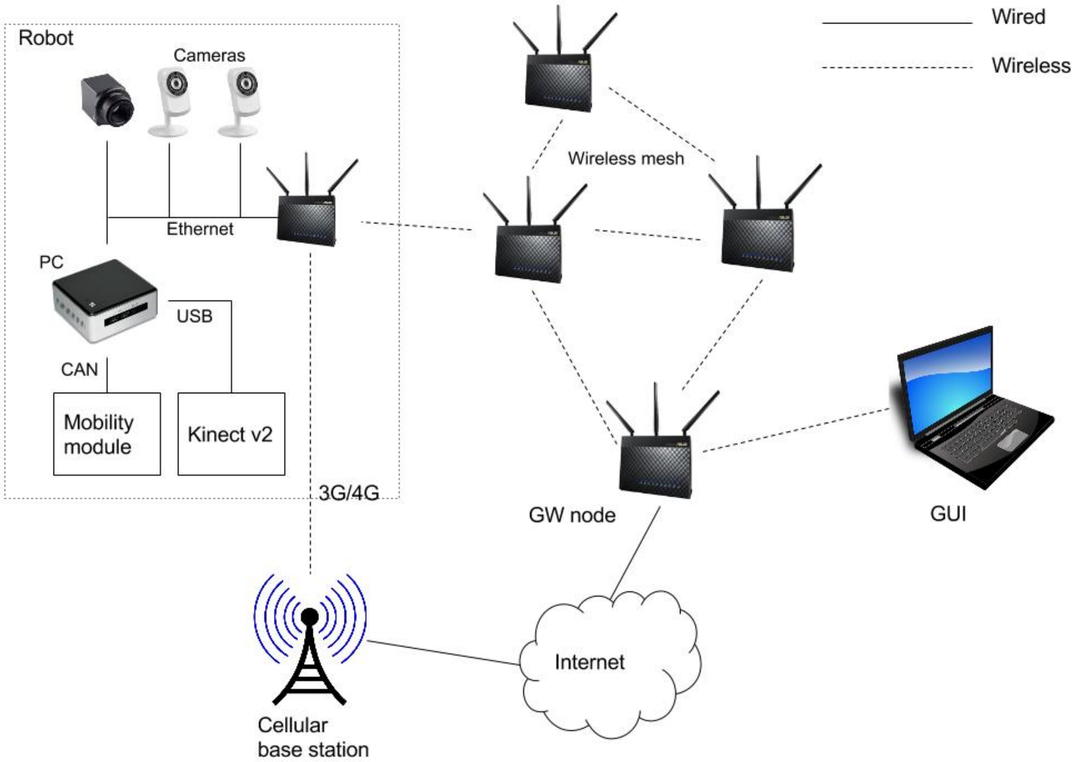

Figure 3. Communication network configuration for the field robot use case.

The network has not yet been fully tested in a rural area. Deploying the Wi-Fi mesh nodes to the actual site has several points to consider. The existing infrastructure constrains the design of the network. If the area has good 3G or LTE coverage, Wi-Fi nodes might not be necessary at all, as the cellular network provides sufficient connectivity. However, if the mobile network coverage is poor, which often is the case in rural areas, mesh nodes have more important role to cover the blind spots of the network. Electrical power infrastructure limits the placement of the nodes, as Wi-Fi is rather power hungry. Additionally, also weather protection and the risk of vandalism should be taken into account when deploying the network.

3.2 Autonomous UGV for Search and Rescue (LTU, SSC)

3.2.1 Control Reconfiguration against network induced time delays

Networked control systems are distributed systems consisting of sensors, actuators and controllers. This kind of systems communicate through shared digital network and implement closed loop control. This technology can be used in a great variety of applications, like a mobile robotic systems, but still exist challenges that may affect its performance. An important problem that occurs inevitably are the induced random time delays in the network which may deteriorate the performance of the system and lead to instability. It is therefore of uttermost importance to compensate the effect of these delays and guarantee stability of the system for real time applications. Systems and Control theory could be employed to enhance the robustness of the mobile robotic system against network induced delays. More specifically, elaborate control schemes are needed to take into account for random delays and stabilize mobile robotic system.

To this end, LTU has proposed a reconfigurable control scheme that is robust against network induced time delays using a switching strategy. Initially, a stability analysis algorithm is introduced in order to evaluate the maximum allowable time delays that the target system can handle for a given-fixed LQR controller. The varying nature of the time delays results in a switching system with the latency time to play the role of a switching rule. Simulation results are presented to outline the effects of the time-induced delays in mobile robotic systems and finally evaluate the overall efficiency of the proposed control scheme.

