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### Long range wireless sensor networks with transmit-only nodes and software defined receivers

Christof Huebner<sup>1</sup>, Rachel Cardell-Oliver<sup>2</sup>, Stefan Hanelt<sup>1</sup>,  
Tino Wagenknecht<sup>1</sup>, Alvaro Monsalve<sup>2</sup>

1. Institute for Industrial Data Processing and Communication,  
University of Applied Sciences Mannheim, Germany
2. School of Computer Science & Software Engineering,  
The University of Western Australia, Australia  
c.huebner@hs-mannheim.de, rachel@csse.uwa.edu.au

#### Abstract

Wireless sensor networks for environmental monitoring and agricultural applications often face long-range requirements at low bit-rates together with large numbers of nodes. This paper presents the design and test of a novel wireless sensor network that combines a large radio range with very low power consumption and cost. Our asymmetric sensor network uses ultra-low-cost 40 MHz transmitters and a sensitive software defined radio receiver with multichannel capability. Experimental radio range measurements in two different outdoor environments demonstrate a single-hop range of up to 1.8 km. A theoretical model for radio propagation at 40 MHz in outdoor environments is proposed and validated with the experimental measurements. The reliability and fidelity of network communication over longer time periods is evaluated with a deployment for distributed temperature measurements. Our results demonstrate the feasibility of the transmit-only low-frequency system design approach for future environmental sensor networks. Although there have been several papers proposing the theoretical benefits of this approach, to the best of our knowledge this is the first paper to provide experimental validation of such claims.

**Keywords:** wireless sensor network; environmental monitoring; path loss; radio propagation model;

# 1 Introduction

Environmental monitoring and agricultural applications can utilise wireless sensor networks to observe physical parameters such as soil water content, temperature, humidity with high spatial and temporal resolution. A prominent example are terrestrial environmental observatories [6] where distributed soil water content measurements at the catchment and sub-catchment scale are required. The typical scale is between 0.1 km and up to 100 km, bridging the gap between point measurements and remote sensing. Since the number of measurement stations required may be many hundreds to thousands, the cost of sensors and radio nodes must be kept as low as possible. The challenge addressed in this paper is to develop fully integrated wireless sensor networks with low power consumption and large broadcast range at low cost [15].

Most existing wireless sensor networks use nodes with a short-range radio and use software protocols to schedule the nodes and co-ordinate multi-hop routing in order to minimise power usage. Nodes have a relatively small radio range up to a few hundred meters that is also affected by the crop growth stage and vegetation density [12]. There are several disadvantages to this approach including the complexity of software protocols required to co-ordinate the nodes' behaviour and the unreliable nature of the short range radio links that requires sophisticated fault tolerance mechanisms.

An alternative design solution is to use low frequency, long-range radios to build a single-hop network of a base station with satellite sensing nodes [22]. For example, the JCUMotes operating in a licence free 40 MHz band with 1 W effective radiated power achieve more than 10 km range. However, the long range is achieved at the expense of high power consumption and large antenna size [20]. Significant advantages of this approach are the much simpler software protocols with no routing features, and that transmissions in the 40 MHz band are expected to be more reliable in outdoor settings than short range transmission in the 433 MHz or 915 MHz band used by most existing sensor network radios.

The main contribution of this paper is to design and test a novel wireless sensor network which combines a very large radio range with very low power consumption and costs. The network is intended for deployment of a large number of nodes for applications in environmental science and agriculture. The paper presents results of experiments with our prototype sensor network in several different outdoor settings that demonstrates the feasibility of this system design for future environmental sensor networks. Although there have been several papers proposing the theoretical benefits of such an approach, to the best of our knowledge this is the first paper to provide experimental validation of such claims.

## 2 Sensor Network Design Rationale

Our design criteria are minimal cost per sensing unit, scalability to thousands of sensing nodes, dependability, and simplicity of software protocols. In this section we outline the different design choices and justify our design decisions for a long-range sensor network of transmit-only nodes.

### 2.1 Radio propagation and frequency selection

Typical radios for sensor network nodes use frequencies of 433 MHz, 868/915 MHz or 2.4 GHz. Reasons for selecting these frequencies include the frequency allocations of the regulatory bodies (e.g. license free industrial, scientific and medical bands) and the corresponding availability of integrated radio circuits for these frequencies. Some frequency allocations exist at lower frequencies, most interestingly in the 40 MHz band, with different bandwidth depending on country specific regulations. For example, in Australia the frequency range is from 40 to 41 MHz divided into two parts with 100 mW and 1 W maximum effective radiated power [16].

