Agriculture meets IEEE 802.11p: A Feasibility Study

Florian Klingler, Johannes Blobel, Falko Dressler
Distributed Embedded Systems, Heinz Nixdorf Institute and Dept. of Computer Science
Paderborn University, Germany
{klingler, blobel, dressler}@ccs-labs.org

***Abstract*—Recent trends towards autonomous driving are complemented by vehicular networking solutions, leading to what we now call cooperative autonomous driving systems. This trend is quite visible to the public in the automotive domain; however, only few know about the massive technological progress in the agricultural world. Here, autonomous driving, i.e., automated harvesting, etc, is already standard and early approaches to cooperative maneuvers have been brought to market already. The open question is how to internetwork all heavy machinery. We address exactly this issue and study the feasibility of wireless communication protocol stacks, in particular IEEE 802.11p, developed for use on the road – now for in-field operation. We performed an extensive measurement study, which brings up several quite interesting findings that need to be taken care of when adopting these protocol stacks to agricultural applications.**

I. Introduction

Wireless communication in the area of vehicular networks already has quite some history. Since almost two decades, protocol stacks have been designed, investigated, standardized, and even commercialized [1], [2]. The most popular standards include ETSI ITS-G5 [3] in Europe and IEEE 1609 WAVE [4] in the U.S., both building upon IEEE 802.11p WLAN [5]. The most prominent day one application in automotive use cases is cooperative awareness [6], [7], in which vehicles periodically broadcast small messages – called beacons – containing their current mobility information, which help receiving nodes to assess safety constraints and to react upon this outcome. Potential use cases benefiting from cooperative awareness are intersection collision avoidance [8] and platooning [9]. Intersection collision avoidance is about having vehicles adjusting their driving behavior at intersections to avoid risky situations and to improve the travel performance by either (semi-)automatically slowing down or accelerating. In platooning, vehicles use received status information to periodically adjust their speed and acceleration by using a distributed control algorithm in order to be able to drive on a highway with very small inter-vehicle distance. This will allow a better utilization of the highways road capacity and allows the human driver to relax on the road.

Automated driving is not only a active research field for traditional vehicles, but also actively investigated and now deployed in the agricultural domain. Here, self driving tractors are already available on the market, and the logical next step is to add wireless communication among these tractors to allow even complex cooperative driving maneuvers. This could range from transmitting telemetry information about the fill level of a trailer up to periodical mobility information to coordinate driving maneuvers involving several vehicles – either longitudinal similar to traditional platooning, or lateral to automatically move a trailer next to a tractor.

Many research issues for platooning, e.g., basic communication protocols and the underlying communication channels [10] or the selection of a fitting beaconing interval [11], have already been addressed in traditional vehicular networks and promising solutions exist. Intuitively, it would be straightforward to apply findings for efficient wireless communication from the vehicular domain to the agricultural domain.

However, there is a fundamental difference between traditional vehicles and agricultural vehicles: Their size and shape. In the past, many works in the literature focused on signal propagation and fading effect for a multitude of different scenarios and configurations [10], [12], [13]. Consequently, from such measurements many simulation models have been developed which take advantage of path loss and shadowing effects in vehicular scenarios [14], [15]. Due to the inherent different mobility and characteristics of agricultural vehicles, e.g., tractors, these models are not directly suitable to be used in agricultural scenarios. To the best of our knowledge there is no prior work, which focuses on signal propagation characteristics of IEEE 802.11p in agricultural domains.

IEEE 802.11p WLAN [5] offers a dedicated frequency spectrum for Intelligent Transportation System (ITS) in the 5.9 GHz band. A higher transmission power ([3]) than usual WLAN in ISM bands allows robust communication covering several hundred metres up to a few kilo meters depending on the environment. Furthermore, the Outside the Context of a BSS (OCB) mode available for IEEE 802.11p allows a node to immediately transmit information to nearby nodes without prior association to a BSSID, which further reduces communication delay and increases stability.

In order to assess its applicability in the agricultural domain, we performed an extensive measurement study on the field. We particularly focused on radio signal propagation and its impact on important network metrics like goodput and delay for typical harvesting maneuvers in the agricultural domain. We believe that the outcome of our study will help to better understand the impact of individual characteristics of agricultural vehicles and their driving maneuvers on the wireless signal propagation, thus, helping to develop adopted protocol stacks and giving guidelines for antenna placements.

