Real-Time Communication based on IEEE 802.11b/g for Automation of Agricultural Vehicles

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***Abstract*—Current farming practices try to reduce soil compaction, carbon-dioxide emission, fuel consumption and to fulfill further environmental goals. Another goal of current farming practices is to minimize the duration for handling a field, in order to become independent of extreme weather conditions. Such environmental and economic goals may be met through increased automation and robotization in agriculture. As known from the industrial sector, automation and robotization is based on reliable communication. On implementing this in agriculture, an important prerequisite for the coordination of farm vehicles are real-time wireless networks. Such networks have to fulfill the demands of real-time systems and take into account the characteristics of mobile vehicles and groups of vehicles with their special mobility patterns and radio environment. We present a new approach for soft real-time networks based on IEEE 802.11. Our idea is the use of available sensory information like the signal strength of transmitters and relative position of vehicles in order to predict the real-time service quality for moving agricultural vehicles. We prototypically implement our method on board of two agricultural vehicles. Finally, we evaluate and discuss the results for agricultural usage and propose further improvements.**

***Index Terms*—real-time; wireless network; farming practices; IEEE 802.11; mobile nodes; agricultural vehicles; automation and robotization; mobile vehicle groups**

I. Introduction

Climate changes and its effects are one of the most significant challenges of this century. A fact we cannot ignore is that we are already influenced by climate changes in many different areas. Despite controversies, the occurrences of billion-dollar damages caused by extreme weather conditions and probably global warming, has increased in recent years [1]. This is one of the main motivations for new "green" technologies. These should save our climate and cushion the climate changes. However, almost all of these technologies depend on natural materials which grow on our fields. The sector of agriculture and forestry, where these materials grow, are highly exposed to climate changes. For instance, the agricultural and forestry industry in the European Union is emitting approximately 14% of the global greenhouse gas emission [2]. Thus, climate change is one of the main challenges for the agricultural sector. It is supposed to feed the worlds population and in parallel to grow the natural materials for non-food demands like "green" technologies [2]. Establishing new technology and processes in the agricultural and forestry sectors might be the key to break the spiral of human made climate changes. Only if mankind is able to run emission neutral agriculture in the future, the "green" technology revolution might work.

For this the agricultural production needs to be further optimized. Optimization problems of such degree of complexity also exist in other areas. The automotive industry for example is using a high degree of automation and robotization to increase productivity, reduce production time, reduce consumption of resources like energy and moreover to be able to improve product quality and production effectivity. Applying this level of automation and robotization to agriculture will change this sector and will result in new farming practices.

Implementing automation and robotization, in the following only referred as automation, in agricultural vehicles necessitates real-time wireless networks. We approach this topic of real-time wireless networks by investigating standard IEEE 802.11b/g communication whether it fulfills the demands of real-time communication within the agricultural sector. For this, we consider the characteristics of mobile vehicles and groups of vehicles, e.g., position changes. Based on this real-time wireless network approach, automation of agricultural vehicles becomes possible. Note that the goals of this work are not autonomous vehicles or a complete autonomous agriculture. For such applications our approach does not guarantee the necessary requirements.

This paper is organized as follows. At first Section II presents examples of application for automation in farming and describes existing methods for real-time networks including their compliance with the needs of automation in agriculture. In Section III, our approach for real-time communication based on IEEE 802.11b/g is presented. In Section IV, a qualitative evaluation of the proposed method with measurements in an agricultural context is discussed. We also demonstrate that our algorithm fulfills the demands of soft real-time on mobile vehicles and of the agricultural sector. Finally, in Section V results are presented and an outlook on further improvement is given.