An important advantage of the 40 MHz band compared to the above-mentioned higher frequency bands is the lower path loss. Free space path loss for frequency  $f$  in MHz and distance  $d$  meters between the transmitter and receiver antennas is given by [13]:

$$L_{free}(dB) = -27.56 + 20 \log_{10}(f) + 20 \log_{10}(d) \quad (1)$$

Increasing the frequency by a factor of 10 raises the free space path loss by 20 dB. When radio waves propagate near the ground with a line of sight path together with ground reflections the plane earth model is more appropriate. For distance  $d$  in meters and the heights of transmit and receive antennas given by  $h_T$  and  $h_R$  respectively the plane earth model is given by [13]:

$$L_{PE}(dB) = 40 \log_{10}(d) - 20 \log_{10}(h_T) - 20 \log_{10}(h_R) \quad (2)$$

This equation is frequency independent but sensitive to the heights of the transmit and receive antennas. In the case of transmission through foliage an additional increase of loss with increased frequency is observed. A lot of effort has been put into empirical modelling of the foliage induced excess loss at different frequencies [13] but there is a lack of empirical path loss data and path loss models for short range communication using the 30-88MHz frequency range [1].

A model for low frequency propagation indoors and over very short distances is given in [1], but this model does not scale for our longer outdoor distances of 1 to 2 km. An additive model that accounts for obstacles in the line of sight is

given in [10]. A receive location behind a building, for example, adds 7 to 9 dB loss (Table 1 page 187 [10]) or 15-24 dB (Table 3 page 188 [10]). The additional path losses of about 15 to 35 dB we observed in our campus experiments with many buildings agree with these observations. Another model that accounts for additional path loss for propagation through a forest can be given in terms of an extra path loss factor added to the plane earth model  $L_{PE}$  of equation 2 [13]. This forest model uses three constants:  $A$ , a constant multiplier for the forest path loss,  $B$  an exponent for the transmission frequency  $f$ , and  $C$  an exponent for the distance  $d$  between transmitter and receiver. Section 4 demonstrates that the  $L_{FO}$  forest model provides the best fit for our 40 MHz experimental data.

$$L_{FO}(dB) = L_{PE} + Af^Bd^C \quad (3)$$

In general using lower frequencies increases radio range. The disadvantage of the 40 MHz band is the larger size of the antenna. A quarter wave antenna of about 1.9 m long using a simple insulated copper wire is required. For our intended agricultural and environmental applications we have found it sufficient for the antenna to be attached to a pole or simply wound around a tree branch or stem.

An additional slight disadvantage of the 40 MHz band is the higher atmospheric noise level which limits the usable sensitivity of the receiver. Man-made noise and interference exist at all frequencies and will present a severe problem if the projected massive use of wireless sensor networks eventuates [23]. Spectral occupancy at VHF in urban and rural areas was investigated in [9] for frequency-agile cognitive radio applications. They concluded that approximately 80% of the 30-60 MHz band is essentially free of signals to within about 7 dB of the environmental noise limit at 30 kHz resolution. Rural areas are much quieter and therefore especially suitable for a 40 MHz wireless sensor network deployment.

## 2.2 Single hop versus multi-hop

The most commonly used data transport technique in wireless sensor networks is multi-hopping. The rationale for this design choice is that it provides long communication range (over multiple hops) at low energy cost (short range radio for single hops). However, a few studies indicate that multi-hop may not always be the optimal solution. For example, [4] claims that single-hop is superior in realistic cases and that a hierarchical structure where low-level nodes communicate with higher layers via a single-hop only is favourable.

Another disadvantage of multi-hop networks is the complexity of software protocols required to manage the network. Software protocols must manage the synchronisation of sensing nodes, discovery of neighbouring nodes, maintenance of

multi-hop routes through the network and fault tolerance for noisy node to node radio communication. A message transmitted over  $n$  hops each with delivery probability  $p$  has probability  $p^n$  of being correctly delivered. Therefore protocols for multi-hop environments must be highly fault tolerant and able to re-transmit lost packets. Conversely, they must also maximise energy efficiency by avoid unnecessary re-transmissions of messages. Advantages of a single hop configuration include no need for routing considerations and therefore simpler protocol stack, lower delay, simpler time synchronisation and the possibility of using centralised media access control. Zhou *et al* propose a single hop asymmetric structure with low-power satellite nodes communicating with a powerful base station that is not energy limited [22]. A highly efficient coding with low encoding complexity is proposed for the low-power radio nodes with high decoding complexity at the base station. Together these coding and decoding strategies are used to increase radio range. Similar conclusions are drawn in [17] where different forward error correction codes from simple repetition to convolutional and turbo codes are investigated.

