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Comparing Selected Sub-GHz Transceivers – Results from the Field

Benjamin Häring, Dimitri Häring, Lukas Reifler, Fabian Schaltegger and Andreas Rüst
Zurich University of Applied Science (ZHAW)
Institute of Embedded Systems (InES)
Winterthur, Switzerland
andreas.ruest@zhaw.ch

***Abstract* — Various chip vendors are offering proprietary Sub-1 GHz RF transceivers with an attractive balance between long communication range and low-power consumption. While datasheets reveal many interesting parameters, it is difficult for users to assess performance, robustness and power consumption of such transceivers for a specific application. Furthermore, it is a challenge to determine the appropriate parameter settings for each of the chips. The paper presents measurement results from a several months long field trial featuring selected transceivers from five different chip vendors.**

Keywords* — *Sub-GHz, LPWAN, IoT, Wireless Sensor Networks

I. INTRODUCTION

State-of-the-art Sub-1 GHz RF transceivers promise to combine low-power operation with high link budget and therefore long communication range. Compared to widely used wireless technologies in the 2.4 GHz band, like Bluetooth Low Energy, Sub-1 GHz offers better wave propagation properties. This is due to the lower transmission frequency. However, a user has to make application-specific tradeoffs between range, throughput and power consumption. While lowering the bit rate may increase the achievable range, it usually also lengthens transmission time and therefore power consumption. Likewise, a user has to set many interdependent parameters on a transceiver, often without knowing the direct effect on performance.

The presented project has evaluated selected transceivers from five different chip vendors for a precision farming application. Specifically the application connects sensors requiring a medium amount of data in vineyards. In the designed set of experiments a central gateway repeatedly connects to wireless nodes placed at different distances in the vineyard. For each transmission, key parameters of the transceivers are set to one of various predefined settings. Resulting performance figures like packet error rate and received signal strength indicator (RSSI) value are recorded for each experiment. The experiments have been conducted over a period of several months. Therefore, it is possible to assess potential external influences, including weather conditions.

The paper presents the obtained measurement results complemented with power consumption measurements. In addition, the paper illustrates the lessons learned during the hardware and firmware design for the individual transceivers. It points out strengths and weaknesses of the evaluated transceivers with regard to specific application areas. The qualitative and quantitative results presented shall support other users in the selection of an appropriate transceiver for their application. Furthermore, they shall facilitate the transceiver-specific choice of an appropriate parameter set fitting the targeted application.

This paper is structured accordingly. We begin by describing the setup of the field test. This includes the test hardware, the test sequence as well as the test parameters. We continue by outlining the scheme used to present the results of the link quality measurements. In the fourth section we present the results of our link quality measurements followed by the results of the power measurements in section five. In the sixth section we summarize strengths and weaknesses for the evaluated transceivers. This is followed by lessons learned in section seven. We end with appropriate conclusions.

II. THE FIELD TEST

The described test setup has been installed in a vineyard in Truttikon (ZH). It has been operational since November 2016 when the first transceivers were deployed. Gradually, over time more types of transceivers have been added. The full setup as described in this paper was attained in June 2017. It has been operational since then till the present date.

A. *Test Setup*

Fig. 1 shows the basic structure of the field experiment. A link quality test is implemented with „Ping-Pong"-message sequences. A central node (B) sends „Ping"-messages to the individual field nodes (Nx) and subsequently receives their responses in the form of „Pong"-messages. Received signal strength and the number of transmitted and received packets are both logged on a server. Packet error rate (PER) is calculated based on these figures.

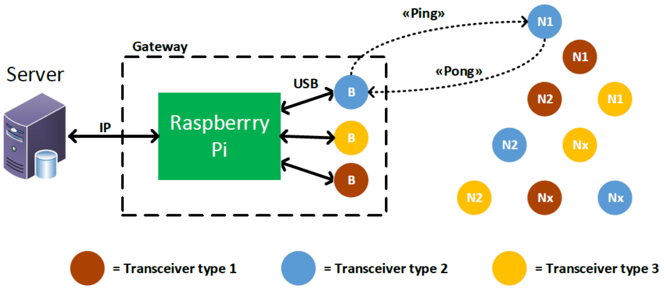

Fig. 1. Test setup in the field

The individual nodes are placed in the field at slightly elevated positions (Fig. 2) to enable favorable receive conditions.

Fig. 2. Nodes in the field in different seasons

As shown in Fig. 3, the rows of nodes are arranged at distances of 35 m, 115 m, 150 m, 180 m, and 200 m. The colors of the pins represent the type of the transceiver. One instance of each transceiver type is placed in each row. The measurement results can thus be compared for the different distances.

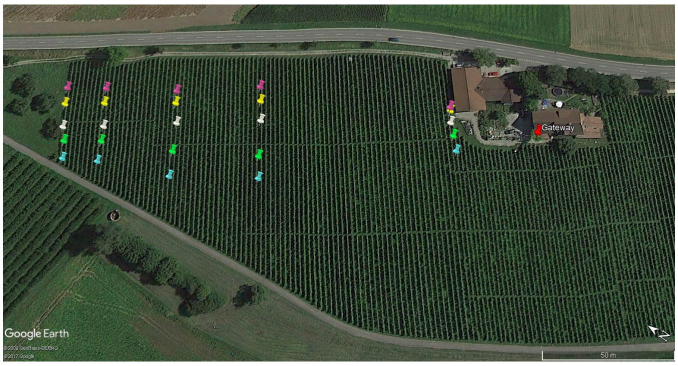

Fig. 3. Placement of gateway and nodes in the field

B. *Test Hardware*

The transceivers evaluated in this paper have been selected as their interesting features made them potential candidates for a specific precision farming application. When the project started, this application was in an early development stage from the sensor point of view. Specifically, the exact requirements for the bit rate could not yet be defined at that moment in time. Therefore, the presented evaluation has been started to support the selection of a transceiver at a later time.

