Choosing an Integrated Radio-frequency Module for a Wildlife Monitoring Wireless Sensor Network

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***Abstract*—We consider the choice of a radio transceiver module for use in a wireless sensor network aimed at wildlife monitoring. In this application, power consumption and communication range in difficult terrain are key challenges. From field measurements we firstly establish that little is to be gained in terms of improved signal transmission by using the lower ISM frequency of 169MHz. Subsequently we evaluate 5 currently commercially available 433MHz radio modules in representative terrain and configurations. Four of these communicate using FSK, while one is LoRa-capable. We find that the LoRa module offers clear advantages in terms of power consumption and range, allowing communication over 5500m at a power of 20dBm with 2% packet loss. We conclude that this technology presents potential for integration into a sensor network for wildlife monitoring.**

***Keywords*—Wireless sensor networks, wildlife sensor networks, low power radio transceiver, LoRa.**

I. Introduction

The ability to monitor animals in their natural habitat without supervision has long been an aspiration in many scientific disciplines, such as conservation and behavioural ecology. As so-called wearable devices which allow for automated collection of data through sensors attached to persons or animals are becoming more commonplace, a way of retrieving this data is needed [1] [2]. Such on-animal nodes are necessarily very low power, and therefore conventional types of communication such as GSM or satellite are not feasible. One solution is the development of a wireless sensor network (WSN) which is deployable throughout the target habitat. One of the main concerns with this approach is the ability to communicate data successfully from the on-animal nodes to the network itself.

Currently, little information is available regarding the power requirements and achievable communication ranges of currently available integrated radio devices. It is known from the basic theory of RF propagation that lower operating frequencies extend the range of communication for a fixed transmission power [3]. However, lower operating frequencies also necessitate physically larger antennas, which may be impractical for animal-borne devices.

Wireless sensor networks have recently become an established technology. However most are confined to environments where power usage and communication range is not a limiting factor [4]. Nevertheless there have been various attempts at building a network to track animals autonomously. One study uses RFID tags attached to European badgers (*Meles meles*) to monitor the movements of these animals in their natural habitat [5]. This study found that, by choosing a radio module with an output power of 20 dBm instead of 0dBm, the range between the nodes could be increased from from 50m to 1km.

As an alternative approach, ZebraNet did not build a dedicated WSN to which data would be communicated, but allowed the data to percolate from one animal to another when they came into contact [6]. This network protocol assumes that one of the animals will pass a base station at some point in the near future. The study noted that one of the biggest drawbacks of the implemented system, was the choice of integrated radio device operating at a frequency of 900MHz. The employed hardware was specified to have a '5 mile range', but when placed in the field, was only capable of communicating up to 1.2km.

A third study compared radios operating at 433MHz and 2.4GHz, and found that the the former was able to communicate over greater distances while consuming less power [7]. This finding is supported by the Friis equation, which indicates that lower frequencies have lower free-space loss and should therefore have a longer range of communication [3].

This study focuses on choosing a low power radio frequency (RF) device which can be used to build a WSN specifically for outdoor and on-animal tracking applications. The paper is organised as follows, Section 2 provides a problem statement and Section 3 addresses the choice of operating frequency. Section 4 considers the choice of radio device and Section 5 concludes with a final assessment.

II. Problem Statement

In order to facilitate the development of a large-scale outdoor WSN, a low-power radio transceiver is needed which is capable of long range communication while remaining physically small. The radios will have to accomplish both WSN node-to-node communication as well as on-animal node to WSN node communication. This provides specific challenges because the on-animal nodes are expected to be located close to the ground, have low gain antennas due to packaging size constraints, and can find themselves transmitting from deep shrubbery depending on the animal's natural environment [8]. With the on-animal node mounted on an ankle, the height can be as low as 10cm from the ground. Therefore the chosen radio should have the following attributes:

- It must provide reliable links between nodes with minimal errors.