### 2.3 Transmit-only versus transceiver

Using radio transceivers in the sensing nodes is the most common technique in wireless sensor networks. The advantage, of course, is bi-directional communication that allows for multi-hopping, automatic repeat requests and information flow in both directions. However, in the case of environmental monitoring and in many agricultural applications the information flow is usually only from the sensors to a base station as a sink. In these cases the use of transmit-only radio nodes can be considered. For example, a hybrid network architecture consisting of transmit-only sensors and cluster-heads with full-duplex capability was proposed in [5]. The transmit-only nodes take sensor measurements and forward them to the cluster-heads. Cluster-heads are responsible for information transport to the sink. The benefits of this approach are the much lower cost of the transmit-only nodes and a possible reduction of their power consumption. A practical implementation of transmit-only sensors are presented in [21] where a 10 times power requirement reduction compared to a transceiver type approach is claimed. In [11] an application for monitoring relative humidity and temperature in an art gallery is described using pure ALOHA for random transmission of measurement data. The term ALOHA may be misleading here since there is no feedback to the transmitter, but this term is also often used for transmit-only stochastic MAC protocols as well. A MAC protocol with short random time intervals added to a long fixed time interval is developed in [14] for a housing community. The probability of successful transmission depends on node density and number of time slots is investigated. The results confirm that it is possible to achieve a high probability of successful data transmission with transmit-only radio nodes.

## 3 System Design

Based on the above considerations we have developed a single-hop transmitter-only wireless sensor network. The main goal was to achieve a long radio range comparable to the communication range of a typical multi-hop wireless sensor network with about 10 hops. This corresponds to at least 10 km range line of sight, a few km in rural areas and at least 1 km in urban areas. If this goal can be achieved, then a single-hop network would be an attractive alternative to a multi-hop network.

### 3.1 Data-Rate and Power Trade-offs

An important constraint for successful implementation of a 40MHz sensor network is a very low data rate requirement for each sensor of about 5 bytes of information every 5 minutes. Applications for measuring soil water content and temperature typically satisfy these constraints. In order to increase a radio link range by a factor of 10 the link budget has to be increased by 20 dB in case of free space propagation (eq 1) and 40 dB in case of the plane earth model (eq 2). Of course it is impracticable to achieve this by increased transmit power since this would mean 1 W compared to the typical 10 mW in the case of 20 dB and even 100 W in the case of 40 dB. The alternative is to increase the sensitivity of the receiver at the base station. The sensitivity of a receiver depends strongly on its bandwidth. Lowering the bandwidth means higher sensitivity as a result of decreased noise. For example, Figure 1 shows that radio chip CC1020 from Texas Instruments is among the most sensitive single chip transceivers available and has a sensitivity of -118 dBm at 9.6 kHz bandwidth compared to -97 dBm at 307.2 kHz [18]. So choosing the smallest bandwidth increases the link budget by 21 dB compared to the largest bandwidth.

The disadvantage of this approach is that the data rate is reduced at the same time. Therefore the transmitter has to be on for a longer time to transmit the same amount of data and that requires more energy. Another problem is that the frequency accuracy of the crystal controlled radio chip is often not sufficient to allow for the smallest bandwidth. The frequency of the crystal changes with temperature and may result in an offset of transmit and receiving frequency of radio nodes and therefore loss of communication. Using larger bandwidths eases the frequency accuracy requirements at the expense of lower sensitivity and lower link budget due to more noise power. A certain frequency offset  $\Delta f$  between transmitter and receiver frequency is less harmful in a wide band system (Figure 2, top) compared to a narrow band system (Figure 2, middle). In case of the narrow band system the bandwidths do not overlap and there is no reception at all. The disadvantage of narrow band systems are the stringent requirements on frequency

Data rate [kBaud]	Channel spacing [kHz]	Deviation [kHz]	Filter BW [kHz]	Sensitivity [dBm]		
				NRZ mode	Manchester mode	UART mode
2.4 optimized sensitivity	12.5	$\pm 2.025$	9.6	-115	-118	-115
2.4 optimized selectivity	12.5	$\pm 2.025$	12.288	-112	-114	-112
4.8	25	$\pm 2.475$	19.2	-112	-112	-112
9.6	50	$\pm 4.95$	25.6	-110	-111	-110
19.2	100	$\pm 9.9$	51.2	-107	-108	-107
38.4	150	$\pm 19.8$	102.4	-104	-104	-104
76.8	200	$\pm 36.0$	153.6	-101	-101	-101
153.6	500	$\pm 72.0$	307.2	-96	-97	-96

**Table 19. Typical receiver sensitivity as a function of data rate at 433 MHz, FSK modulation, BER =  $10^{-3}$ , pseudo-random data (PN9 sequence)**

Figure 1: Typical Receiver Sensitivity - CC1020 datasheet Table 19 page 32 [18]

accuracy which are hard to achieve with low cost components. On the other hand their advantage is the better sensitivity due to less total noise power in the smaller bandwidth.