II. Related Work

Current and possibly future techniques for automation in agriculture have in common that they can only be realized with wireless real-time networks. To obtain an overview of

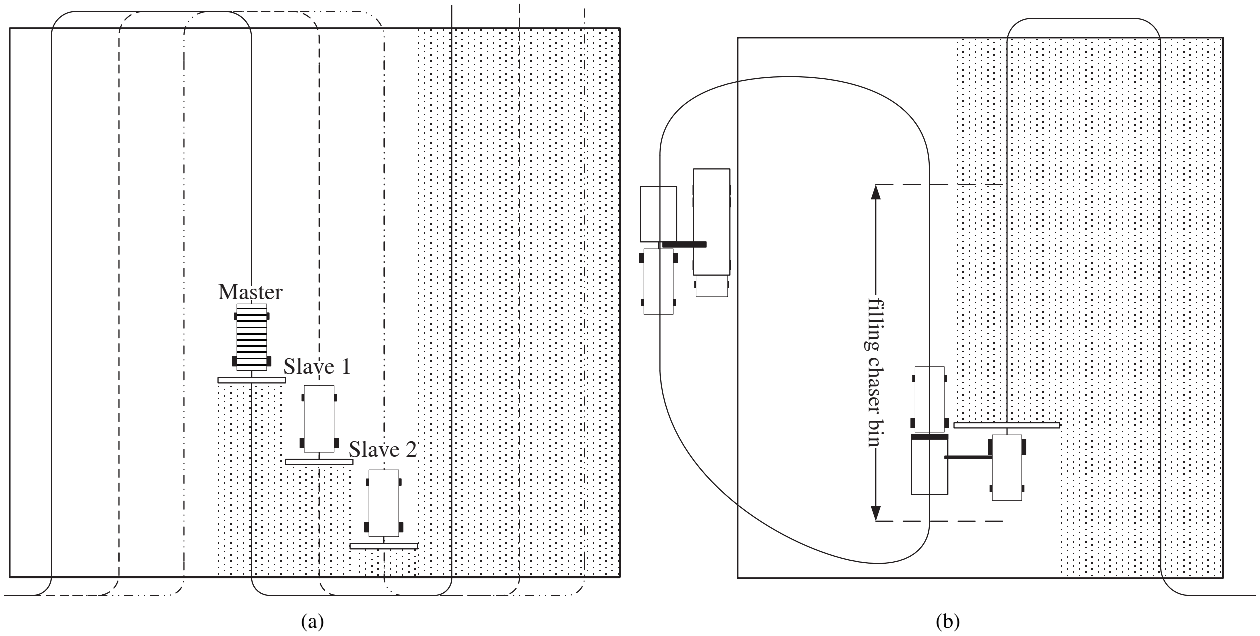


Fig. 1. Automation examples: (a) one master vehicle with n slave vehicles, (b) chaser bin synchronized between harvester and truck

this area, we only introduce some important wireless real-time network techniques and discuss their applicability to farming practices. Additionally, as a basis for better understanding, a brief summary of the wireless IEEE 802.11b/g standard is given.

A. *Automation of agriculture*

Automation and optimization — these two terms are intertwined. Due to automation, processes in many sectors have been continuously improved. In order to show the potential of automation in the optimization of, e.g., fuel consumption or time on field and its related topics like soil compaction, carbon-dioxide emission and weather independency, we highlight two practices.

The first practice is the parallel cruise of n agriculture vehicles. As shown in Figure 1(a) one master vehicle interacts with $(n - 1)$ slave vehicles. With additional information like, e.g, the working width of the implement and distance between following vehicles, each driving lane is calculated. Here, the optimization of many parameters is possible, like the minimization of the overlapping working width in order to save seeds and fuel, the minimization of soil compaction by using the same lane, or the maximization of driving speed to decrease the time spent on the field. This practice for $n = 2$ tractors is implemented as a proof of concept by an agriculture company, but not yet released. For the wireless communication between the vehicles, an in-house development based on WirelessHART is used [3].

The optimization of harvesting practices requires a synchronization of one or more harvesters and one or more the chaser bins. As shown in Figure 1(b), the chaser bin commutes between the truck on the border of the field and the harvester. With an interlink between the involved vehicles, many optimization goals based on harvesting conditions can be reached. In difficult weather conditions, the harvesters have to operate continually and only a good path finding of the chaser bins provide this. The path finding on huge fields can be ensured via a wireless communication network, that compute the best paths with the most minimal idle time of the harvesters. Usually, tractors with large power outputs and a consequently large fuel consumption are used for chaser bins. So, for normal weather conditions, the vehicles optimize their processes for different goals, e.g., the fuel consumption reduction or small carbon dioxide emission. In addition minimal routes can ensure an optimal usage of the bins and reduce soil compaction.