- It must communicate over long distances, typically over 2 km, to limit the number of nodes needed by the network.
- It must offer a sleep mode with low current consumption.
- It must have an operating frequency in an ISM band.
- It should have a maximum transmit power of 100mW or less and abide by ICASA regulations [9].

By means of practical measurements, we will first evaluate the most appropriate operating frequency for the radios. Then, 5 radios will be evaluated in terms of communication distance, accuracy of communication and dropped packets.

III. Choice of operating frequency

The frequency at which the radios will operate is very important. It will determine the antenna size, power requirements for communication over a certain distance and the cost of materials. This study will first identify possible frequencies which are likely to be used as the operating frequency for the WSN. Practical measurements will then be taken to ensure that the chosen frequency provides the best communication between the on-animal node and a WSN node, as it is accepted that this will be the most difficult part of the communication.

A. Possible ISM bands

The operating frequency will be chosen from the Industrial, Scientific and Medical (ISM) licence free bands as they have the greatest variety of commercially available equipment. The ISM bands which are popular for wireless sensor networks are 433MHz, 915MHz, 2.4GHz and 5.725GHz with plans to incorporate 169MHz as an ISM band in the near future [10]. Previous studies which implemented a WSN operating at 915MHz and above did not achieve the range that is required for this project [6] [11]. Therefore this study will consider the 433MHz and 169MHz ISM bands only.

B. Antenna Size

Due to the robust environment in which wild animals live, the on-animal antenna will need to fit within the packaging of the node. A study on rhino collars indicated that the dimensions of the packaging of an on-animal node should not exceed 40mm by 60mm [8]. The length of a simple half wave antenna is given by: $\frac{speed\ of\ light}{2*frequency}$. Using this formula, half wave length antennas for 169MHz and 433MHz will be 0.88m and 0.34m in length respectively. This means that specialised antennas need to be designed for operation at both frequencies. However, the antenna design for 169MHz will be more difficult as the wavelength is much longer.

C. Experimental Procedure

In order to address the two considered frequencies, practical measurements were made to determine the following:

1) Whether there is an improvement in the received signal strength when operating at 169MHz instead of 433MHz.
2) How raising the receiving antenna affects the received signal strength at each frequency.

For these experiments, the Jan Marais park in Stellenbosch was chosen as the testing location. This allowed a testing range of up to 500m without any man-made obstructions or elevation change. The park contains approximately 1m tall foliage growth, which approximates the habitat of wild animals.

TABLE I
Average measured received signal strength for each frequency over all distances

Rx Height [m]	169MHz [dBm]	433MHz [dBm]	Difference [dBm]
0.63	-74.64	-78.11	3.47
1	-72.51	-76.36	3.85
2	-69.39	-72.61	3.22
3	-68.01	-70.48	2.47
3.5	-66.64	-68.48	1.85
Total Change	8	9.64	

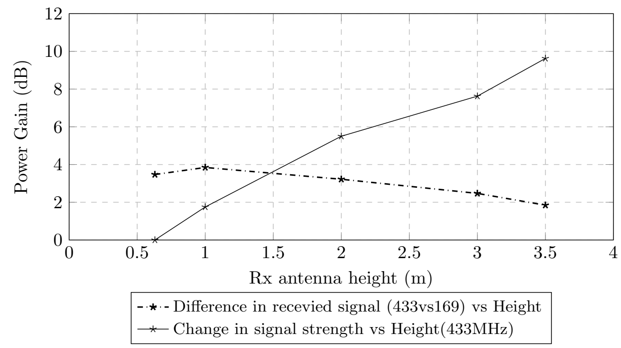

Fig. 1. Received signal strength difference between 169MHz and 433MHz vs antenna height as well as the change in received signal strength for 433MHz vs antenna height.