To overcome these problems the authors propose an approach using a software defined radio receiver at the base station. The transmitters may transmit at an arbitrary frequency between a predefined lower bound  $f_1$  and upper bound  $f_2$  (Figure 2 bottom). The software defined receiver is able to receive this complete frequency range and then select and filter individual nodes even if many nodes are transmitting. Multiple and adjustable narrow band filters are tuned to the specific transmitting frequencies for reception with very high sensitivity. Decoding can be performed with a time-frequency spectrogram analysis. This corresponds to a multichannel receiver. The transmitter data rate is chosen to be very small, in the order of 10 bit/s resulting in a bandwidth of approximately 10 Hz. The software defined receiver is capable of filtering the small bandwidth signal out of the complete frequency range using digital signal processing. Due to the small bandwidth the sensitivity is extremely high. In practical implementations a sensitivity in the order of -140 dBm was achieved resulting in a link budget improvement of more than 20 dB compared to the best integrated radio circuits at their lowest bandwidth. The theoretical limit is -174 dBm/Hz respectively -164 dBm for 10 Hz bandwidth considering thermal noise only. So further improvements are possible. At 10 bit/s the transmitting time is relatively long. So part of the energy reduction due to the transmitter-only approach is lost but the nodes are still very energy efficient at low data rates.

Another advantage of the software defined radio approach is the capability to receive several signals at the same time if they differ in frequency. Our solution has some similarities to a software-define radio system for backscattering sensors

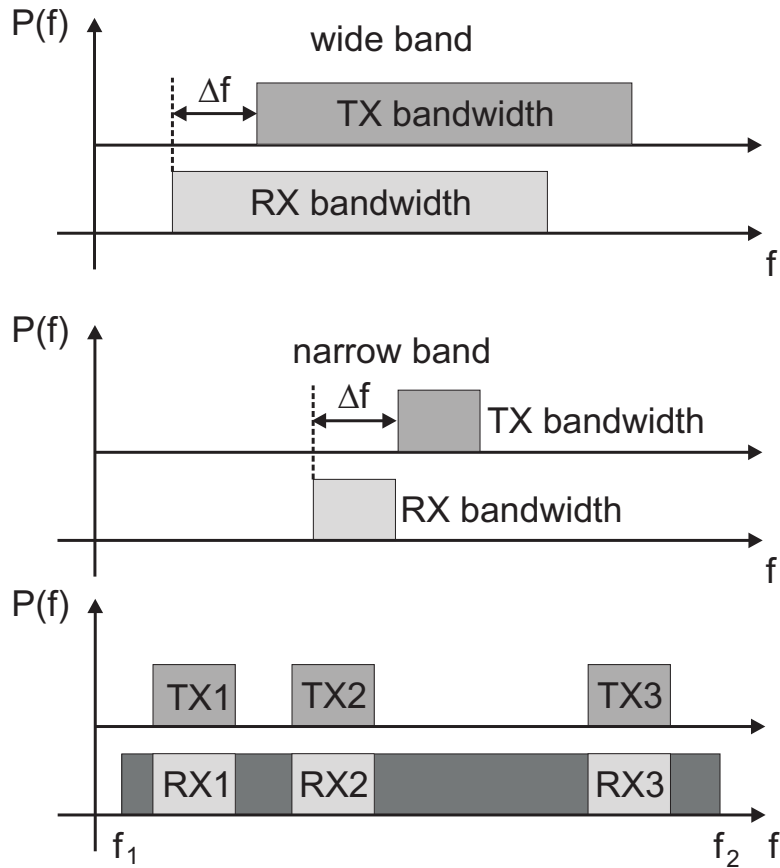


Figure 2: Transmitting and receiving spectrum for wide band (top), narrow band (middle) and multichannel (bottom) systems

where the goal is to install a 100 m range 1000 sensor network in a botanical garden [19]. Each sensor's signal is a narrow-band signal centered around its own unique subcarrier frequency allowing multiple sensors to operate simultaneously. The software defined receiver provides highest sensitivity and multi-channel reception. Therefore the media access control protocol can be considered as a combined TDMA/FDMA concept when the transmitting nodes are frequency variable. This way the constraints of the ALOHA protocol are relaxed as there are both time slots and frequency slots. Therefore it is possible to have a very high density of nodes. Using a channel bandwidth of about 100 Hz it would be possible to get 10,000 channels in the frequency band between 40 MHz and 41 MHz. With 5 second transmit time each 5 minutes there would be 30 time slots. In total there are  $10,000 \times 30 = 300,000$  time/frequency slots available in a 5 minute period. It should be mentioned that besides the combined TDMA/FDMA solution spread spectrum techniques with code division or code phase division multiplex may be