Our main contributions can be summarized as follows:

- We first investigate typical application scenarios and derive requirements and relevant metrics for wireless communications on the field (Section II),
- we prepared a measurement setup and validated the system in an initial rather simple measurement campaign using a harvester and an additional tractor (Section III), and
- we finally performed some realistic harvesting maneuvers and studied the signal propagation characteristics in this scenario to get a more detailed picture on IEEE 802.11p application in agricultural environments.

II. IEEE 802.11p in Agriculture

In this section, we summarize application requirements and challenges for vehicle-to-vehicle communication in the agricultural domain. These requirements will allow us to derive a set of metrics on which we focus in our measurement campaign to evaluate the feasibility of IEEE 802.11p in various on-field scenarios. We also briefly introduce our measurement setup and prototypes used to perform the measurements.

A. Application Scenarios and Requirements

Platooning (or coordinated driving in general) is probably the most prominent application for agriculture vehicles which can benefit of communication between vehicles [16]. The core idea is to build a distributed control system to allow one or more vehicles to follow others with a very small inter-vehicle distance. Advantages of platooning in the agricultural domain is twofold: First it allows coordinated automated driving with a constant distance to a vehicle in front or beside. Secondly, additional meta data (e.g., fill status of a trailer) can be communicated. To accomplish the formation and maintenance of platoons, strict requirements on the underlying communication technology are necessary to deliver needed control to nearby vehicles in time.

Often, a periodic update rate of 10 Hz is cited for platooning to achieve string stability [17], which leads to an average generated traffic of 64 kbit/s per vehicle assuming a frame size of 800 Byte. Although this value seems to be rather small for modern wireless networks, it does not scale well when the amount of communicating nodes is high. Assuming a node density of just 30 vehicles within communication range, each transmitting 800 Byte frames at 10 Hz, this leads to a traffic rate of 1.92 Mbit. These limitations become even more critical when using, e.g., video streaming to get a better overview of the vicinity of the remote vehicle. Here the required data rate easily gets in the range of several Mbit/s.

Overall, a core aspect of cooperative assisted platooning is to deliver information *(a)* in a timely manner and *(b)* with a (very) high success probability.

B. Network Metrics

In the following, we outline the three main metrics we have chosen to evaluate the performance of wireless communication in the agricultural domain.

1) Received Signal Strength (RSS): To measure the received signal strength at a certain distance from the transmitter, we take advantage of the information included in the radiotap header of each received frame from the wireless card. For this, we broadcast a predefined number of frames with a given Modulation and Coding Scheme (MCS) and include the GPS information of the transmitter (longitude, latitude, GPS time) in each frame. At the receiver, we record this data together with the GPS information of the receiver and the perceived signal strength stored in the radiotap header of each frame. As we also know the number of transmitted frames, we can calculate the Packet Delivery Ratio (PDR) as $r_{\text{PDR}} = \frac{\text{\# sent frames}}{\text{\# received frames}}$. This way, we get a good estimate about the path loss at a certain distance as well as the fraction of lost frames.

2) Delay: To get an indication about the delay for unicast communication employing retransmission at the Medium Access Control (MAC) layer as well es potential retransmissions at the transport layer (e.g., TCP), we take advantage of the tool Sockperf.[1] This tool allows us to measure the communication delay under load for both UDP and TCP traffic. The operation of Sockperf is as follows: The sender saturates the wireless channel with either UDP or TCP traffic and asks the receiver to reply with a frame for a small portion of the packets. For each reply, the timestamps are recorded, which allows to derive a one-way delay from the measured round trip time.

3) Goodput: Another important metric is the application layer throughput, which is influenced by the selected MCS of the rate selection algorithm of the sender, as well as the number of dropped packets at the receiver due to bit errors. We use iperf to saturate the wireless channel with either TCP or UDP traffic and measure the received data. For our measurement platform, we used ath9k based wireless cards, which use the Minstrel rate selection algorithm[18] implemented in the Linux kernel.

C. Measurement Approach

We are interested in the performance of wireless communication for different distances between sender and receiver and selected driving maneuvers of sender and receiver. Therefore, our measurement framework supports two different types of experiments.

Static: Sender and receiver have a static position and do not move during the recording of the metrics. When the measurement is successfully finished, both nodes can move on to the next position. For this measurement type, all metrics can be recorded. One use case for this type could be along a street with a measurement point every few meters or around a circle where the transmitter (or receiver) stays in the middle and every few degrees a measurement point is taken.