Delay Dependent switching modelling

Initially, the system is represented in the discrete state space using the following equations:

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k \end{aligned} \tag{1}$$

where $x_k \in \Re^4$, $u_k \in \Re^2$, $y_k \in \Re^4$ with $k \in \mathbb{Z}^+$, $C = I_{6\times 6}$ and the state space matrices A, B defined as:

Additionally to these system equations, a controller a state feedback Linear Quadratic Regulator (LQR) [24] can be designed as shown in (4), considering zero latency feedforward and feedback connections in the closed loop system by minimizing a quadratic cost function as described in (5):

$$\begin{aligned} u_k &= -Kx_k \\ J_u &= \sum_{k=1}^{\infty} [x^T(k)Qx(k) + u^T(k)Ru(k)] \end{aligned} \tag{2}$$

where Q and R are the quadratic weights of the cost function, weighting respectively the state deviation and the input.

The calculation of the LQR's gain K is a sufficient condition to guarantee the overall stability of the closed-loop system, while the corresponding discrete time state space model is also asymptotically stable, regardless of the stability of the open loop system keeping the modulus of the poles or eigenvalues of A smaller than one, while this analysis is true for a zero latency case. In the case of time delays, the closed loop poles of the system are varying towards the limits of the unitary circle and thus the bigger the time delay is, the easier the system approaches the instability region, provided a fixed control structure. In the case that varying time delays are induced to the system from network latencies, multiple bounded delayed regions can be defined, meaning that the maximum delay can be assumed known a priori (worst case scenario), while the notation of the time delay can be defined as $\tau(k) \in \Re^{+}$. In a zero latency connection, meaning that $\tau = 0$, the controller, corresponds to a static output feedback defined as $\tilde{u}(k) = Ke(k) = K(r(k) - y(k))$. However, since the amplitude of processing time exceeds the system update rate response time, time delays cannot be neglected in the design of the controller. To this end, the applied control signal is $e(k) = r(k) - y(k - \tau(k))$ and for the case of the position regulation problem r is set to zero, while for simplicity in the notations we define $d(k) = \left\lceil \frac{\tau(k)}{T_s} \right\rceil$, with $d \in \mathbb{Z}^{+}$ be the overall delay at sampled instance k and T_s the selected sampling period. If the overall time delay d is time varying the resulting control law is provided by:

$$u(k) = KCy(k - d(k)) \tag{3}$$

For the scope of the analysis, the state vector $x(k)$ is transformed to an augmented version in order to include all the delays, as shown below:

$$\tilde{x}_{k+1} = [x_k^T, x_{k-1}^T, \ldots, x_{k-D}^T]^T \tag{4}$$

with $\tilde{x}_k \in \Re^{(D+1)\times(D+1)}$ and D the maximum bound of the delay. The augmented state space representation of the system at sample time $k$can be described in following equation:

$$\begin{aligned} \tilde{x}_{k+1} &= \tilde{A}\tilde{x}_k + \tilde{B}u_k \\ y_k &= \tilde{C}\tilde{x}_k \end{aligned} \tag{5}$$

where the matrices $\tilde{A}$, $\tilde{B}$ and $\tilde{C}$ are defined as:

$$\tilde{A} = \begin{bmatrix} A & 0 & \cdots & 0 & 0 \\ I & 0 & \cdots & 0 & 0 \\ 0 & I & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & I & 0 \end{bmatrix}, \qquad \tilde{B} = \begin{bmatrix} B \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \tag{6}$$

$$\tilde{C} = \begin{bmatrix} 0 & \cdots & 0 & C & 0 & \cdots & 0 \end{bmatrix}$$

By combining (3) and (6), the state feedback closed loop discrete system can be summarized in the following equations:

$$\tilde{x}_{k+1} = (\tilde{A} + \tilde{B}K\tilde{C})\tilde{x}_k$$
$$y_k = \tilde{C}\tilde{x}_k \tag{7}$$

Under the assumption that at every time instance k the latency time d can be measured, and therefore the index of the switched–state is known, the system can be described as:

$$x(k+1) = \sum_{i=0}^{D} \xi_i(k) A_i x(k) \tag{8}$$

where $\xi(k) = [\xi_0(k), \dots, \xi_D(k)]^T$ and $\xi = \begin{cases} 1, mode = A_i \\ 0, mode \neq A_i \end{cases}$