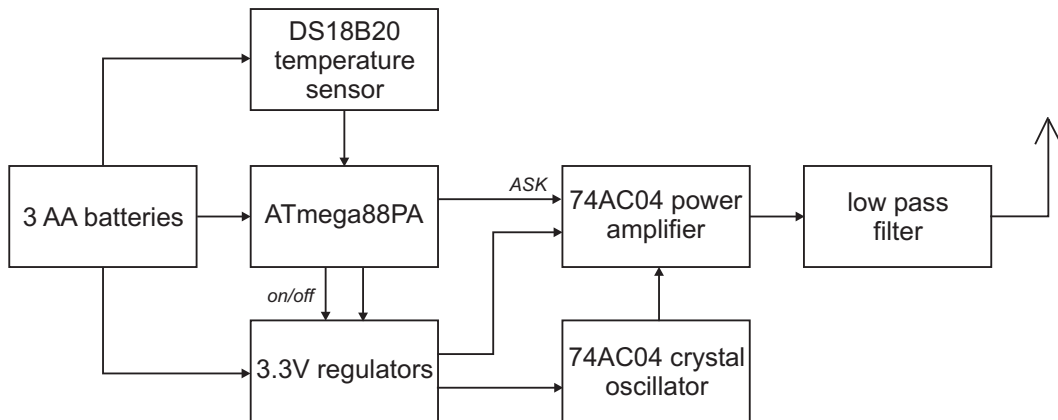


Figure 3: Block diagram for the transmitter

an alternative. In [8] a transmit-only system with a satellite-based receiver for asset tracking, perimeter sensing and environmental monitoring is described. The philosophy is the same by shifting complexity away from many distributed transmitters into a sophisticated receiver to reduce costs. The applied code division multiplex seems to be well suited for satellite-based systems where the near/far problem of the spread spectrum technology is not as severe as in terrestrial applications. TDMA/FDMA is less vulnerable in case of weak signals appearing together with strong signals which is typical in a wireless sensor network topology. Therefore we decided on this solution. In the following sections the practical design of transmitter and receiver are described to demonstrate the feasibility of the proposed approach.

### 3.2 Transmitter Design

The transmitter design is shown in Figure 3. It uses separate voltage regulators for the crystal oscillator and the power amplifier to achieve exceptional frequency stability. The bandwidth of the transmitted signal is less than 10 Hz. Total component costs are less than \$15 in small quantities which can be further decreased in mass production. The transmitter is based on an Atmel AVR Mega88PA microcontroller requiring about 1 mA in active mode at 1 MHz clock and 4V and a few  $\mu\text{A}$  in powerdown mode. Instead of a dedicated radio chip a simple and low cost crystal oscillator with high speed logic gates similar to the design of [7] but with ASK instead of FSK modulation was developed. Using 4 CMOS inverter gates from a 74AC04 integrated circuit in parallel an output of 40 mW (16dBm) was achieved requiring about 30 mA at 3.3 V. The transmitter generates a stable signal with low phase noise which is important for maintaining a low bandwidth. The short term drift is low enough so that no automatic frequency control on the

receiver side is required. The crystals of individual radio nodes differ in their absolute frequency due to production uncertainties. In our case this is actually desired. Typical absolute frequency accuracy of the crystals is 20 to 50 ppm which corresponds to 800 Hz to 2 kHz deviation at 40 MHz. In order to introduce an additional frequency offset the crystal can be loaded with capacitances for tuning. This will be used to increase the probability that two nodes transmitting at the same time do not interfere due to a sufficient frequency difference. The temperature dependence of the crystal frequency further introduces some randomness in the transmit frequency. Nevertheless the tuning range of a crystal is limited to a few kHz, so for covering a 1 MHz band a PLL (phase locked loop) or DDS (direct digital synthesis) will be required. This way it will be possible to change the transmission frequency from one transmission to the other creating a slow frequency hopping system. For the demonstration in this work the tuning range of a few kHz was sufficient. The energy consumption is mainly dependent on the time for transmission. 5 minute intervals with each 5 seconds transmission time means 24 minutes total transmission time per day and a consumption of  $24/60 \cdot 30\text{mAh}/2 = 6\text{mAh}$  per day (consider that with ASK respectively on-off keying full power is only needed half of the time), With 2000 mAh batteries the node life time is about 333 days neglecting battery self-discharge and sleep mode consumption.