A wide band antenna, set up as the receiving station, was attached to a signal analyser. The height of this antenna could be adjusted to 0.63m, 1m, 2m, 3m and 3.5m above the ground. A second wide band antenna, set up as the transmitting station, was attached to a portable signal generator, and was fixed at a height of 0.1m above the ground. This corresponds to the estimated height of an on-animal antenna when attached to the ankle. The transmitting station was placed at a distance of 100m, 300m, 350m and 500m from the receiving station. At each distance a 25dBm signal was generated first at 169MHz and then at 433MHz, and the received signal strength measured using the signal analyser. The measurements at each frequency are normalised based on the individual gain differences for each antenna at each frequency. At each of the 4 distances the receiving antenna was adjusted to each of the considered heights.

D. Results

The measurements at each of the 4 considered distances were averaged and presented in Table I. The table shows the average, over all distances, of the received signal strength at each receiving antenna height. The table also shows the difference in received signal strength between 169MHz and 433MHz. The total change is the difference between the received signal strength measured at an antenna height of 0.63m and 3.5m.

TABLE II
KEY CHARACTERISTICS OF THE 5 CONSIDERED RADIO DEVICES.

Device	SI4463	RFM96W	RFM22B	RFM23BP	E31-TTL
Vendor	SI	HopeRF	HopeRF	HopeRF	EByte
Tx power [dBm]	+20	+20	+20	+30	+30
Sensitivity [dBm]	-120	-148	-121	-114	-126
Current Tx [mA]	88	120	85	550	510
Current Rx [μA]	13.7	12.1	18.5	18.5	15.5
Current sleep [μA]	1	0.2	1	1	1.7
Supply [V]	3.3	3.3	3	5	5
Modulation	FSK	LoRa	FSK	FSK	FSK
Interface	SPI	SPI	SPI	SPI	UART

Fig. 2. An example of the terrain and vegetation found in the testing environment at Cape Point nature reserve.

The results in Table I confirm that, for all receiving antenna heights, the measured signal is stronger at $169\mathrm{MHz}$ than at $433\mathrm{MHz}$. However, as illustrated in Figure 1, the difference in received signal strength between the two frequencies lessens as the receiving antenna height is raised. At a height of $0.63\mathrm{m}$ this difference is $3.47\mathrm{dB\,m}$ and at $3.5\mathrm{m}$ it is only $1.85\mathrm{dB\,m}$.

The radius r (in meters) of the widest point of the Fresnel zone is given by the Fresnel equation $r = 17.32 * \sqrt{\frac{d}{4f}}$, with d the distance between links (in km), and f the frequency (in GHz) [12]. The Fresnel zone at $169\mathrm{MHz}$ is larger than that of the $433\mathrm{MHz}$ signal. By raising the antenna to $3.5\mathrm{m}$, a smaller proportion of the Fresnel clearance is obstructed by foliage for the $433\mathrm{MHz}$ signal than for the $169\mathrm{MHz}$ signal. This leads to a reduction in the difference in received signal strength.

Table I also shows that, as the receiving antenna is raised from $0.63\mathrm{m}$ to $3.5\mathrm{m}$, the measured signal strength increases by $8\mathrm{dB\,m}$ for the $169\mathrm{MHz}$ signal and by $9.64\mathrm{dB\,m}$ for the $433\mathrm{MHz}$ signal. Therefore raising the receiving antenna significantly increases the received signal strength at both frequencies. The change in received signal strength for $433\mathrm{MHz}$ vs antenna height can be seen in Figure 1.

E. Conclusion

The results of the experiments show that the received signal strength is higher for $169\mathrm{MHz}$ than it is for $433\mathrm{MHz}$. However, as the height of the receiving antenna is increased, this difference decreases. Figure 1 shows that the effect of raising the receiving antenna is far larger than that of lowering the frequency to $169\mathrm{MHz}$.

When also considering the higher antenna complexity at the lower frequency, $433\mathrm{MHz}$ was judged to be the more appropriate choice for our application.