Stability

The stability of the switched system is ensured if $D+1$ positive definite matrices P_i, $i = 0, \dots, D$

can be found to satisfy the following LMI:

$$\begin{bmatrix} P_i & A_i^T P_j \\ P_j A_i & P_j \end{bmatrix} > 0, \forall (i,j) \in I \times I$$
$$P_i > 0, \forall\, i \in I = \{0, 1, \dots, D\} \tag{9}$$

Based on these positive definite matrices it is feasible to calculate a positive Lyapunov function of the form $V(k, x(k)) = x(k)^T(\sum_{i=0}^{D} \xi_i(k) P_i)x(k)$ whose difference

$\Delta V(k, x(k)) = V(k+1, x(k+1)) - V(k, x(k)))$ is a negative function for all the $x(k)$ solution of the switched system ensuring the asymptotic stability of the system.

Simulations

The aforementioned switching system is evaluated in a mobile robot with state space equations:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2.7507 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 29.459 & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ 0.08 \\ 0 \\ 0.1879 \end{bmatrix}, \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

assuming sampling time $T_s = 0.005s$.

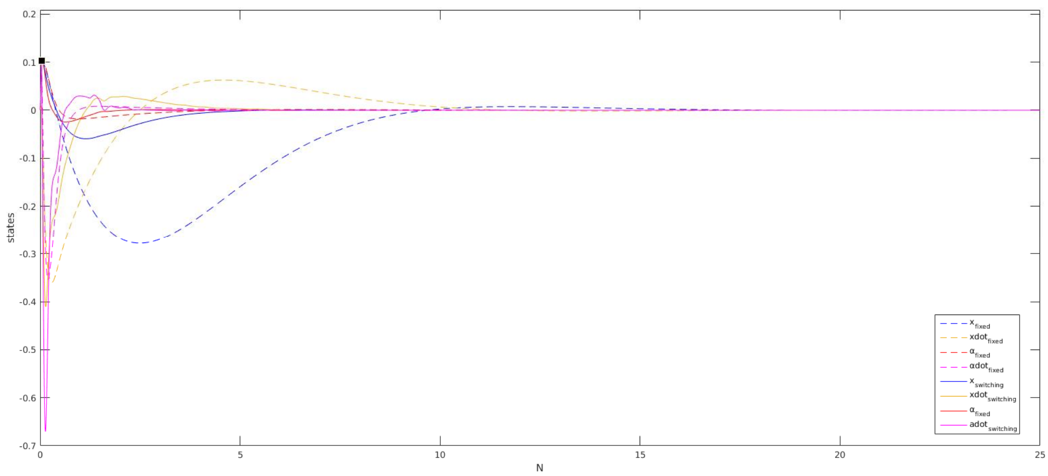

Figure 4. State responses for fixed and switching control case.

From the obtained results it is obvious that the proposed switching scheme is able to provide a better regulation with faster settling times, independently of the encountered time delays. Furthermore, based on the previous analysis, it should be highlighted that the system is able to tolerate now larger amount of time delays, when compared to the fixed controller case, while ensuring a good performance.

3.2.2 Network Architecture

Communication with the UGV is handled by using IEEE 802.11 and cellular technologies, while there are also analog links in the field of the trials that can be used only as emergency communication channel, e.g. send a general stop command. Additional to this infrastructure UWB digital communication has been also evaluated as an alternative long range communication channel, in the form of wireless sensor networks.

3.3 RUAV cooperation with WSN in Rural Areas (IMCS)

3.3.1 Network Architecture and requirements

IMCS is developing a demonstration task T43.6 “RUAV cooperation with WSN in rural areas”, which is based on WSN and RUAV communication. WSN can be of arbitrary type in the rural area with a different usage. Central idea of the task is that RUAV flies to the WSN, which can be located in hardly accessible place, communicates with this WSN, and can combine it’s functionality with this WSN. That means that only non-standard requirement for this WSN, is a RUAV ability of dynamical communication with the WSN nodes.

Main idea how to achieve this task - was to put a standard WSN node on the RUAV for the communication purpose. This node acts in same way as any other nodes (see Figure 5).

For the WSN network testing, a test environment was developed. This was simplified indoor test environment, where WSN communication is easier observed.