However, there is a tradeoff between the optimization goals of farming practices. Depending on the specific situation, the automation in the agricultural sector can reduce fuel consumption, the soil compaction, the time on field, the carbon emission and increase on the other hand the harvesting performance [4]. To enable this automatized farming practices, a new real-time communication technique on IEEE 802.11 is presented here.

B. *Real-time wireless networks*

In recent years, real-time wireless networks have become more and more common in the industrial sector. This trend originates by the flexibility of wireless connectivity and the reduced costs compared to wiring. Figure 2 shows a modified version of Tengs taxonomy of wireless real-time MAC standards [5]. Based on this taxonomy, wireless real-time networks are evaluated if they may comply with the needs to enable automation of agriculture. Below, the three most important points from agricultural perspective will be described.

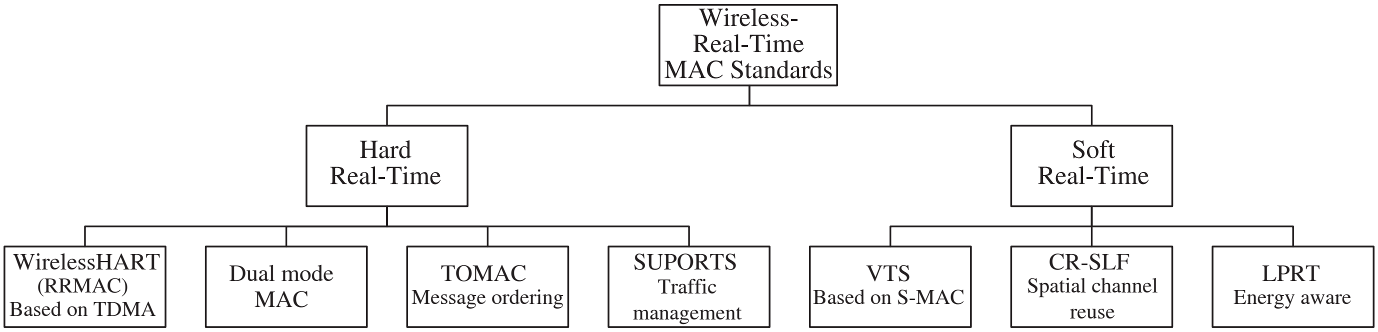


Fig. 2. Taxonomy of wireless real-time MAC Standards [5]

1) WirelessHART:
The seventh version of industrial networks, the Highway Addressable Remote Transducer (HART) standard has been extended in 2007 by a wireless protocol, the WirelessHART. The physical data transfer of WirelessHART is done by IEEE 802.15.4 for the 2.4GMz ISM frequency band with a frequency gap of 5MHz and with an emitting power of 10mW maximum. For modulation a DSSS with a pseudo random channel shift sequence is implemented to prevent interferences.

The upper network layer implements TDMA to ensure the requirements of hard real-time networks. TDMA requires the network to be set up every time when participants join or leave the network. The data security against data modification of WirelessHART is established by 128bit AES [6], [7].

Today, WirelessHART devices and applications are off-the-shelf solutions, which are already used for stationary industrial facilities. Due to the initialization of TDMA that occurs for every change in the number of participants, WirelessHART cannot be used for all kinds of devices that have positioning changes and that leave or join the network. Therefore, WirelessHART can only be used for farming practices like parallel cruise as shown in Figure 1(a), where vehicles can initialize synchronously together and do not leave the communication range. Practices like in Figure 1(b), where the chaser bin leaves the communication range of the harvester and enters the communication range of the truck, while driving towards the truck, cannot be implemented using this standard.