Dynamic: Both sender and receiver can be mobile in this type of experiment. Here, we can only record the received signal strength of each received frame. This allows us to determine the impact of, e.g., obstacles during driving maneuvers on the received signal strength. Evaluation of other metrics in a

[1] https://github.com/Mellanox/sockperf

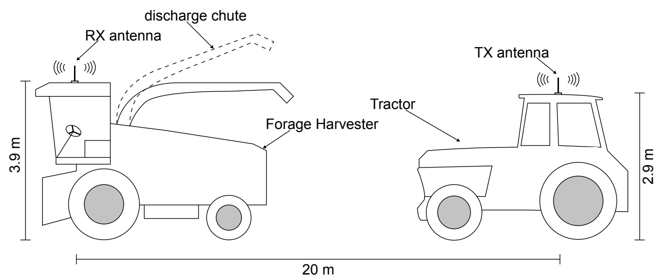


Figure 1. Overview of the used vehicles and the position of the antennas.

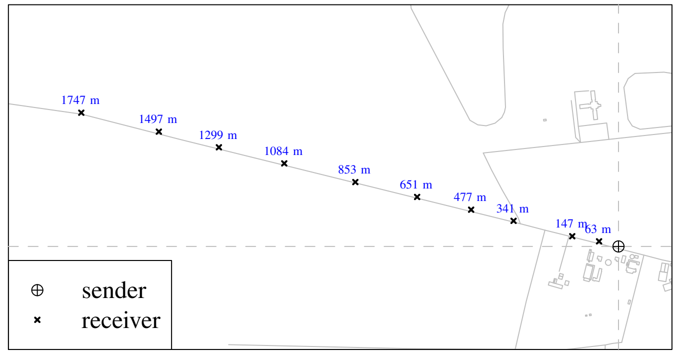


Figure 2. Map of our validation scenario including all measurement points.

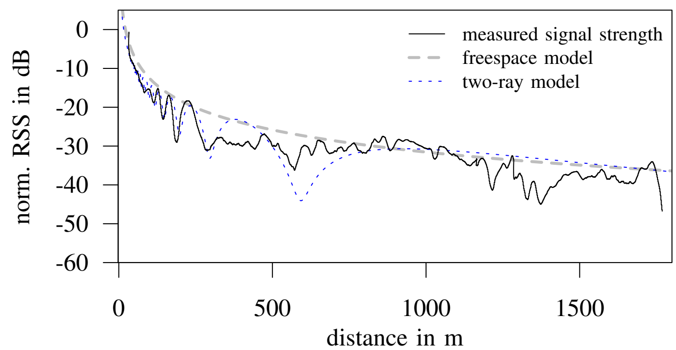


Figure 3. Signal strength of dynamic measurements in line scenario.

dynamic measurement is problematic since the rate selection algorithm of the wireless card also takes time to determine the best transmit data rate. This would falsify our measurement results.

For our measurement campaign, we used two embedded Linux nodes running a orchestrated version of the OpenC2X [19] software stack. In particular, we used PC Engines APU2,[2] which offer a quad core 64 bit CPU together with 4 GB of memory, an MSATA slot for an SSD, and two mini-PCIe slots for wireless cards. As wireless cards, we used Mikrotik R11e-5HnD[3] high power 5 GHz cards. These cards use a wireless chip supported by the ath9k Linux driver and offer a specified maximum output power of 27 dBm. We extended the ath9k Linux driver of OpenWrt 17.01.4 to allow operation in the 5.9 GHz band [20] and adjusted the maximum available transmit power to correspond to the ETSI ITS-G5 standard [3]. Moreover, we allowed all available data rates (3, 4.5, 6, 9, 12, 18, 24 and 27 Mbit/s) to be selected by the rate control algorithm. In particular, we configured a frequency of 5.890 GHz using a channel bandwidth of 10 MHz. As antennas, we use a Mobile Mark ECOM9-5900[4] omni-directional roof-mount antenna for each sender and transmitter, each having a antenna gain of 9 dBi.

In order to measure the performance of IEEE 802.11p in the agricultural domain, we installed our measurement hardware on a self-propelled Claas Jaguar forage harvester and a John Deere tractor. The forage harvester was equipped with the RX-part of our framework while the TX counterpart was installed on the tractor. With this setup, we conducted multiple dynamic and static measurement campaigns in order to measure different characteristics of the system on the field.