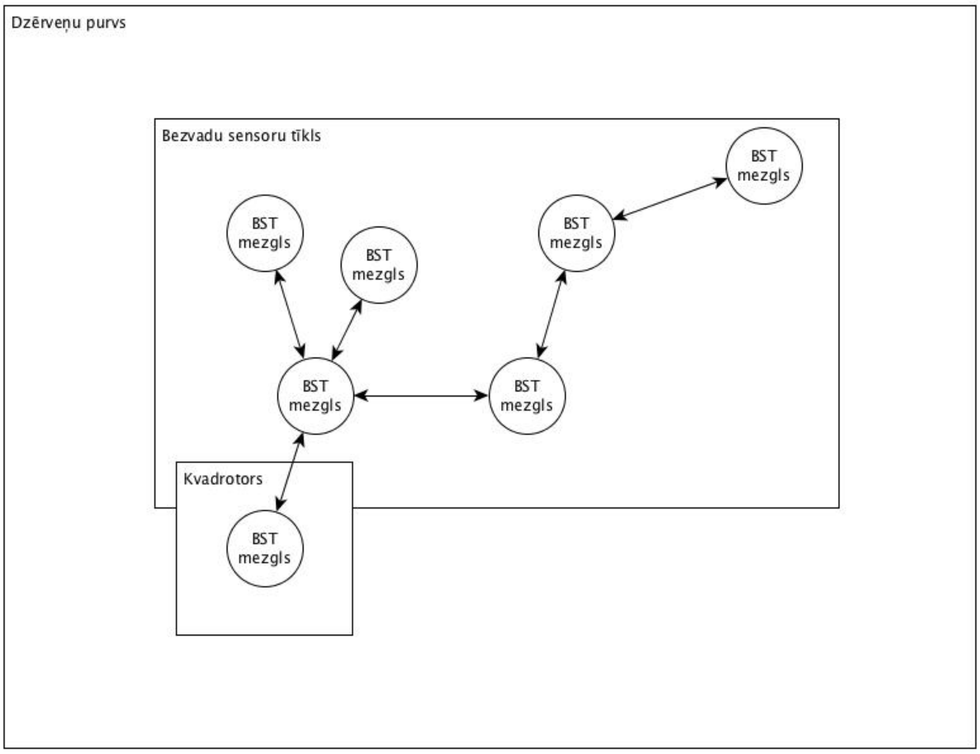

Figure 5. Network architecture with RUAV as a WSN node.

3.3.2 WSN Testing

Test Environment

During the WSN network tests, mainly was tested the approach of how RUAV can communicate with WSN network. For the testing of this approach (also taking in account that during winter time we had to do the testing indoors) simplified tests were defined:

1) WSN node is placed on the RUAV
2) RUAV executes only limited flight in the indoor conditions
3) RUAV central Control code manages WSN node via ROS.
4) IQRF nodes are used, because it was available. In the demonstrator tasks T43.6 final demonstrations that can be changed, if required. We had only 3 nodes, so we choose configuration (See Figure 6). We think that this test satisfies main requirements and on the results of those tests will be possible to develop demonstrator task T43.6.