All selected transceivers had to be standalone, i.e. no Systems-on-Chips with an integrated microcontroller. Porting the measurement application to individual microcontrollers would have caused additional development overhead. Furthermore, the power consumption of the microcontroller part would have made it difficult to assess the power consumption of the transceiver part.

Test nodes had to be designed for each transceiver type. In fact, for each transceiver type the same hardware has been used for the individual nodes (Nx) as well as for the central node (B). Each test node includes a Nucleo STM32 microcontroller board from STMicroelectronics [1].

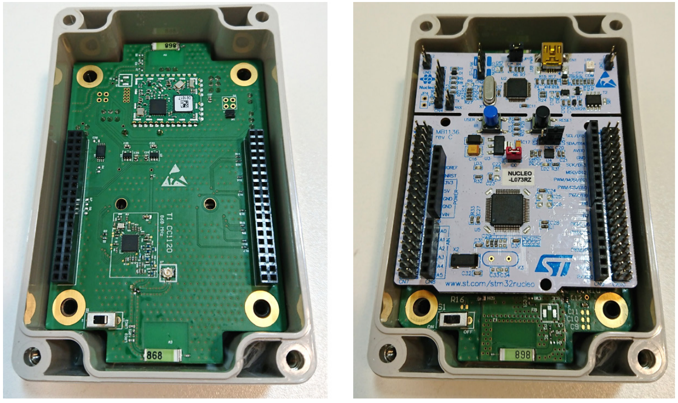

Fig. 4. Test nodes once without and once with Nucleo microcontroller board

The firmware on the microcontroller contains an application that can be controlled either through a LoRa transceiver module [2] (in case of the field nodes) or through a USB interface (in case of the central node). The same application is running on all the nodes. This is facilitated through the definition of a common transceiver API (application programming interface). A unique firmware layer has been written for each transceiver type to adapt the driver of the transceiver to the common API.

C. Test Sequence

The field nodes are programmed to wake-up in regular intervals. They connect to their central node through LoRa. The central node answers on LoRa by sending the parameters and the starting time of the next test run. Thus the field node knows when to listen for the first "Ping"-message. The central gateway then sends a sequence of 10 "Ping"-messages. After each one it waits for the associated "Pong"-message. The test is repeated at different times of day. Overall packet error rates and average RSSI values are calculated over several days or weeks.

D. Test Parameters

The tests have been carried out with different FSK parameter settings. Particularly, individual combinations for bit rate (BR) and frequency deviation (f_{dev}) have been chosen. Using equations (1) and (2) respectively the modulation index (η) and the bandwidth (BW) can be approximated [3].

$$\eta = (2 * \mathrm{fdev}) / \mathrm{BR} \qquad (1)$$

$$\mathrm{BW} = 2 * (\mathrm{fdev} + \mathrm{BR}) \qquad (2)$$

This paper will focus on the results for 10 distinct FSK parameter sets, up to a bit rate of 40 kbps. The parameter sets are summarized in TABLE I.

TABLE I. FSK PARAMETER SETS IN FIELD TEST

Nr.	**BR [kbps]**	**f_{dev} [kHz]**	**η**	**BW [kHz]**
1	2.5	1.25	1	7.5
2	2.5	2.5	2	10
3	2.5	5	4	15
4	10	5	1	30
5	10	20	4	60
6	10	45	9	110
7	33	33	2	132
8	40	20	1	120
9	40	40	2	160
10	2.5	50	40	105

Although further data is available, this paper will focus on the results for a transmit power P_{TX} = 7 dBm. Clearly, higher link quality results (i.e. lower PER) can be achieved if transmit powers above this chosen setting are applied. However, the goal of the presented test results is to reveal performance limits. Likewise, at 7 dBm differences between transceiver types as well as between parameter settings emerge.

III. PRESENTATION SCHEME FOR LINK QUALITY

The results for link quality will be presented individually for each transceiver. This chapter explains the uniform scheme used. Additionally it provides guidance on how to read and interpret the presented results.

The presented plots attempt to display the relationships in a single graphic. First the plot in Fig. 5 introduces the influence of bit rate and frequency deviation on sensitivity. Usually, FSK transceivers achieve the highest sensitivity in the green region 1 with a low bit rate and a low frequency deviation. An increase of either the bitrate or the frequency deviation results in a lower sensitivity. This is represented by the yellow areas. Furthermore, the simultaneous increase of both parameters leads to an even lower sensitivity. This is shown by the red area.

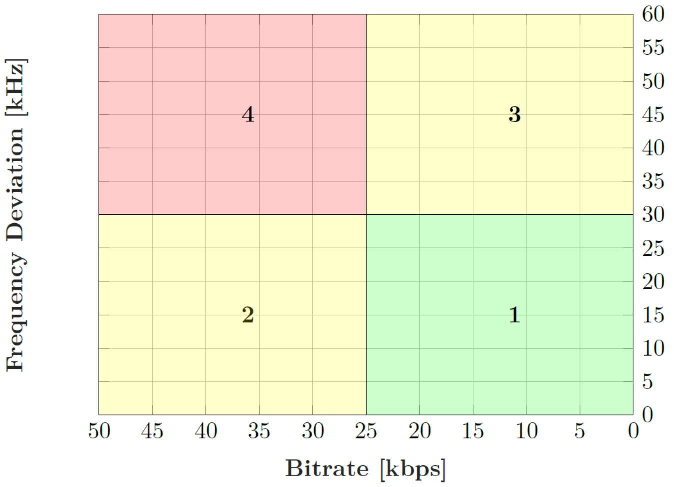

Fig. 5. Regions of transceiver sensitivity depending on bit rate and frequency deviation

Next we add the third dimension to the plot. This is the distance between gateway and node. Finally we encode the resulting Packet Error Rate (PER) with a color and display it as a colored dot. We can therefore display the PER as a function of the three input parameters bit rate, frequency deviation and distance. As an example, the fictive results for two configurations are plotted for five nodes in Fig. 6.