### 3.3 Receiver Design

Two different single sideband receivers were used (Yaesu VR-500 and Winradio G-305). Both convert the received ASK signal into an audio signal. The audio frequency depends on the offset of the received frequency compared to the nominal receiving frequency. Bandwidth is 3 kHz for the VR-500 and up to 15 kHz for the GR-305. The audio signal is filtered and demodulated using digital signal processing. For demonstration purposes the limited bandwidth of the receivers is sufficient but future large scale deployments would require larger bandwidths and high speed digital signal processing. Newest software defined radio receivers like the Winradio WR-G31DDC are equipped with 2 MHz-wide instantaneous bandwidth available for recording, demodulation and further digital processing in a frequency range up to 50 MHz. For the demonstration digital signal processing was not performed in real-time but the audio signal was recorded in mp3 format in 4 hour chunks on a CF card with a low-power embedded PC placed together with the receiver near the antenna. Later digital signal processing (filtering, demodulation and decoding) was performed on standard PC.

## 4 Experimental Results

### 4.1 Radio Coverage

Radio propagation experiments were performed in two different outdoor environments: a parkland and an urban setting. A 40 MHz transmitter with 16 dBm output was placed at a base position with a vertical half wave dipole. The same antenna was used for a mobile receiving station with the Winradio G-305 and an additional GPS receiver provided location information. Path loss was calculated from the S-meter readings from the experiments using the following formula.

$$L_{Exp}(dB) = P_{tx} + G_{tx} + G_{rx} - L_{tx} - L_{rx} - P_{rx} \quad (4)$$

where  $P_{tx} = 16$  is the transmit power in dBm and  $P_{rx}$  the receive power measured in dBm by the S-meter.  $G_{tx} = 2.15$  and  $G_{rx} = 2.15$  are the transmitter and receiver antenna gains, respectively, in dBi.  $L_{tx} = 1$  and  $L_{rx} = 1$  are cable loss for the transmitter and receiver in dB.

Figure 4 shows the relative magnitude of measured path loss at different receiver positions in the park and on campus. The transmitter is at position 0,0 in both graphs. Distances were estimated in meters using the Haversine formula for great-circle distances between two signed decimal latitude/longitude points. Path loss ranged from 66.3 dB to 132.3 dB in the Kings Park experiment and from 64.3 dB to 129.3 dB in the University campus experiment. On the campus with a transmitter placed on the roof of the school building at a height of approximately 12 meters, it is possible to cover the whole campus area (about 1.1 km x 0.5 km) with a single hop, even though there are massive obstructions of line of sight from many buildings. Compared to previous experiments in the same environment at 915 MHz and 2.4 GHz it was discovered that spatial fading (constructive and destructive interference due to multi-path propagation) is less pronounced at 40 MHz. The parkland chosen is a site with lawns and native bushland. Both transmitting and receiving antennas were placed approximately 2 m above the ground. The 40 MHz radio coverage for these landscape is shown in Figure 4. Former experiments at 915 MHz achieved about 250 m range through the bushland. With the 40 MHz systems it seems feasible to cover distances of up 1800 m.

Figure 5 shows the measured path loss in dB against distance in meters from the transmitter for both experiments. Theoretical predictions of the path loss are also given for the three different models introduced in Section 2: free space, plane earth and a fitted forest model. The difference in the plane earth model curves for the two experiments is because of the height of the transmitter antenna differed: 12 m on the campus experiment and 2 m in the parkland experiments.