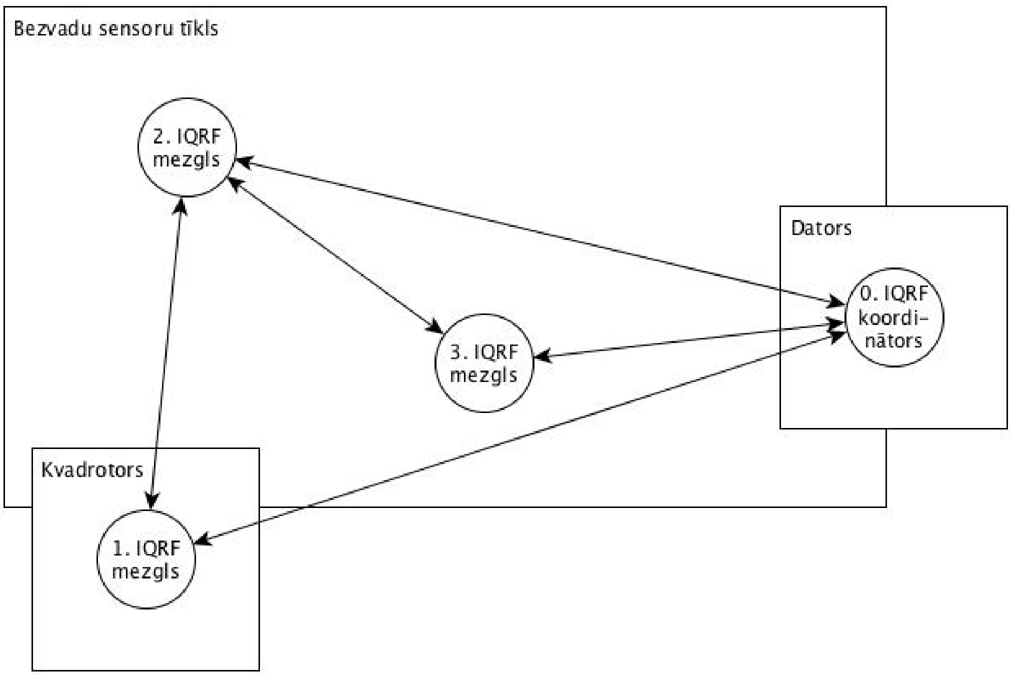

Figure 6. WSN configuration for the indoor tests

Main elements what we want to test in this environment:

1) WSN placement on the RUAV .Hardware and software solutions
2) Possibility to use ROS (drivers etc.)
3) test mesh solutions for that WSN, which can be used for establishing communication with RUAV

Hardware Solution

For a WSN network was used IQRF [16] network. It was available in IMCS on the start of the test and this IQRF network was satisfying the requirements for the test (including the mesh possibilities with IQMESH [17] protocol). Using this protocol it is possible to create dynamic sensor networks, where exist nodes, which can move along the network. Using IQMESH data packets are delivered using Flooding mechanism. For using IQMESH it is necessary during initialization to make the Discovery of the nodes.

For our indoors test the simpler star topology network was used which was satisfying test requirements.

For the task was used following IQRF components:

1. DCTR-52 transceiver (see Figure 7)
2. CK-USB-04A programmer (see Figure 8)
3. IQRF IDE

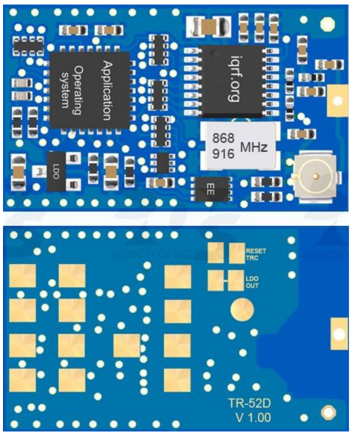

Figure 7. DCTR-52 transceiver

Figure 8. IQRF programmer with a double sided scotch

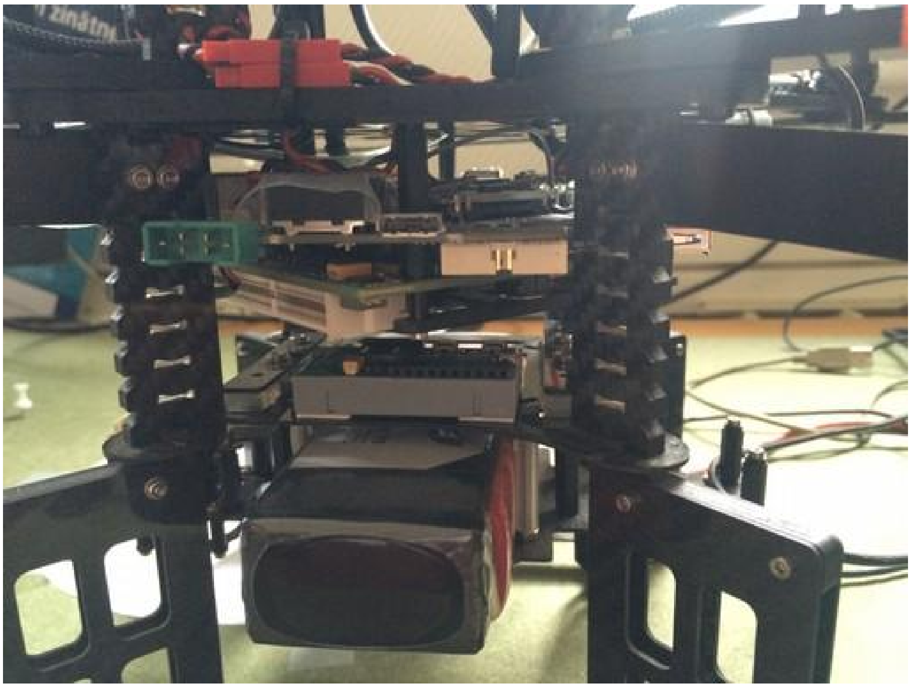

Figure 9. IQRF programmer placement on the RUAV

Software Solution

Driver for the IQRF WSN node was developed and deployed on onboard PC (see Figure 10) with such functionality:

a) with other entities on the onboard PC driver communicates via ROS
b) With WSN nodes hardware driver communicates via USB
c) driver was developed in Python

All other ROS nodes in the figure are dedicated to operate the RUAV and are irrelevant to those WSN tests.