III. Validation: Line Scenario

The first scenario was a line scenario in order to validate the measurement framework and to evaluate the distance that we can achieve. In this scenario, the tractor (TX) was placed on a fixed position and was sending with maximum possible transmit power supported by the hardware while the forage harvester (RX) moved away stopping at multiple measurement points on a straight road (cf. Figure 2). At each measurement point, multiple static measurements were conducted.

[2]https://www.pcengines.ch/apu2.htm
[3]https://mikrotik.com/product/R11e-5HnD
[4]https://www.mobilemark.com/product/ecom9-5900/

After the static measurements, the forage harvester was driving back towards the tractor with a constant speed of 2 km/h. During this drive, we conducted dynamic measurements.

A. *Received Signal Strength*

Figure 3 shows the results from the dynamic measurements. The black line shows the actual measurements of the RSS, the grey dotted line shows the expected values for a freespace model (using a fitted path loss exponent $\alpha = 1.9$) and the blue line shows the two-ray model [15]. After 1700 m, the road took a slight turn to the right, after which we lost line of sight and were not able receive any packets.

B. *Delay and Goodput*

The results of our delay and goodput measurements are shown in Figures 4 and 5. We use the RSS on the x-axis instead of the distance to normalize the measurements. The plots show the median of delay and goodput and are surrounded by the 25 % and 75 % quartile. It can be clearly seen that TCP has a much higher delay compared to UDP, which is expected as TCP has additional retransmissions in case of packet loss.

The drop in delay at −11 dB comes from the Minstrel rate adaption algorithm of the wireless driver, which switched to another MCS at this point. Thus, two measurement points were taken at distances of 650 m and 341 m, which have a similar RSS. In one case, the rate selection algorithm has chosen a better modulation scheme for this particular RSS, which explains the different delay values.

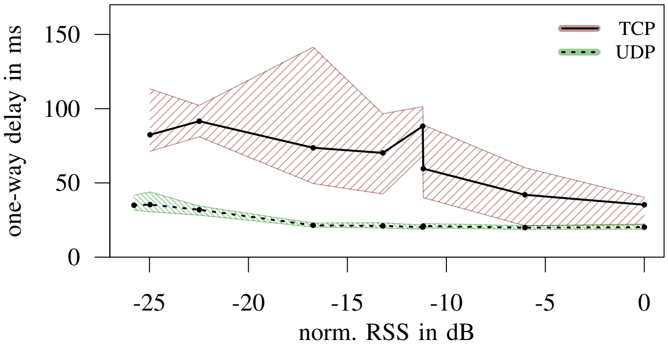


Figure 4. Delay of TCP and UDP traffic in line scenario.

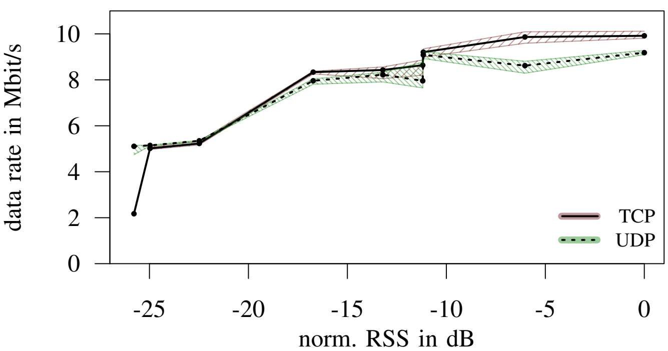


Figure 5. Goodput of TCP and UDP traffic in line scenario.

Figure 5 shows the goodput (application layer throughput) of the static validation measurements. UPD and TCP show similar performance even though TCP is slightly better for higher RSS values. This is the case since we have to use fixed packet sizes for UDP while TCP always fills a datagram to the Maximum Transfer Unit (MTU). The spike at −11 dB is again a result of the rate selection algorithm.

Please note that we observe that the maximum achievable data rate is below the theoretical data rate of around 14 Mbit/s in the validation scenario, which could be caused by distortions of the WLAN amplifier when using the maximum transmit power configurable in the ath9k driver. We thus lowered the transmit power in the following experiments.

C. Received Signal Strength with reduced transmit power

We finally performed a set of experiments with reduced transmit power (to around 10 dBm) and repeated the dynamic measurements. The sender was kept at its fixed position and the receiver was slowly driving away, turning and then driving back. Figure 6 shows the results of these two drives. The gray solid line shows the measurement results when driving away from the sender and the black line shows the results when coming back. As can be seen in the plot, there is a difference of 5–10 dB depending on the orientation of the forage harvester, which we investigate in more detail in the next set of experiments.