2) TOMAC:
Message Ordering Based Real-Time MAC (TOMAC) is an experimental MAC that guarantees hard real-time conditions in a distance of one hop. It is implemented based on the earliest deadline first method. Each message is assigned a priority that increases every μ seconds until the priority reaches a certain level when the message will be sent. For the physical transmission the standard IEEE 802.15.4 or IEEE 802.11a can be used.

The implementation of TOMAC for multiple Hops, mobile nodes or a dynamic number of nodes in the network, is not yet available [8], [9].

Higher layers on top of TOMAC influence the real-time ability. Due to this fact a possible application has to be implemented directly within or on top of the MAC layer. Essential functionality like end-to-end communication must also be implemented in the application due to the missing network and transport layer. As a consequence TOMAC does not fit the needs of implementation for agricultural practices.

3) VTS-MAC:
Virtual TDMA for Sensors (VTS) describes a MAC protocol, which dynamically adds and detracts nodes. VTS-Mac based on the sensor MAC (S-MAC) protocol. The original S-MAC protocol is used for the synchronization of the nodes. For establishing real-time conditions a virtual TDMA-structure is used. In contrast to the usual TDMA structure, that needs to know the number of nodes in the initialization process, the virtual TDMA allows dynamic numbers of nodes.

Because of the virtual TDMA, VTS-MAC is able to establish soft real-time behavior. VTS-MAC is an interesting technique for real-time communication for the agricultural sector, but the authors of VTS-MAC remark that VTS-MAC assumes a static network without moving nodes. The dynamic functionality is only designed to replace nodes e.g., when it has depleted its battery or the network is out of reach [10].

C. IEEE 802.11

In 1997 the Local Area Network Standards IEEE 802.1 up to IEEE 802.10 were extended by the Wireless Local Area Network Standard IEEE 802.11. This standard establish the basis for wireless network products, which use the radio spectrum for data transfer. All standards of the IEEE 802 family describe the two lowest layers, the physical layer and the data link layer, of the open system interconnection reference model for networking. The IEEE 802.11 defines two different basic service sets that enable the standard to build up different network architectures like, e.g., ad-hoc networks, hot spot networks and point-to-point networks [11], [12]. The physical transfer of the data is done in the 2.5GHz or 5GHz ISM frequency band with different modulation techniques like direct sequence spread spectrum (DSSS), frequency hopping spread spectrum or orthogonal frequency division multiplexing. In dependency of the alphabetical extension of this standard, the detailed specification of the techniques used in the data link and the physical layer, as well as their parameters, are given.

III. Real-time on IEEE 802.11

Today, the dominant wireless standards are IEEE 802.11, IEEE 802.15.1, 868MHz ISM, ZigBee and DASH7. Many of these wireless standards have routines for ad-hoc networks, dynamic routing, resp. dynamic routing over many hops or dynamic handle of joining and leaving nodes. Normally, these wireless standards provide round trip times (RTT) which are small enough to match the requirements of soft real-time conditions.

To be able to connect agricultural machines as described in Section II the machines have to be interconnected by a real-time network, which covers at least the requirements of soft real-time system. We describe their requirements later on.

Our main idea for fulfilling agricultural requirements is the design of a prediction function for the RTT between two nodes in the wireless network. Therefore, the automation application is able to take into account the reaction time of the wireless network before sending. Thus, the real-time constraints can be checked before the communication takes place. In case the RTT prediction exceeds these constraints the system or the agriculture vehicle switches into a safe mode, i.e., a non-automation mode, and gives the controls back to the driver. With such a predictor the necessary requirements of a soft real-time system can be reached.

Our goal is to maximize the number of correct predictions. As bounding conditions, to ensure soft real-time, we demand that the rate of false positive prediction should be at most 1%. In our case false positive prediction lead to a fatal system state because the predictor predicts a RTT that fulfill the real-time requirements, vehicles stay in the automation mode. But indeed the RTT does not fit these requirements and the vehicles should switch to the safe, non-automation, mode.