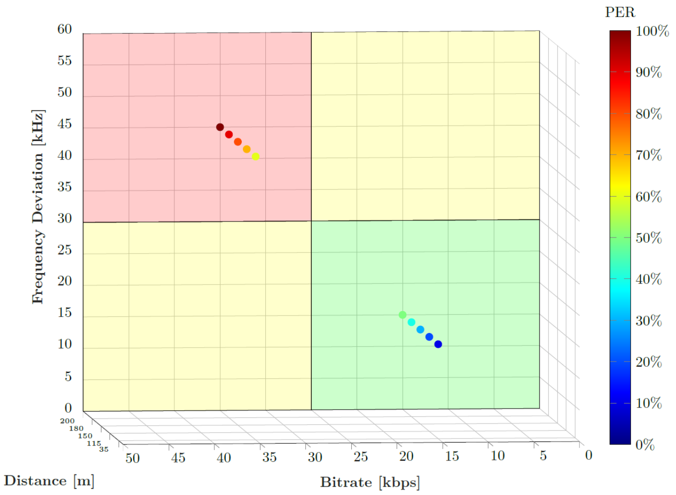

Fig. 6. Fictitious example showing the calculated PER as a function of the three input parameters bit rate, frequency deviation and distance.

The first configuration is 15 kbps with a frequency deviation of 15 kHz. As the distance increases, the fictitious PER increases from 10% to 50%. In the second configuration at 35 kbps and a frequency deviation of 45 kHz, the PER increases from 60% to 100%.

IV. LINK QUALITY RESULTS

This chapter presents the results for the individual transceiver types.

A. *Microchip MRF89*

Fig. 7 shows PER results for the MRF89 transceiver of Microchip [4]. The tests have been performed using Microchip's MRF89XAM8A module with an integrated PCB antenna [5].

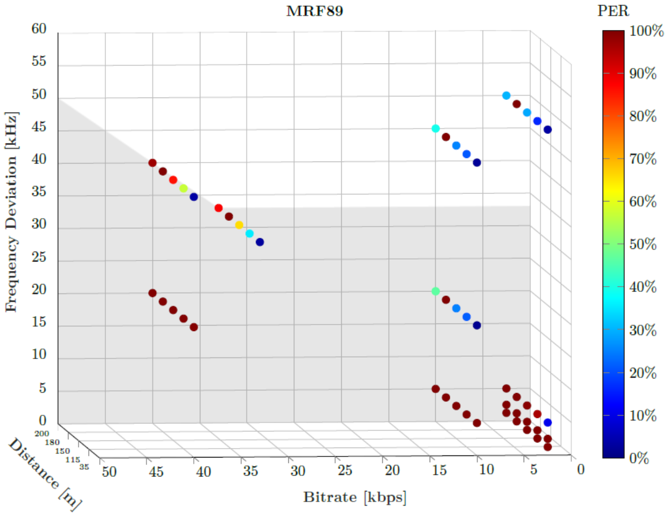

Fig. 7. Packet Error Rates for Microchip MRF89

The MRF89 transceiver has two significant limitations. First, Microchip guarantees the functionality of the MRF89 only for frequency deviations between 33 kHz and 200 kHz [4]. The second limitation is that the modulation index must not be chosen lower than two. Indeed, most of the defined FSK parameter sets lie outside of these limiting specifications (see gray area in Fig. 7).

In general, the PER increases with higher distances between node and base station. This behavior corresponds with the theoretical assumptions. The two configurations on top right are within the specified parameter range of the transceiver. On these settings, successful links with packet error rates of less than 30 % (depending on the distance) are reached. The node located at a distance of 180 m is not able to successfully transmit/receive packets independent of the used settings. Similar behavior of the nodes at 180 m can be seen with other transceivers as well.

On the FSK parameter sets number 1 to 4, the frequency deviation is significantly lower than 33 kHz. Almost all packets are lost using these configurations. The parameter sets 5 and 8 both use a frequency deviation of 20 kHz but different modulation indices. The higher modulation index (η=4) of parameter set 5 leads to a successful communication link with a PER of less than 40%. On the other hand, parameter set 8 (η=1) loses all packets.

Parameter sets 7 and 9 feature a modulation index of two. The parameter sets yield acceptable PER values for shorter distances. Clearly, the performance is degraded and shows the limitations as stated in the datasheet.

B. *STMicroelectronics Spirit1*

Fig. 8 shows PER results for the Spirit1 transceiver of STMicroelectronics [6]. The tests have been performed using Nucleo shield X-NUCLEO-IDS01A4 [7]. However, the transceiver module has been changed to SPSGRFC-868 with U.FL connector [8]. The PC81 PCB antenna from Taoglas [19] is attached to the U.FL connector. The Spirit1 library version V3.2.3 has been used as a base for the driver.

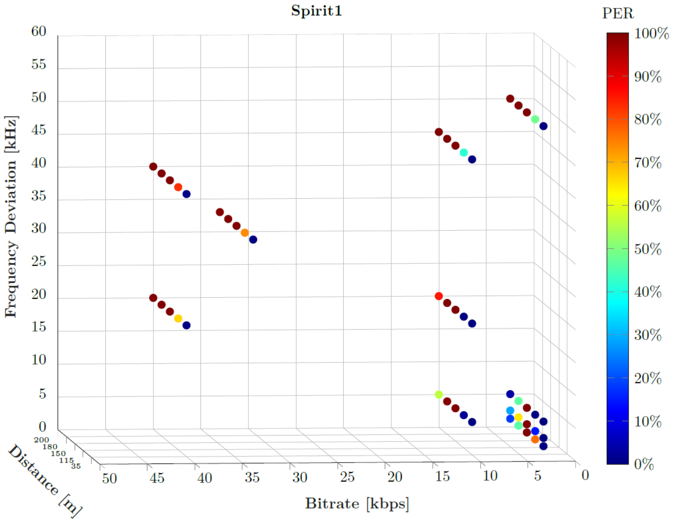

Fig. 8. Packet Error Rates for STMicroelectronics Spirit1

At the nearest distance of 35 m the Spirit1 works reliably with all settings. For distances over 35 m connections are not possible with bit rates over 10 kbps or frequency deviations over 20 kHz, i.e. the settings in quarters 2, 3 and 4. The other configurations in quarter 1 show lower PER. In these configurations also nodes at higher distances can be reached. The configurations 2 and 3 have a decent PER at a distance of 115 m and still a moderate PER at the maximum distance of 200 m. Configuration 1 shows a similar behavior as configurations 2 and 3. However, the achieved PER are higher. This is probably due to an increased susceptibility to frequency divergences between transmitter and receiver. This is an individual effect for each node and not dependent on distance.