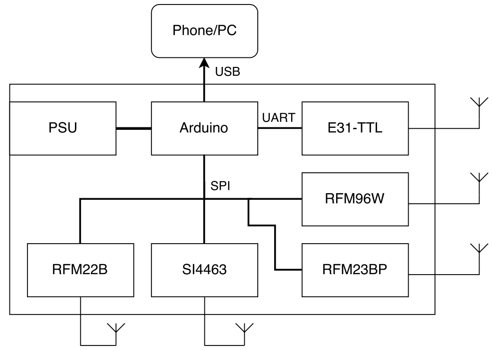

Fig. 3. A block diagram of the testing station.

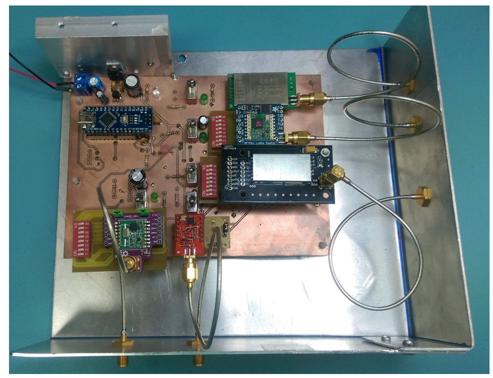

Fig. 4. A photograph of the testing station. A metallic box surrounds the PCB and short 50Ω cables connect the radios to the female SMA connectors grounded to the box. The metallic box acts as a ground plane, as well as ensuring that no torque is placed directly on the SMA port of the radio itself.

IV. CHOICE OF RADIO DEVICE

The 5 radios chosen for testing are listed in Table II. These radios were chosen as they communicate at $433\mathrm{MHz}$, and all have a maximum transmitting (Tx) power of at least $20\mathrm{dB\,m}$. Previous tests with lower power radios at this frequency indicated that these would not be satisfactory for an outdoor WSN. All radios listed in Table II are currently commercially available. The chosen devices interface with a micro-controller (MCU) using either SPI or UART. All have a specific instruction set developed by the manufacturer.

Table II also indicates that a family of RF chips was considered, namely the RFM22B and the RFM23BP. These devices share the same communication protocol and therefore are able to communicate with each other [13]. In our application this pair would have the advantage that the more powerful radio could be used in the stationary WSN nodes where power consumption is less critical, while the lower power radio could be used in the on-animal nodes where power conservation is critical. The SI4463 radio module has almost identical specifications in sensitivity, output power and Tx current draw to the RFM22B, while the E31-TTL has similar Tx current and output power to the RFM23BP [14] [15].

As a fifth option, a Long Range (LoRa) capable radio was included among the candidates. LoRa has been claimed to

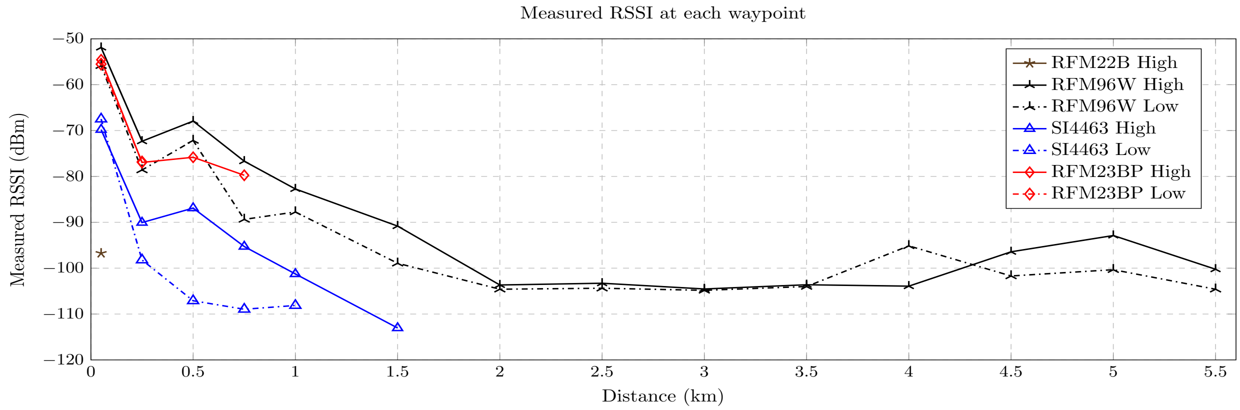

Fig. 5. The RSSI measurements at each waypoint (from 50m to 5500m) from each radio when the mobile antenna was set to 4m (high) as well when the antenna was set to 0.1m (low).