Here, we try to predict the RTT wireless standard IEEE 802.11b/g connections. An implementation of this approach on other wireless standards is also conceivable. The usage of IEEE 802.11p appears preferable in this agriculture scenario due to its maximal legal transmission power of 1W, its large transmission range and its high stability based on the usage of the otherwise little used 5.9GHz ISM frequency. However, IEEE 802.11p is only allowed to implemented car-to-car communication to increase traffic safety. Therefore, the p extension of IEEE 802.11 cannot be used [13]. Similarly preferable alphabetical extensions of IEEE 802.11 that e.g., providing quality of service or operating at sub GHz bands cannot be used due to other usage restrictions [11].

A. Applicability of IEEE 802.11

In a first test series we show the general applicability of IEEE 802.11b/g for soft real-time purposes. As a result RTT over many communications should be predictable. If this can be shown for the IEEE 802.11b/g standard, the requirements of soft real-time can be met in general.

For this test setup we measure the RTT of each transmission between two nodes with a small constant distance over two hours. We employ two off-the-shelf consumer hardware devices within a distance of 3m from each other as nodes

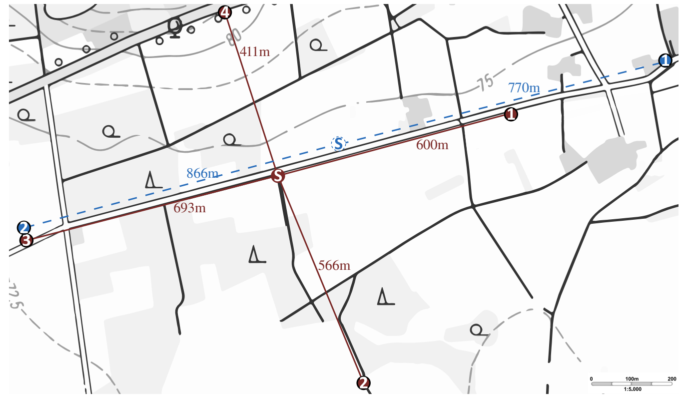


Fig. 3. Topographic overview of testing field for one test setup with two series of tests marked with red and blue dashed ink

and mesh these nodes with the ad-hoc network architecture. With a modified version of the Linux 'hping' command a 64bytes data package is sent via TCP to the other node within a repetition rate of 0.25s. Other data sizes were not tested, since the agricultural application needs a maximum data size of 64bytes.

While the average result shows a sufficient RTT of 10ms, many outliers with an RTT above 300ms are a serious setback. Such IEEE 802.11b/g RTT behavior does not match any real-time requirements. A closer investigation shows that the outliers appear periodically. To evaluate these results the same setup was rebuilt by replacing the consumer hardware by a embedded Linux distribution on industrial hardware. The result of this run showed a Gaussian distribution with a small standard deviation of the RTT around the averaged RTT of 4ms over all samples. These RTT values are capable to accomplish the requirements of soft real-time. Hence, IEEE 802.11b/g appears of be capable to fulfilling the necessary time restrictions for automation in agriculture.

Further test setup modifications show that the cycle time of periodical outliers heavily depends on which Linux distribution is used on the consumer hardware. Based on this observation we assume that some periodic routine in the non-embedded Linux distribution causes these outliers.

B. Factors influencing the RTT

The factors influencing the RTT are the base for our approach of real time communication on IEEE 802.11b/g. For this, we determine the influencing factors and how large their impacts on the RTT are. Based on theoretical consideration some factors like e.g., the distance or the signal strength have a higher influence on the RTT than others.

In two setups with several test series these theoretical expectations are investigated. As a simplification in the tests, one node is designated as the moving node and the other one as non-moving node. As seen in Figure 3, the mobile node is starting next to the non-moving node S, moves to the turning point, e.g., point 1, and moves back. During the test trips the actual RTT of each transmission and a bundle of possibly influencing factors were measured.