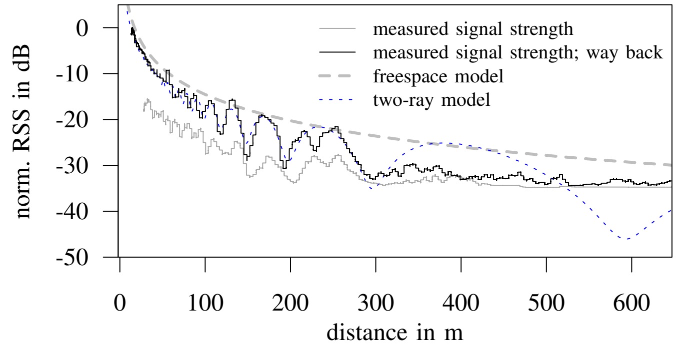


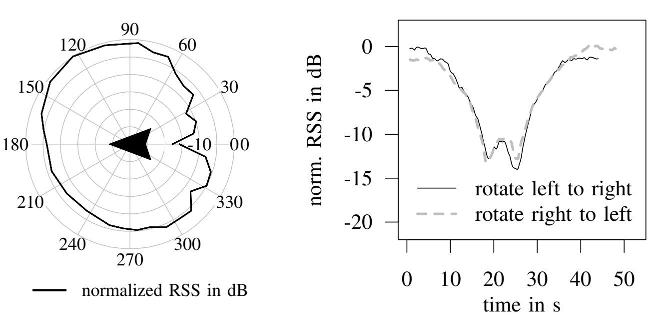
Figure 6. Signal strength of dynamic measurements with reduced transmit power in line scenario.

IV. Shadowing: Circular scenario

The previous measurements suggested that the large back of the forage harvester its discharge chuteseem to have an impact on the signal propagation. To further validate this assumption, we conducted measurements of the antenna pattern and the influence of the discharge chute. We executed three scenarios where the forage harvester (receiver) was placed on a fixed position on a field. In the first experiment, the sender was moved to different positions on a circle with a radius of 20 m while the orientation of the tractor was always in the same direction. The results of this experiment are shown in Figure 7a. It can be seen that when standing behind the forage harvester the RSS is reduced by 17 dB.

For the second experiment in this scenario, the tractor was placed behind the forage harvester at a distance of 20 m. We then put the discharge chute to its highest position and let it rotate from the rightmost to the leftmost position and back. Figure 7b shows the results of this experiment. The influence of the discharge chute can be clearly seen as it traverses the line of sight path between sender and receiver. If it is directly between the sending and receiving antenna, the RSS drops by 14 dB.

Finally, we where driving with the tractor along the circle with a constant speed of 2 km/h. Additionally, we changed the height and the angle of the discharge chute in additional measurements to evaluate its influence. The results are shown in



(a) Antenna pattern (b) Signal strenth

Figure 7. Impact of discharge chute of forage harvester on RSS

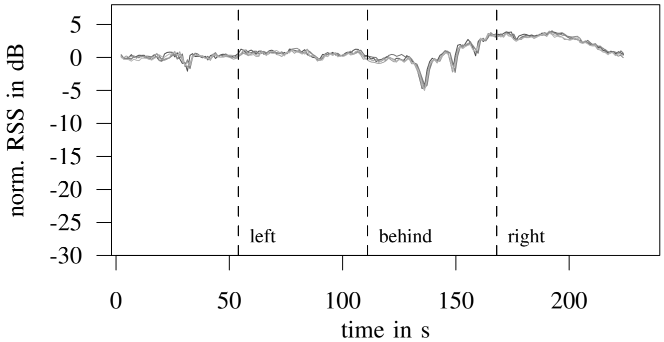


Figure 8. RSS while driving around the forage harvester with the discharge chute at its lowest position.

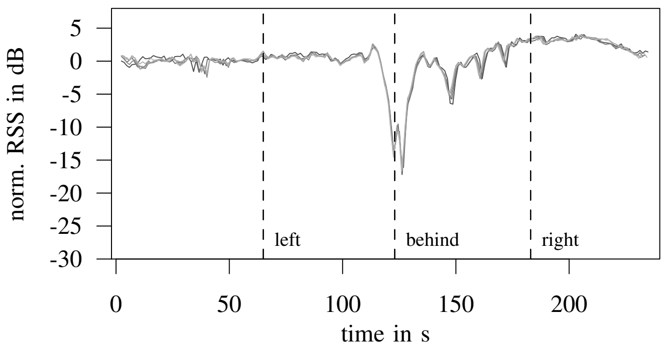


Figure 9. RSS while driving around the forage harvester with the discharge chute elevated.