achieve far greater communication ranges than OOK or FSK based radios [16]. LoRa achieves this greater range by trading data rate for sensitivity and by increasing the transmitted signal bandwidth within a fixed channel bandwidth [17]. The LoRa signal is modulated by a patented stable chirp, created using a fractional-N phase lock loop [18]. It is claimed that LoRa is capable of efficiently demodulating signals 19.5dB below the noise floor, while comparative frequency shift keying (FSK) systems need a signal power of 8-10dB above the noise floor for successful demodulation [17] [19]. The LoRa capable RFM96W was chosen, since it offers a very high sensitivity of -148dBm while drawing only 0.2µA in sleep mode [20].

Two of the radios which were included for testing, the RFM23BP and E31-TTL, have an Tx power of 30dBm even though this falls outside of the ICASA regulations for communication at this frequency. These devices were included to give an indication of what range would be possible with a higher output power. Where possible the radios were set to transmit at a data rate of 1.2kbps.

A. *Test Site*

The test site was chosen to resemble the environment in which the network can be expected to be deployed. This type of terrain is generally quite flat, with few trees. During the rainy season, very thick grass and shrub growth can develop. Measurements were carried out over distances varying between 0 and 5500m. A location in Cape Point nature reserve was chosen as it not only offers suitable terrain type with thick fynbos growth up to about 1m in height, but it also allows for testing up to a distance of 5.5km without large changes in elevation. Waypoints were placed at set intervals for placement of the mobile antenna during testing. Figure 2 gives an indication of the type of terrain.

B. *Experimental Procedure*

The objective of the test was to determine how the radios will function when used for WSN node-node communication as well as on-animal node to WSN node communication. Therefore one testing station, henceforth known as the base station, remained at a single location with its antenna fixed at 4m above the ground. The other testing station, henceforth referred to as the mobile station, moved to the predetermined waypoints and tests were conducted with its antenna placed 10cm (low) and 4m (high) above the ground.

At each waypoint, each of the 5 radios sent 30 packets of data from the mobile station to the base station. Each packet received by the base station was replied to with a response packet from the base station to the mobile station. Each time a packet was received at a station, the received signal strength indicator (RSSI), packet number as well as the data sent was stored. Therefore, for each particular configuration of waypoint and antenna height, 60 packets are sent between stations. Since the E31-TTL radio does not provide an RSSI, only the data received and packet number was stored for this device.

Each of the two testing stations consisted of the 5 radios interfaced with an arduino MCU and placed on a single PCB. Power was supplied by a 12V battery to allow for portable operation. Each radio can be switched on individually allowing for a single radio to be tested at a time. The measured data was transferred for external storage to a computer from the arduino via serial port.

A block diagram of the testing station is shown in Figure 3. The base station and the mobile station were identical in design. Figure 4 shows a completed station.

The base station antenna has a gain of 5dBi and was fixed on a pole 4m above the ground. The mobile station antenna was attached to a fibreglass pole and can be set to 0.1m or 4m above the ground. This antenna has a gain of 0dBi at 433MHz.

The experiments determined the RSSI for each packet received as well as the number of packets sent between the stations. These two measurements give an indication of how reliably a radio works at each distance.