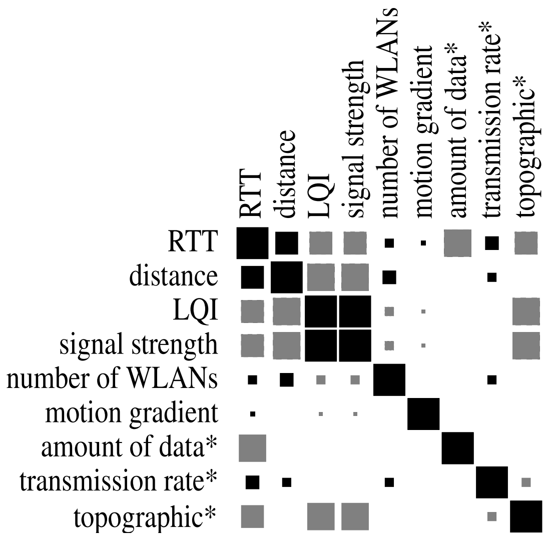


Fig. 4. Graphical correlation matrix of the most important factor on RTT. The size of the rectangle indicates the factor of correlation and the color gray indicate a reciprocal correlation. * correlation based on interpolated assumptions

We collected more than $8,000$ datasets over all test series and calculate the correlation of all factors. The correlation of the most important factors are presented as a graphical correlation matrix in order to identify factors with a direct connection on RTT. As seen in the graphical correlation matrix in Figure 4, a significant connection between RTT and, e.g., the distance between the nodes, the link quality indication (LQI) and the signal strength occurred. Figure 4 also shows the relation between each factor for example the expected relation between LQI and signal strength. Taking into account the relation between these factors, then only three independent factors have important influence on the RTT. The most important factor is the the amount of data followed by signal strength and the distance. In case that the amount of data is fixed to 64bytes, the algorithm for the predictor of the RTT relies only on the signal strength and the distance between the nodes.

To reduce measuring errors and other influencing factors, like weather conditions, these tests were run twice on two different days and showed almost the same results.

C. Guaranteed real-time based on signal strength

First, we implement a simple approach solely based on the signal strength. The measured points are represented in a three-dimensional space with distance, signal strength and RTT as dimensions. Based on this measured points a nearest neighbor interpolation is done. Regarding this interpolation a simple threshold function is defined. For example the required maximal admissible communication time between two nodes is 25ms. Thus, the resulting RTT is 50ms. The threshold of the signal strength is chosen as -75dBm. By using a threshold function we can only predict if the real-time condition is fulfilled or not. As a result of this very simple approach we reach 63% correct assertions and only 0.3% false positive assertions of the real-time property.

A further big disadvantage of this very simple approach is that the predictor cannot really forecast the future because the function depends on an actual measured value that is hard to forecast.