In addition the node at a distance of 150 m unfortunately has an operational issue and is not working. Therefore, no results could be collected.

C. *Digi XBee-868-LP*

Fig. 9 shows PER results for the XBee-868-LP transceiver of Digi. The tests have been performed using Digi's module XB8-DPPS-001 with firmware version 1074 [9].

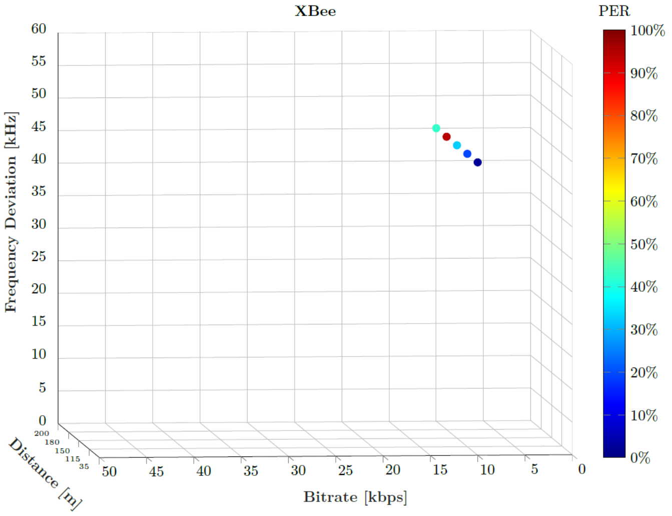

Fig. 9. Packet Error Rates for Digi XBee-868-LP

As the Xbee868LP supports only a single configuration the graphic is almost empty. The only supported configuration is at a bit rate of 10 kbps and a presumed frequency deviation of 45 kHz. The PER shows the usual pattern. Low PER values are achieved for nodes at short distances. With increasing distances the packet error rates increase as well. At 180 m, no connection is possible. On the other hand, a successful exchange of packets with the node at 200 m is possible.

D. *Silicon Labs Si4461*

Fig. 10 shows PER results for the Si4461 transceiver of Silicon Labs. The tests have been performed using a dedicated PCB design with the chip version SI4461-C2A-GM [10]. The design is based on the reference design [11] and applies a chip antenna from Taoglas [18]. The values for the configuration registers have been established using WDS version V3.2.11.0 [13].

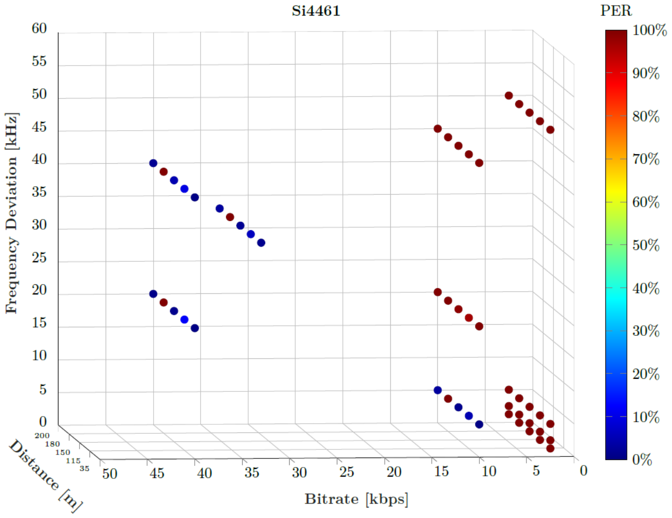

Fig. 10. Packet Error Rates for Silicon Labs Si4461

Obviously, the Si4461 transceiver shows a fairly binary behavior in the achieved link quality. Most points have either a dark blue color or a dark red color. I.e. either all packets have been successfully received or all packets have been lost. Furthermore, the results show that the Si4461 works fine with a modulation index below two and a bit rate above 10 kbps. All other settings are practically ineffective. In addition, the node placed at a distance of 180 m has an extremely poor performance in all configurations.

For the poor performance of the node at 180 m it is assumed that the path losses are too large. All nodes closer than 200 m are placed in the middle of the vines and have left and right rows with other vines. These probably cause a strong attenuation due to the reflection of the waves. For all nodes closer than 180 m the signal strength is above the sensitivity limit of the transceiver. At 180 m the path loss becomes too high and the signal strength falls below the sensitivity limit. In contrast, the node placed at 200 m works fine. One reason could be the placement at the edge of the vineyard. As a result the radio waves are reflected by the vines on one side whereas on the other side they can spread unhindered.

The reason for the failures of parameter sets with either a modulation index larger than 2 or a bit rate lower than 10 kbps is very likely a programming error. The Si4461 is not built to handle dynamically changing configurations. In a typical scenario a tool provided by Silicon Labs is used to generate a lengthy look-up table with the values for the registers of the Si4461. Indeed, the Si4461 requires an individual look-up table for each application specific set of parameters. I.e. an individual look-up table for each of the 9 FSK parameter sets would be required in the presented experiment. To allow a lean integration into the test setup we have used a common look-up table and then have overwritten only few individual registers for each parameter set. This approach has not worked well for the parameter sets in question.

E. Texas Instruments CC1120

Fig. 11 shows PER results for the CC1120 transceiver of Texas Instruments. The tests have been performed using a dedicated PCB design with the chip version CC1120RHBR [14]. The design is based on the reference design [15] and applies a chip antenna from Taoglas [18]. The values for the configuration registers have been established using "smartRF studio" version V2.6.1 [16].