C. *Results: RSSI Measurements*

An RSSI measurement is not a definite measure of how successfully a radio is receiving packets at a certain distance. However, it does give a very good indication of how close a

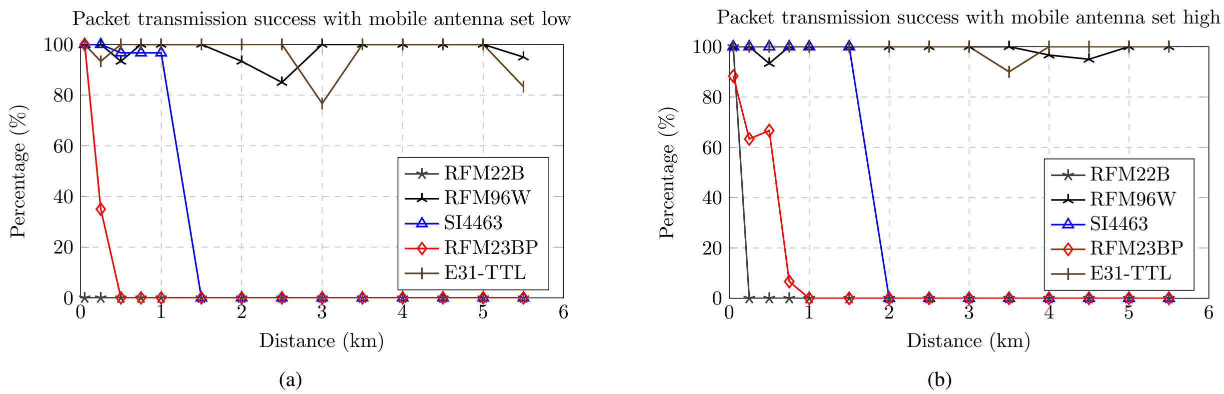

Fig. 6. The percentage of packets which were successfully transmitted between stations for (a) antenna low and (b) antenna high positions. Each marker indicates the percentage at a specific distance, where 100% corresponds to no packet loss, while 0% indicates that no packets were successfully transmitted.

radio is to the limits of its sensitivity and thus the limits of its range.

RSSI measurements are shown in Figure 5. No results are given for the E31-TTL since this radio does not provide an RSSI measurement. From the figure it is possible to identify the distance at which a particular radio was no longer able to establish communication as the point at which its plot terminates. We see that, the further the radios are from one another, the lower the RSSI. This is expected as the signals between the radios experience increased free space losses as the distance between the stations increases [21]. The signals are also progressively disrupted and deflected by objects in the environment and absorbed by the ground and foliage.

Another trend observed in the figure is that the RSSI for the mobile antenna set at $4\mathrm{m}$ is on average higher than it is when the antenna is set to $0.1\mathrm{m}$. This is due to increased absorbance by the ground as well as increased signal absorption by foliage due to the low antenna height. The high antenna is clear of most ground clutter and therefore the signal is stronger.

At $50\mathrm{m}$ separation, all radios show an RSSI of above $-70\mathrm{dB\,m}$ except the RFM22B which has an RSSI of $-96\mathrm{dB\,m}$. No RSSI measurements were obtained from the RFM22B at $50\mathrm{m}$ when the mobile antenna was in its low position, meaning that the signal had dropped below the sensitivity of the radio. The RFM23BP is able to determine the RSSI up to a distance of $250\mathrm{m}$ with the antenna low and $750\mathrm{m}$ with the antenna high.

The SI4463 is able to determine RSSI up to $1000\mathrm{m}$ and $1500\mathrm{m}$ when the antenna is low and high respectively. This is far better than could be achieved with the RFM22B or RFM23BP. However the LoRa capable RFM96W was able to determine RSSI over the entire $5.5\mathrm{km}$ range considered during testing.

The RSSI for the RFM96W initially decreases as the distances between the stations increases, but reaches a minimum of approximately $-105\mathrm{dB\,m}$ at $2000\mathrm{m}$ after which it remains almost constant. Furthermore, unlike the other radios which exhibited considerable differences in RSSI between the high and low antenna positions, the RFM96W does not show a large difference between these testing conditions.

TABLE III
PERCENTAGE OF SUCCESSFUL PACKET TRANSFERS BETWEEN STATIONS AVERAGED OVER ALL CONSIDERED DISTANCES.