D. Guarantee real-time with signal strength, positioning information and driving direction

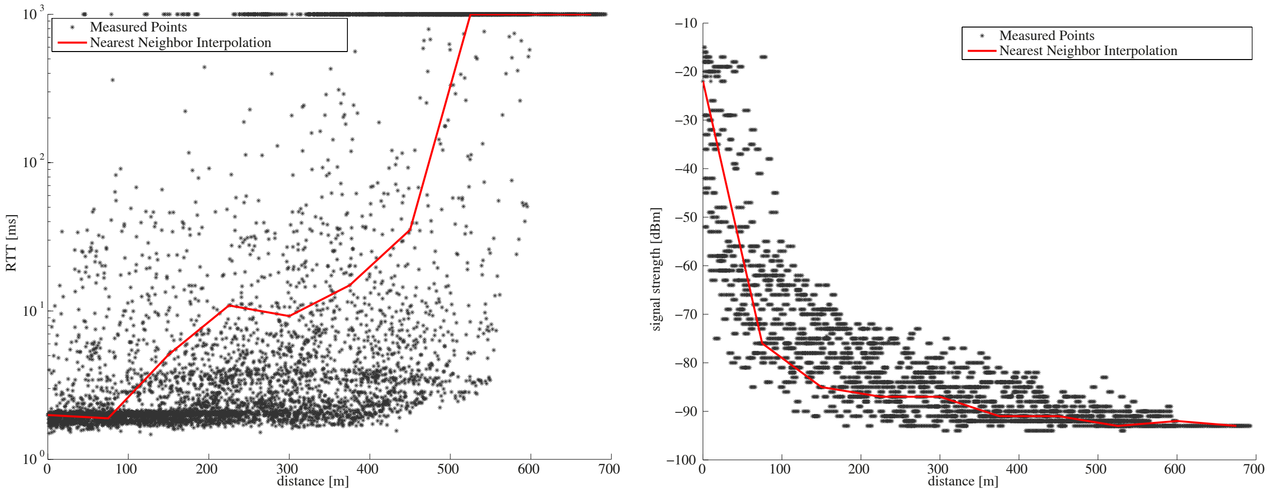
The extension of the above shown threshold function by using the distance improves the correctness of the results significantly. Through the extension by the distance there is a variable that can be predicted with a high accuracy in a limited period of time in future. The prediction of the distance between nodes at the time $t_n + t_p$ in t_p second in future, is based on the actual position information, the driving direction and the driving speed at time t_n. The exchange of the position information,driving direction and driving speed of each node can be done, for example, via ISM band on 868MHz or via IEEE 802.11b/g. Based on the coherence of RTT, signal strength and distance a threshold function was built that predicts the RTT 2s in the future. With this threshold function more than 64% of the predictions were correct and only 0.6% were a false positive. The false positive rate is higher than in the previous simple approach, but in contrast this approach is able to predict the future. The measured result of three different test series S_I to S_{III} using this threshold prediction function is shown in Table I. The quality of this function is heavily dependent on the predicted time span t_p in future.

TABLE I
POSITIVE AND NEGATIVE PREDICTIVE VALUES OF THREE TEST SERIES EXEMPLARY, DETERMINED BY A THRESHOLD FUNCTION USING THE SIGNAL STRENGTH AND DISTANCE BETWEEN TWO NODES

	t_p	t_n	f_n	f_p
$t_p =$	$2s$	$2s$	$2s$	$2s$
S_I	43.4%	16.9%	39.2%	0.5%
S_{II}	40.7%	28.0%	30.5%	0.8%
S_{III}	37.0%	27.5%	35.0%	0.5%

Up to now, the prediction function only predicts, whether the required RTT for the real-time communication will be violated or not. To get a RTT prediction in the range of milliseconds an equation is chosen that matches the nearest neighbor interpolation of Figure 5. By using Equation 1 a very good prediction of the RTT over all test series can be achieved. With the same real-time requirements as above 73% of the predictions are correct and the fatal false positive predictions not exceeding the critical 1% mark. Unfortunately, the coefficients $a, b, c \ldots, f$ of Equation 1 depend on the hardware with its components like antennas, transmission power and so the coefficients must be determined once[1]. The signal strength and the distance between the nodes is represented by v_P and

[1]Example values are $a = 520$ms, $b = 590$m, $c = 62.8$m, $d = 8,977,000$ms, $f = -121$dB, $g = 2.5$dB.



(a) (b)

Fig. 5. Measured points and nearest neighbor interpolation (a) RTT versus distance; (b) signal strength versus distance

$s_{A,B}$. Comparable to the predicted time span into the future the quality of this RTT prediction will be decreasing if the maximal communication time between nodes is close to the averaged RTT.

$$RTT = 4a \cdot e^{-\left(\frac{b-s_P}{c}\right)} + 4d \cdot e^{-\left(\frac{v_P - f}{g}\right)} \quad (1)$$

where $s_P = s_{A,B} + t_P \cdot \Delta s_{A,B}$ is the predicted location using the prediction time t_P and the vehicular speed $\Delta s_{A,B}$.

Summarizing this section we show that a prediction of the RTT based only on two easily available variables is possible. As a consequence soft real-time requirements of the application can be met, which enable the automation for the agricultural sector. Hard real-time requirements cannot be met, due to the fact, that our predictor still provides a small number of false positive errors.