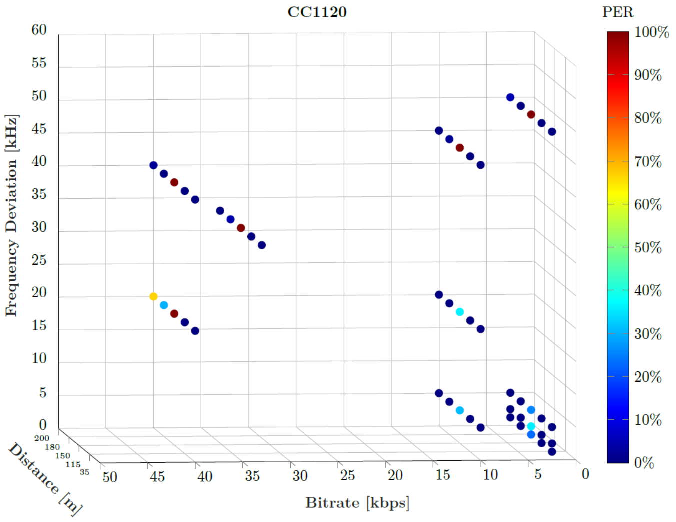

Fig. 11. Packet Error Rates for Texas Instruments CC1120

The CC1120 has very low PER for almost all settings (<10%). The only exception is the node at a distance of 150 m. It cannot receive packets at bit rates above 10 kbps or deviations above 20 kHz. For smaller values the node can receive packets, but with a higher PER than the other nodes (40%).

The measurements with a bit rate of 40 kbps and a frequency deviation of 20 kHz have the lowest performance. At distances of 35 m and 115 m the PER are still good (<10%). At longer distances the PER increase from 40% at 180 m up to 60% at 200 m.

The reason for the very low performance of the node at a distance of 150 m was not yet found. Maybe the hardware is damaged or there are too many reflections at this point of the vineyard. With lower bit rates and frequency deviations the node sporadically received packets. This is because of the higher sensitivity for these settings.

The reason for the worse results on the setting with 40 kbps bit rate and 20 kHz frequency deviation may be the modulation index of "1". This means the frequency deviation is small in relation to the bit rate. So the frequencies may affect each other.

V. POWER CONSUMPTION

A specific sequence is used to measure the individual power consumptions of the evaluated transceiver types. The sequence includes the repeated transmission and reception of a single packet (ping-pong sequence) with different parameters. A power analyzer device of Keysight [22] has been used to perform the measurements. Next the measured current profile is analyzed with the analysis software from Keysight [23].

Fig. 12 shows the timing behavior of the current for a single ping-pong sequence. Particularly the current values for the different transceiver states can be read out.

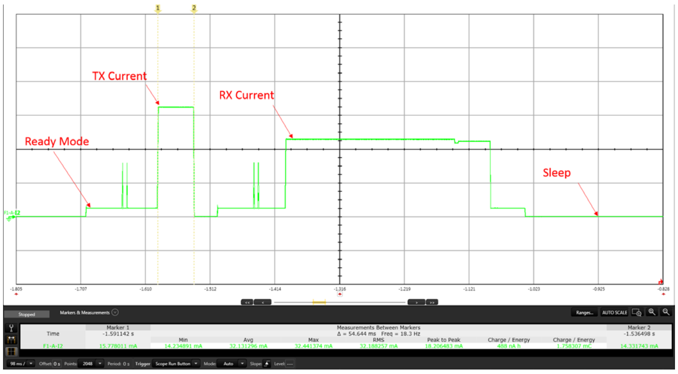

Fig. 12. Current profile of CC1120 given as example

A. *Transmission*

The TX current depends on the output power. Additionally the TX time, i.e. the time to send a single packet, was measured. Markers are set at the beginning and at the end of the TX current. Obviously the TX time depends on the payload length and the bit rate. Consequently the total required energy for transmission of a single packet is calculated according to (3).

$$\text{Energy}_{TX} = \text{Time}_{TX} * V_{Supply} * I_{TX} \qquad (3)$$

TABLE II. and TABLE III. show the energy required to transmit a single packet with 4 bytes and 55 bytes respectively for each transceiver type.

TABLE II. TRANSMISSION OF SINGLE PACKET WITH 4 BYTE PAYLOAD @ 3.3 V, P_{TX} = 7 DBM, 10 KBPS

		MRF89	**Spirit1**	**XBee 868LP**	**Si4461**	**CC1120**
I_{TX}	mA	19.7	12.5	25.5	22.5	32.4
Time	ms	17.1	14.1	79.0	24.3	13.7
Overhead	%	75	76	95	83	75
Energy	mJ	1.1	0.6	6.6	1.8	1.4

TABLE III. TRANSMISSION OF SINGLE PACKET WITH 55 BYTE PAYLOAD @ 3.3 V, P_{TX} = 7 DBM, 10 KBPS

		MRF89	**Spirit1**	**XBee 868LP**	**Si4461**	**CC1120**
I_{TX}	mA	19.7	12.5	25.5	22.5	32.4
Time	ms	58.0	55.0	120.0	65.1	54.4
Overhead	%	18	19	60	26	18
Energy	mJ	3.8	2.3	10.1	4.8	5.8

Obviously the Spirit1 requires the lowest amount of energy to send packets. This is due to a low current and a low packet overhead. Due to its high proportion of overhead and its high current the XBee868LP needs a lot of energy. While the CC1120 achieves fair values for short payloads it requires a high amount of energy for longer payloads. This is due to its packet structure with low overhead and its high transmission current.

The proportions of the overhead, shown in TABLE II. and TABLE III. , are calculated based on the frame structures given in the datasheets.

B. *Reception*

TABLE IV. displays the measured receive currents for the evaluated transceiver types. The indicated energy is calculated based on the individual transmission time for each transceiver. Admittedly, this time has to be somewhat larger in real systems as the receiving device does not know precisely when the transmitting device transmits.