The path loss measured experimentally is higher than both the free space and

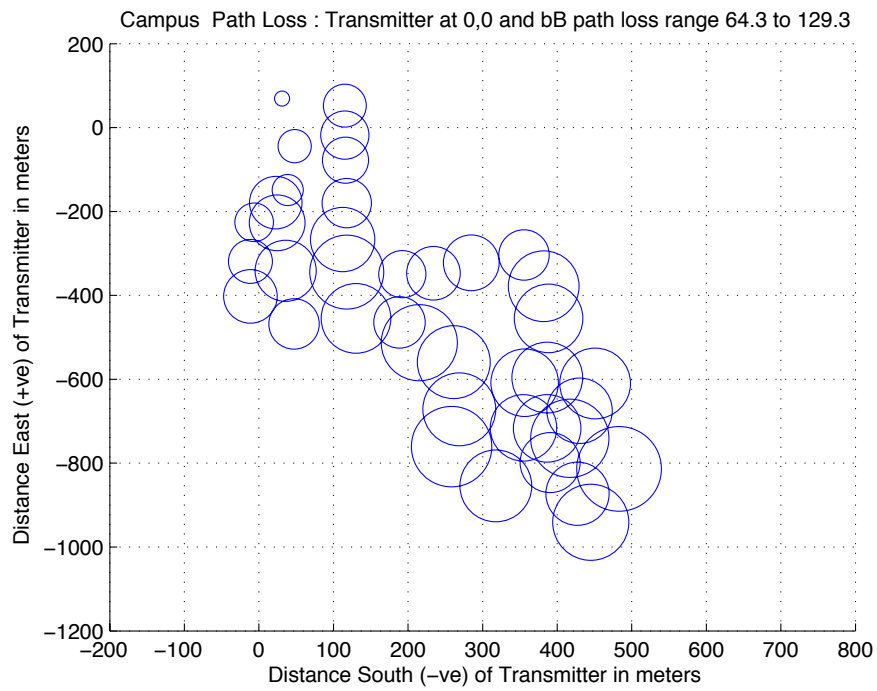
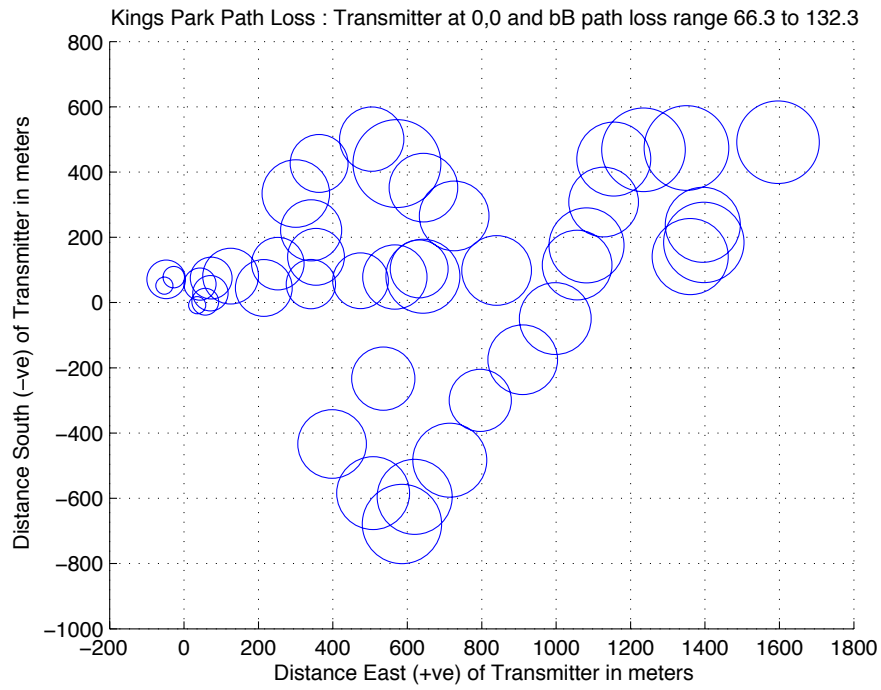


Figure 4: Path loss at different receiver locations from 66.3 dB to 132.3 dB in Kings Park (left) and from 64.3 bB to 129.3 bB in University campus (right) both with transmitter at (0,0)