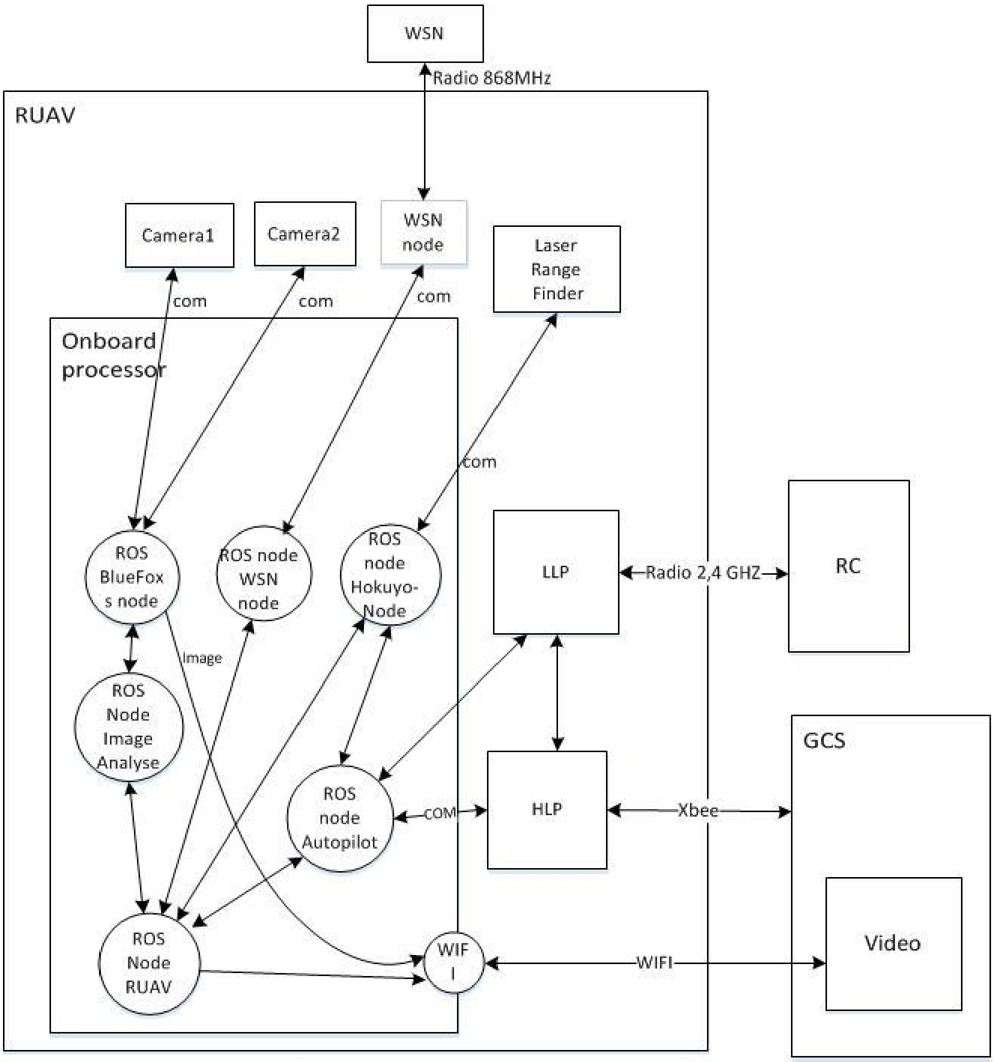

Figure 10. Software components using ROS

Results

1) Main objective was reached. The communication between RUAV and WSN was established. Command from RUAV to WSN node was sent. WSN node received the command and switched on the red light. Reply command was sent.

2) Those tests show that idea how RUAV and WSN network communicates works. IMCS can proceed with developing demonstrator application T43.6. All the details of this communication will be developed, preparing the final demonstration.

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