IV. Experimental Evaluation in agricultural environment

The objective of this section is the evaluation of our novel technique to ensure soft real-time on mobile nodes and show its actual limits. For this, two extreme evaluation setups of the agriculture domain and the behavior of the RTT predictor are described. These extreme setups are based on real situations, which can occur in such a domain.

A. Shielding and reflection

The first evaluation setup describes a massive shielding suddenly appearing between the nodes. This setup describes a large empty clamp-silage that exists on many farms and through which one node is driving. In our evaluation setup the nodes are driving in parallel with a distance of 12m. After a while one node enters a clamp-silage with the dimensions of 3m height and 30m width.

Due to the reinforced concrete walls of the clamp-silage a strong impact via shielding and reflection on the IEEE 802.11b/g is to be expected. The evaluation shows that our approach fails with over 30% of fatal false positive predictions according to the RTT because in our case the nodes are getting the position and the driving information via 868MHz, which is not influenced by the shielding and reflection of the clamp-silage. Thus, this rate of fatal prediction must be reduced significantly before it can be used in any real-world application. Still, the fact that the nodes are not supposed to drive completely autonomously, a usage of our technique is still possible.

B. Topographic surface differences

From the present point of view the second scenario does not occur very often, whereas the target of the automation of agricultural are wide barrier-free fields. Most of these fields do not have large topographic altitude difference. The realization of this evaluation setup is the same as the test setup in Figure 3 but each series of evaluation has a topographic altitude difference of at least ±30m as shown in Figure 6.

In this evaluation setup the RTT is predicted as good as in the first test setup, so our technique appears to be applicable.

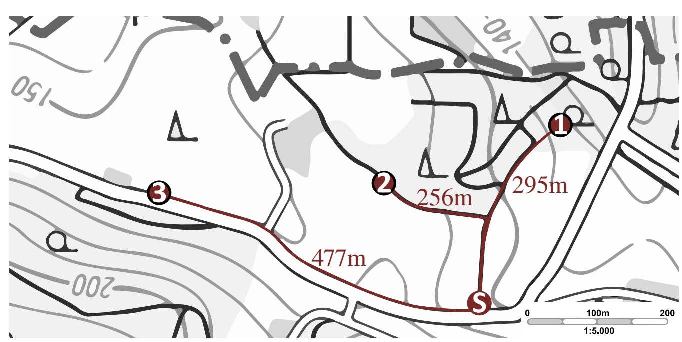


Fig. 6. Evaluation field with huge topographic surface differences

V. Result, Conclusion and Outlook

We introduced a novel technique to ensure soft real-time communication via IEEE 802.11b/g on mobile nodes, which is working in our prototype implementation better than expected. However, still more progress is needed before it can be used in practice. Due to the fact that we only make a prototype implementation to test the conceptual design of our approach, one next step in improving this technique is to use online learning algorithm to automatically adjust the prediction of the RTT to the real measured RTT. As a consequence, we expect a rising number of correct predictions and also an improvement in the shielding and reflection evaluation setup.

Another very important step is a non-prototypical implementation of this technique next to or in the TCP layer. Thus, an application gets only the information whether "the connection fulfills soft real-time" or not. This leads to a basic method, for which further larger tests and evaluation series need to be performed.

Based on our real-time wireless network approach, automation of agricultural vehicles is possible, which are necessary to manage the effects of the climate changes and to minimize the impact of the agriculture on global warming, in our opinion. But our approach enabling soft real-time communication on IEEE 802.11b/g is only a part of the automation of agricultural vehicle. Another important part is for example the computation, the planning and the management of the driving paths of each vehicle to reach the desired optimization that e.g., reduced soil compaction or full consumption.

For countries, where farming vehicles do not have expensive steering systems, a smart phone or a laptop application might support the driver to drive on the optimal driving lane to reach a optimization goals. Due to usage of standards in our approach, most of the smart phones and laptops fulfill the necessary hardware requirements to establish a soft real-time communication network. The challenges for implementations in this case, are the handling of the different hard- and software combinations, as mentioned in Section III and the limited computational power of the devices.

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