Packets Received	RFM22B	RFM23BP	SI4463	RFM96W	E31-TTL
Low [%]	0	9.64	35	97.62	96.67
High [%]	7.14	16.07	42.86	98.93	99.29
Average [%]	3.57	12.86	38.93	98.28	97.98

From the RSSI measurements in Figure 5, the RFM96W appears to be the best radio to use for the outdoor WSN. However, RSSI measurements by themselves are insufficient. Most manufacturers determine the RSSI by measuring power at the input of the transceiver, and this does not indicate whether the data has been corrupted during transmission. To determine whether such corruption has occurred, we must determine the percentage of packets successfully communicated between the stations.

D. Results: Packet Transmission

Figures 6a and 6b indicate the percentage of successful packet transmissions as a function of distance for low and high receiving antenna positions respectively.

In general, packet transmission is worse in Figure 6a than in Figure 6b. This can be ascribed to the reflections and absorption introduced by objects near the ground. Overall, the trends in Figure 6a are similar to those of the RSSI measurements. The RFM22B was not able to transmit a single packet successfully and the RFM23BP was only able to transmit 35% of its packets successfully at $250\mathrm{m}$ after which packet transmission reached 0%. The SI4463 was able to transmit all its packets without error until the distance between the stations reached $1000\mathrm{m}$. After this packet transmission rapidly approached 0%.

The RFM96W and E31-TTL are similarly effective in terms of successful packet transfers when the antenna is set low, with the radios successfully transmitting an average of 97.62% and 96.67% respectively of all packets over the maximum considered range of $5500\mathrm{m}$.

The trends in Figure 6b are also similar to those of the RSSI measurements. The SI4463 transmitted all of its packets successfully up to a distance of 1500m, after which packets were no longer received. The RFM96W and E31-TTL successfully received 98.93% and 99.29% of their transmitted packets respectively with the mobile antenna set high.

A summary of the percentages of packets successfully transmitted over all considered distances is presented in Table III. As noted from Figure 6, the radios perform better when the antenna is set to the high position than when it is set to low. The table also shows that there are large differences in packet reception between the 5 radios.

The radios which display most of the attributes required for our WSN as set out in Section 2 are the RFM96W and the E31-TTL. Overall, the RFM96W was able to successfully receive 98.28% of all packets while the E31-TTL was able to receive 97.28% of all packets transmitted. This indicates good performance by the LoRa capable RFM96W, which transmits with 10x less power than the E31-TTL.

V. Summary and Conclusion

We have considered the choice of a commercially available radio transceiver module for use in wireless sensor networks suitable for wildlife monitoring applications. Constraints include power consumption, physical size and communication range. Experimental evaluation firstly established that 433MHz offered a more compact antenna while maintaining almost the same signal strength achieved at 169MHz. Subsequently, experimental evaluation of 5 currently available radio modules indicated that the LoRa-capable RFM96W was able to outperform the other candidates. Using this device, it was possible to achieve 2% packet loss over a 5500m range at a power of 20dB m. We conclude that newly available LoRa communication modules offer a practical candidate for wildlife sensor networks.

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References

[1] J. Marais, S. Petrus, L. Roux, R. Wolhuter, and T. Niesler, "Automatic classification of sheep behaviour using 3-axis accelerometer data," in *Proceedings of the twenty-fifth annual symposium of the Pattern Recognition Association of South Africa (PRASA)*, 2014, pp. 97–102.

[2] Carlos Eduardo Cugnasca, Antonio Mauro Saraiva, Irenilza de Alencar Nääs, Daniella Jorge de Moura, and Gabriela Werner Ceschini, "Ad Hoc Wireless Sensor Networks Applied to Animal Welfare Research," in *Livestock Environment VIII, Iguassu Falls, Brazil*. St. Joseph, MI: American Society of Agricultural and Biological Engineers, 2008.