TABLE IV. RECEIVE CURRENT @ 3.3 V; ENERGY CALCULATED FOR SINGLE PACKET WITH 55 BYTE PAYLOAD @ 10 KBPS

		MRF89	**Spirit1**	**XBee 868LP**	**Si4461**	**CC1120**
I_{RX}	mA	2.8	9.1	20.9	13.1	22.9
Time	ms	58.0	55.0	120.0	65.1	54.4
Overhead	%	18	19	60	26	18
Energy	mJ	0.5	1.7	8.3	2.8	4.1

Clearly, the MRF requires by far the lowest amount of energy to receive a packet. In contrast the XBee868LP and the CC1120 require the most energy. Spirit1 and Si4461 are located in the middle.

C. *Sleep*

TABLE V. shows the sleep currents both from the datasheets and from the measurements for the evaluated transceiver types.

TABLE V. SLEEP CURRENT @ 3.3 V

		MRF89	**Spirit1**	**XBee 868LP**	**Si4461**	**CC1120**
I_{Sleep} (datasheet)	uA	0.1	0.9	1.7	1.7	0.5
I_{Sleep} (measured)	uA	0.1	1.4	1.5	11.0	0.2

Most of the measured values are in the ranges indicated by the datasheets. The only exception is the

Si4461. Clearly, the MRF89 and the CC1120 have significantly lower sleep currents than the other three devices.

VI. SELECTING A TRANSCEIVER

Each one of the presented transceiver types has its specific strengths and weaknesses. This requires a careful selection with regard to the targeted application.

A. *Microchip MRF89*

The MRF89 offers only a limited number of configuration parameters. However, this makes the chip easy to use. Within its narrow application scope it achieves decent link quality at an extremely low receive current.

1) Strength: Easy to use, low complexity

The MRF89 is easy to use. The limited feature set keeps programming complexity low. Only a low number of configuration registers need to be programmed. An SPI interface and some additional GPIOs are sufficient to access all functionalities of the MRF89.

2) Strength: Low receive and sleep currents

In receive mode, the MRF89 only consumes a supply current of around 3 mA. The value of the RX current is by far the lowest of all evaluated transceivers. This makes the MRF89 a good choice for applications with long listening intervals. Moreover also the sleep current is very low.

3) Weakness: Requires high frequency deviations

The transceiver has restrictions regarding transceiver parameters. The frequency deviation must be set higher or equal than 33 kHz. This limitation leads to a relatively high transmission bandwidth of minimum 66 kHz plus the symbol rate (which is the same as the bit rate). The high bandwidth causes low spectral efficiency and demands a high filter bandwidth on receiver side.

4) Weakness: Minimum modulation index of 2

Microchip recommends not using a modulation index below two. This means that the frequency deviation has always to be equal or greater than the bit rate. Therefore, high bit rates automatically cause a big amount of used bandwidth and reduce the spectral efficiency of the transceiver.

B. *STMicroelectronics Spirit1*

The Spirit1 is a very flexible and versatile transceiver that allows detailed control of transmission parameters. Unfortunately this asset makes it very challenging to design reliable applications. However, the transceiver features attractive energy consumption figures.

1) Strength: Large range of parameters supported

The Spirit1 supports a broad range of parameters including many possible settings for bit rate and frequency deviation.

2) Strength: Low operational power

Clearly the Spirit1 requires the lowest transmit power to send a packet of all evaluated devices. In addition it features a significantly lower receive current than the other transceivers except for the MRF89. A low receive current is especially important in cases when the receiving device does not know exactly when the transmitting device will send the packet.

3) Weakness: Rather complex and difficult to use

Although the Spirit1 features good documentation, many example applications and a USB dongle with a GUI to perform experiments with, the Spirit1 still requires a lot of effort and know-how to develop reliable applications. Clearly the Spirit1 has caused the highest amount of effort of all the transceivers in the test. This unfortunately applies to both the hardware as well as the firmware.

4) Weakness: Highly temperature dependent center frequency

The center frequency highly depends on the frequency of the used quartz crystal. In cases where low bit rates are required, slight temperature changes between receiver and transmitter have large impacts on packet error rates. This is due to a center frequency offset between receiver and transmitter of the two transceivers. Multiple crystals have been tested and showed no sign of improvement. In addition, an increase of the bandwidth filter showed no improvement of the packet error rate for such a scenario. As a workaround a specific offset for the base frequency can be programmed by measuring the node temperature and performing a linear approximation to a previously recorded temperature vs. frequency behavior. Furthermore, a temperature compensated quartz could be used.

C. *Digi XBee-868-LP*

The XBee-868-LP can be easily setup and offers many powerful features to facilitate complex network topologies and higher communication layers. However, this comes with a high purchase price and with very limited possibilities to adapt transmission parameters. Nonetheless, the chip achieves good link qualities at the single available parameter setting.

1) Strength: Easy to use – works out of the box

Due to the construction form of the XBee868LP as a module, it is easy to integrate on a hardware design. The modules are available with 3 different antenna options. Similarly, the integration effort on the software side is low. E.g. the device is pre-configured as a UART bridge. This makes it easy to integrate into an application. For configuration the module can be easily accessed either through AT commands or through an API. The module has a huge community. Examples and code are readily available on the internet.

2) Strength: Powerful system

The XBee868LP module is much more than just a transceiver. It is already equipped with many gadgets as network or cluster identification and algorithms for ETSI compliance and so on. Many powerful functions of the network layer are already built in.

3) Weakness: Single parameter setting

The XBee868LP only supports a single, predefined parameter set at a bit rate of 10 kbps. The applied frequency deviation is not given in the datasheet.

4) Weakness: Large overhead

Digi uses a proprietary but unfortunately undocumented frame format. As this frame also contains fields for the higher communication layers it features a high amount of overhead.

5) Weakness: High price

As the module features a complete communication system and therefore has another target market than the other evaluated transceivers, it has a high price.

6) Weakness: High power consumption

The XBee868LP exhibits one of the highest receive currents. In combination with the large protocol overhead introduced by the higher layers, this results in the highest power consumption for sending and receiving packets of all the evaluated transceivers.