Figures 8 and 9. If the discharge chute is at its lowest position the shadowing effect at the back of the forage harvester is rather small. If it is in the elevated position, the same drop in RSS can bee seen again. Also, the asymmetric pattern of the antenna shown in Figure 7a is visible in the measured data.

V. Realistic Harvesting Scenario

To measure the wireless performance in a realistic harvesting scenario, we focused on a typical loading/unloading scenario involving three vehicles (cf. Figure 10). Figure 11 shows the trajectories of the sender and the receiver, where on the marked

Figure 10. Picture of an overtaking maneuver in the harvesting scenario.

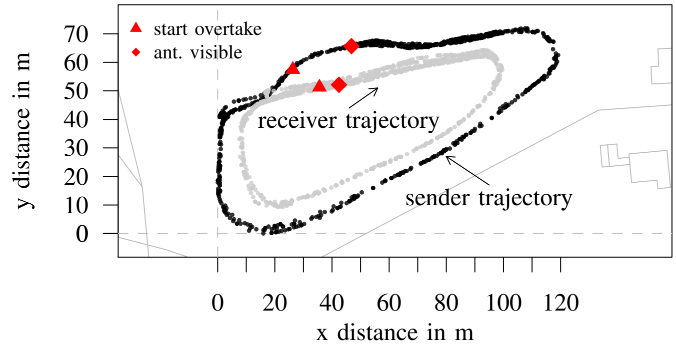


Figure 11. Position traces of all three vehicles in the harvesting scenario.

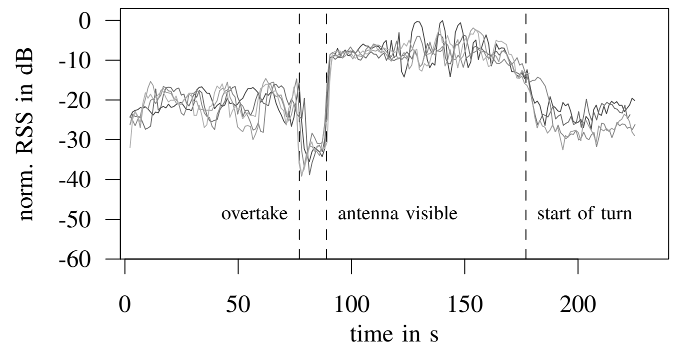


Figure 12. Received signal strength in the harvesting scenario.

points a overtake of one vehicles takes place. During the overtake a tractor with a trailer drives from behind in between the sender and the receiver. The position when the antennas of receiver and transmitter are within LOS again is also marked.

For the results of the received signal strength, we expect a sudden drop of the RSS during the overtake process, and again a increase of the signal strength when the antennas have LOS again. Indeed, we can clearly see this effect in Figure 12. We observe a difference of up 30 dB when the antennas are within LOS again. Two different shadowing effects can be seen in this plot: the shadowing of the third tractor with a trailer in between the sender and the receiver (which causes the drop at the "start of turn" point) and the additional shadowing due to the discharge chute during the overtaking maneuver.

VI. Conclusion

In this paper, we studied the feasibility of using IEEE 802.11p in the agricultural domain. Our results show that there are no major problems using this vehicular networking protocol stack developed for automotive applications. The range that can be covered is clearly sufficient, especially since there are typically no major obstacles such as buildings on an open field. However, the size of the harvesting machines and additional mechanics as the discharge chute have a huge impact on the RSS as indicated in our measurement results. This has to be taken into account when designing communication systems for agricultural vehicles. A possible countermeasure could be the use of multiple antennas at different positions on the vehicle.

Our results also show that TCP is not suitable for the envisioned inter-vehicular communication applications as it substantially increases the experienced delays.

In future experiments, a large number of additional effects could be investigated. The experienced two-ray propagation of the radio signal is likely to be different on a solid road than compared to an empty field or when the field is covered with plants. Also during the harvest, there is a lot of moist dirt in the air, which could additionally attenuate the radio signal.

VII. Acknowledgements

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