[3] "Range Calculation [APPLICATION NOTE]," 2015. [Online]. Available: http://www.atmel.com/Images/Atmel-9144-Range-Calculation_Application-Note.pdf

[4] P. Magaña-Espinoza, R. Aquino-Santos, N. Cárdenas-Benítez, J. Aguilar-Velasco, C. Buenrostro-Segura, A. Edwards-Block, and A. Medina-Cass, "WiSPH: A Wireless Sensor Network-Based Home Care Monitoring System," *Sensors*, vol. 14, no. 4, pp. 7096–7119, 2014.

[5] V. Dyo, S. A. Ellwood, D. W. Macdonald, A. Markham, C. Mascolo, B. Asztor, S. Scellato, N. Trigoni, R. Wohlers, and K. Yousef, "Evolution and Sustainability of a Wildlife Monitoring Sensor Network General," in *SenSys '10 Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, 2010, pp. 127–140.

[6] P. Zhang, C. M. Sadler, S. A. Lyon, and M. Martonosi, "Hardware design experiences in ZebraNet," in *Proceedings of the 2nd International Conference on Embedded networked Sensor Systems - SenSys '04*. New York, New York, USA: ACM Press, 2004, pp. 227–238.

[7] L. Zheng, J. Li, M. Hayes, and B. O 'Flynn, "Design of a Low Power Wireless Sensor Node for Environmental Monitoring," in *ISSC, 22nd IET Irish Signals and Systems Conference*, 2011.

[8] R. Du Toit, "Modern technology for rhino management," *Pachyderm*, vol. 22, pp. 18–24, 1996.

[9] Independent Communications Authority of South Africa, "The Radio Frequency Spectrum Regulations 2015," pp. 68–69, 2015. [Online]. Available: www.gpwonline.co.za

[10] T. Rama Rao, D. Balachander, T. Nishesh, and M. V. S. N. Prasad, "Near ground path gain measurements at 433/868/915/2400 MHz in indoor corridor for wireless sensor networks," *Telecommunication Systems*, vol. 56, no. 3, pp. 347–355, 2014.

[11] L. Ruiz-Garcia, P. Barreiro, and J. Robla, "Performance of ZigBee-Based wireless sensor nodes for real-time monitoring of fruit logistics," *Journal of Food Engineering*, vol. 87, no. 3, pp. 405–415, 2008.

[12] B. J. Henderson, P. Eng, R. Coudé, and P. V. Eng, "Radio Mobile Program Operating Guide," Calgary, Alberta, Canada, 2013. [Online]. Available: http://www3.telus.net/hendersb/documents/Radio Mobile.pdf

[13] HopeRF Electronic, "RFM22B/23B ISM TRANSCEIVER MODULE," pp. 1–70. [Online]. Available: http://ee-classes.usc.edu/ee459/library/datasheets/RFM22B.pdf

[14] Silicon Labs, "Si4464/63/61/60." [Online]. Available: https://www.silabs.com/documents/public/data-sheets/Si4464-63-61-60.pdf

[15] Chengdu Ebyte, "E31-TTL-1W_Datasheet_EN_v1.0." [Online]. Available: http://www.cdebyte.com/en/product-view-news.aspx?id=142

[16] M. Bor, J. Vidler, and U. Roedig, "LoRa for the Internet of Things," in *International Conference on Embedded Wireless Systems and Networks*. Junction Publishing, 2016, pp. 361–366.

[17] Semtech, "AN1200.22 LoRa Modulation Basics," 2015. [Online]. Available: http://www.semtech.com/images/datasheet/an1200.22.pdf

[18] C. A. Hornbuckle, "Fractional-N synthesized chirp generator," 2010. [Online]. Available: https://www.google.com/patents/US7791415

[19] Semtech Corporation, "LoRa FAQ." [Online]. Available: http://www.semtech.com/wireless-rf/lora/LoRa-FAQs.pdf

[20] HopeRF, "RFM95/96/97/98 Datasheet." [Online]. Available: http://www.hoperf.com/upload/rf/RFM95_96_97_98W.pdf

[21] A. Zogg, "Multipath delay spread in a hilly region at 210 MHz," *IEEE Transactions on Vehicular Technology*, vol. 36, no. 4, pp. 184–187, 1987.