D. Silicon Labs Si4461

The Si4461 is a very versatile transceiver that achieves high link qualities. It allows detailed control of transmission parameters and a flexible packet structure. Unfortunately the programming through large individual lookup tables for each parameter set makes adapting the parameters in the field somewhat inflexible and complex.

1) Strength: High link quality

The Si4461 offers a high sensitivity over a broad parameter range. The chip can thus achieve a connection at a higher bit rate or longer range than other transceivers in the test. By either lowering the transmission power or increasing the bit rate the high sensitivity allows reducing the required energy for the transmission of a packet.

2) Strength: Powerful frequency correction

The receiver part of the Si4461 has an automatic frequency correction (AFC) to correct the frequency in the PLL using the preamble. A correction of up to +/- 0.35 times the IF bandwidth can be achieved.

3) Strength: Good hardware guidelines

Silicon Labs has a variety of freely accessible reference layouts. These layouts are mostly from devkits and can be downloaded for evaluation purposes. Further online available auxiliary documents support the layout process substantially. An example is the document „AN627: Si4460/61 Low-Power PA Matching“ [12].

4) Strength: Flexible packet structure

There are a variety of combinations for configuring the packages. Single field configuration is used for a fixed length of the complete packet. Otherwise, payloads with variable lengths require a two-field structure. The first field can be adapted according to your own requirements and thus allows an individual header to be configured. In addition the Si4461 supports a match function of up to 4 bytes at the beginning of the first field. This is often used to perform a header check. Specific addresses or network IDs can be checked.

5) Weakness: Inflexible programming using lookup tables

The Wireless Development Suite (WDS) [13] has to be used to generate an individual lookup table for each parameter set. The lookup tables have to be integrated into the firmware. This makes the flexible modification of parameters, like bit rates and frequency deviations, difficult. The lookup tables cannot be easily deployed to the field. Specifically in our test setup the evaluation of an additional bit rate therefore requires a firmware upgrade of a node instead of a simple parameter change through an API.

6) Weakness: Tx-Power configuration

Transmission power is controlled by a multi-stage MOSFET output. The desired transmit power cannot be written directly into a register. This register contains only the number of activated stages (0-127). The required active stages depend on the chosen hardware design and cannot be calculated exactly. For this reason, the number of stages for a specific transmit power setting must be determined through measurements. The non-linear behavior of the output power makes this process even more difficult.

E. Texas Instruments CC1120

The CC1120 is a very versatile transceiver that achieves high link qualities with all the tested parameter sets. It allows detailed control of transmission parameters. Unfortunately the device draws high amounts of currents, both in receive and in transmit mode. In contrast the sleep current is attractively low.

1) Strength: High link quality

The CC1120 offers a high sensitivity over a broad parameter range. The chip can thus achieve a connection at a higher bit rate or longer range than other transceivers in test. By either lowering the transmission power or increasing the bit rate the high sensitivity allows reducing the required energy for the transmission of a packet.

2) Strength: Powerful frequency correction

Every time the CC1120 receives a packet it makes an estimation of the frequency offset. As a result frequency offsets between the sending and receiving oscillators can be corrected. This works well with an accuracy of about 100 Hz, which is adequate even for low bit rates.

3) Strength: Documentation

The CC1120 has good data sheets. The registers and the functions of the CC1120 are precisely described and easy to understand. The evaluation boards with the «smartRF studio» software can be easily used to change the registers, send and receive packets. Unfortunately in «smartRF studio» only the configurations of four different FSK-2 settings are given. It is difficult and needs a lot of time to find good settings for other configurations.

4) Weakness:Draws high currents in receive and in transmit mode

The CC1120 exhibits the highest currents in both the receive mode and the transmit mode. This is somewhat mitigated through the low overhead protocol. Additionally the superior transmission properties may allow choosing a higher bit rate to further mitigate the elevated power consumption.

5) Weakness: Bandwidth filters have only a few settings for high bit rates

From 66 to 200 kHz only 3 different bandwidths are possible. For high bit rates a higher bandwidth than 200 kHz would be useful.

VII. LESSONS LEARNED

A. Common Transceiver API

To facilitate the use of several transceiver types in the same application, a common API has been defined. Once the specific driver of a transceiver has been ported to this standardized API, nodes using this transceiver can be easily integrated into the measurement setup. The setup comprises of three steps. (1) Reading the transceiver type at runtime from the EEPROM and setting the function pointers to the appropriate driver. (2) The specific driver initializes all required microcontroller peripheral modules. (3) The transceiver driver registers its callbacks by setting the appropriate function pointers in the common interrupt file. Clearly, the interrupt handling has been the most challenging part during driver integration.

B. Remote Control

The test setup has been designed for remote control. This is an important feature to run the tests in the field. Both, test control and collection of results are done through a remote server. This allows dynamically adapting test parameters without visits to the field. Additionally results can be monitored at any time.

C. Path Loss

An important factor for the link quality is the strength of the received signal. Each transceiver is able to measure a received signal strength indicator (RSSI). Equation (4) shows the dependency of the RSSI on the transmit power P_{Tx} and the path loss L.

$$RSSI = P_{Tx} - L \qquad (4)$$

The measured RSSI values were logged during the field test. TABLE VI. shows the average RSSI values for the individual transceivers.

TABLE VI. AVERAGE RSSI VALUES

Distance	**MRF89**	**Spirit1**	**XBee 868LP**	**Si4461**	**CC1120**
m	dBm	dBm	dBm	dBm	dBm
35	-77	-97	-83	-79	-74
115	-94	-104	-94	-96	-94
150	-96	N/A	-97	-94	-107
180	N/A	-115	N/A	N/A	-103
200	-99	-111	-92	-92	-100

Each transceiver implements an individual algorithm to estimate the RSSI value of the received packet. Therefore, the absolute RSSI values differ for each type of transceiver and would require calibration.

Interestingly, all transceivers, except for the MRF89, show a decrement in the RSSI when the distance is extended from 150 m/180 m up to 200 m. This behavior could be caused by the topological characteristics of the vineyard or other environmental influences.

For the given transmit power (P_{TX} = 7 dBm), the path loss can be approximated with the Hata model [17]. The Hata model distinguishes between urban, sub-urban and rural environments. Fig. 13 plots the RSSI of the transceivers together with the approximations of the Hata model. Clearly, the measured RSSI values lie between the curves for the urban and the rural areas. Only the Spirit1 provides values outside this range.

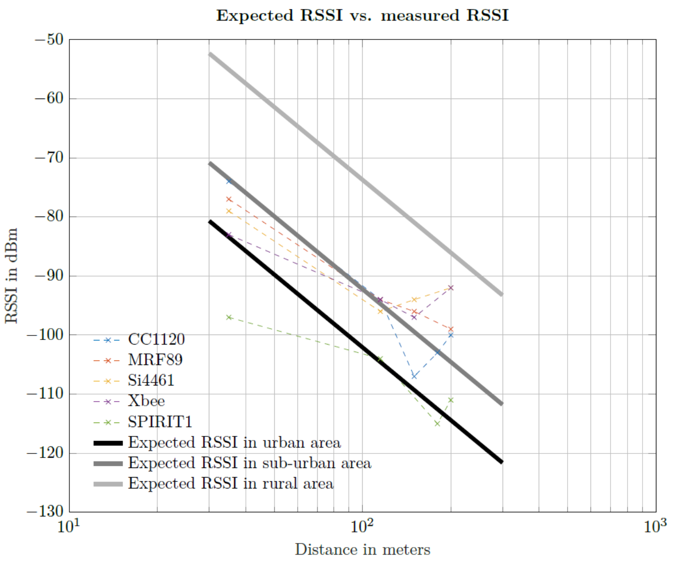

Fig. 13. Comparison of measured RSSI to the Hata model

D. *Influence of Vegetation*

Vegetation has a strong impact on the attenuation of radio waves. This can be noticed in the RSSI values of some of the nodes. In the second half of May, there is a frenzied growth of leafs on the grapevines. Within only a couple of days, the plants grow their thick leafage. Fig. 14 shows the RSSI values of several nodes during the month of May. Two of the nodes show a sudden reduction of the RSSI value between May 20 and June 1. The nodes at distances of 115 m and 150 m, show reductions of 6 dBm and 5 dBm respectively. Clearly, within a few days, the path loss is significantly increased due to the newly grown leafage surrounding these nodes.

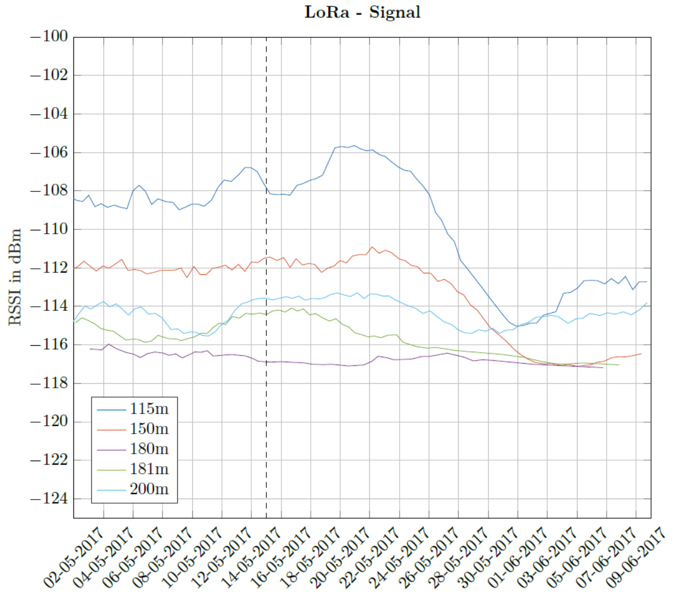

Fig. 14. RSSI values during explosive growth of leafage

RSSI values of LoRa are shown as these have a higher resolution in time, i.e. more measurement points than the individual Sub-1 GHz transceivers.

E. *RF Hardware Issues*

Vendor data sheets usually include clear statements on the RF output power. On many radios, different levels of output power can be configured in software through programmable registers. However, the output power values need to be measured and calibrated individually on each design. The project clearly showed variations between the programmed power levels and the effectively radiated power levels. Therefore it is good practice to plan ahead and to include an U.FL connector in the hardware design. This U.FL connector can then be used to measure the actually radiated output power. Based on the results, the applied register values can be adapted in software.

The project attempted to use available transceiver modules wherever possible. Unfortunately, for some of the transceivers, there were no modules available in a suitable form factor. Or they became available only at a later time. Even worse, we had one module, which did not reach the expected performance. In this case, a lot of time has been spent debugging the firmware (i.e. the driver). Eventually, it turned out that a badly designed antenna matching on the module in question was responsible for the low performance. So, also purchased modules can have their weaknesses. In retrospective, an extensive amount of project time has been consumed on tuning the performances of the individual transceivers. Each transceiver requires specific know-how and experience to attain the optimal interaction of hardware and firmware and therefore to make full use of the potential of the transceiver chip.

VIII. CONCLUSIONS

This paper presents measurement results from a several months long field trial with five different Sub-1 GHz transceivers from different chip vendors. The porting of the individual drivers to a newly defined powerful and common API has proven to be the key to successful integration of the individual transceiver types. The resulting measurement platform has been installed in a vineyard to collect the results presented in this paper. Test parameters can be flexibly controlled from a remote server. The same server logs and analyzes the results. Importantly, the measurement platform can be easily extended to other transceiver types and installed in other locations.

Based on the measurement results, transceiver types have been compared. Individual strengths and weaknesses have been identified. Admittedly the experiment does not encompass all possible transmission features and details. However, we are convinced that the presented results support the selection of an appropriate transceiver. Furthermore, they facilitate the setting of fitting parameters for the specific application at hand.

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