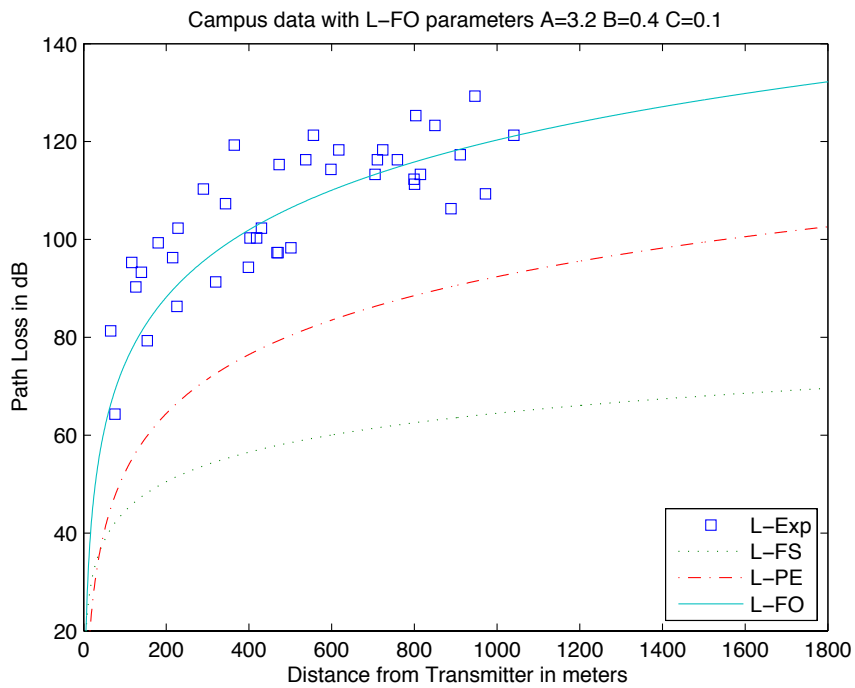
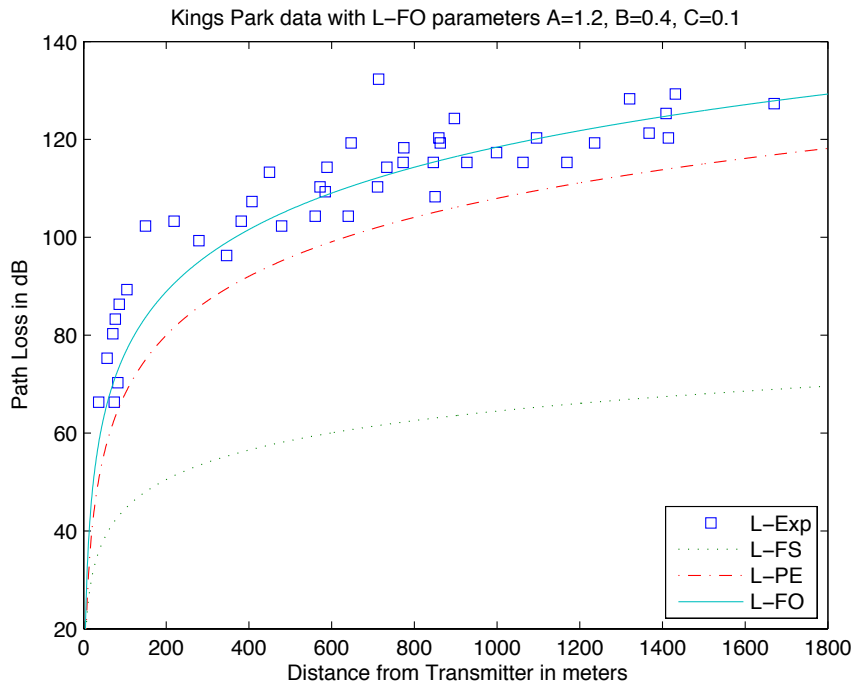


Figure 5: Path Loss versus distance for Kings Park (left) and University campus (right) showing experimental data (L-Exp) and the Free Space(L-FS), Plane Earth (L-PE) and Forest (L-FO) models

plane earth models because in reality obstructions between the transmitter and receiver have a significant effect on path loss. The forest path loss model given in equation 3 extends the plane earth model with a factor for path loss due to obstructions. Experiments in [13] at 300 MHz up to 1000m distance in a forest least squares error fitting to experimental data identified the constants  $A=0.48$ ,  $B=0.43$  and  $C=0.13$  for equation 3. Our setting uses the lower frequency of 40 MHz over larger distances. After preliminary analysis, we decided to use similar constants to [13] for the frequency and distance exponents and varied only the constant parameter  $A$  to fit the forest model to our data to minimise the least squares error. It can be seen in Figure 5 that the forest path loss model  $L_{FO}$  with  $A = 1.2$  and  $A = 3.2$  provides a good fit for parkland and urban experiments, respectively, when  $B = 0.40$  and  $C = 0.10$ .

Figure 6 compares the measured path loss against distance from both experiments. Interestingly, it seems that although the plane earth model predicts lower path loss with a higher receiver, the experimental results appear to be independent of the antenna height. We believe this is because in the campus setting the much higher rate of obstructions cancelled out the improved performance from the higher antenna. In future work we plan to investigate further experimental evidence to validate theoretical models for our proposed application area of agricultural and environmental monitoring using a 40 MHz sensor network with 1 to 2 km range.

## 4.2 Radio Consistency

The previous experiments show the quality of radio links across a landscape where all measurements were taken within a period of a few hours. At typical sensor network frequencies of 433 MHz or 915 MHz, radio links are known to vary significantly over time. So we performed a further experiment to measure the stability of long range radio links over several days when a 40 MHz transmitter is used. This experiment also differed from the previous ones in that 4 transmitters and one receiver were used, and all nodes were static throughout the experiment, except for a few periods where nodes were removed for corrections. For this experiment, four transmitters were placed at distances of 400 m, 600 m, 800 m and 1200 m from a receiver mounted on the roof of our building. Each transmitter sent a temperature measurement once every 5 minutes. The network ran continuously over 4 days.

Figure 7 shows the range of link quality observed over a 72 hour period from the experiment for the transmitters at different distances from the receiver. The largest distance was about 1 km with high buildings obstructing line of sight. Though the roof-top air condition system produced strong interference in the 40 MHz band all transmitters could be received. The performance of the most distant transmitter S-1000 was worst, with a median of 5 packets received out of 12 transmitted per hour. The other three nodes all performed well with medians of 8 or 9 packets out

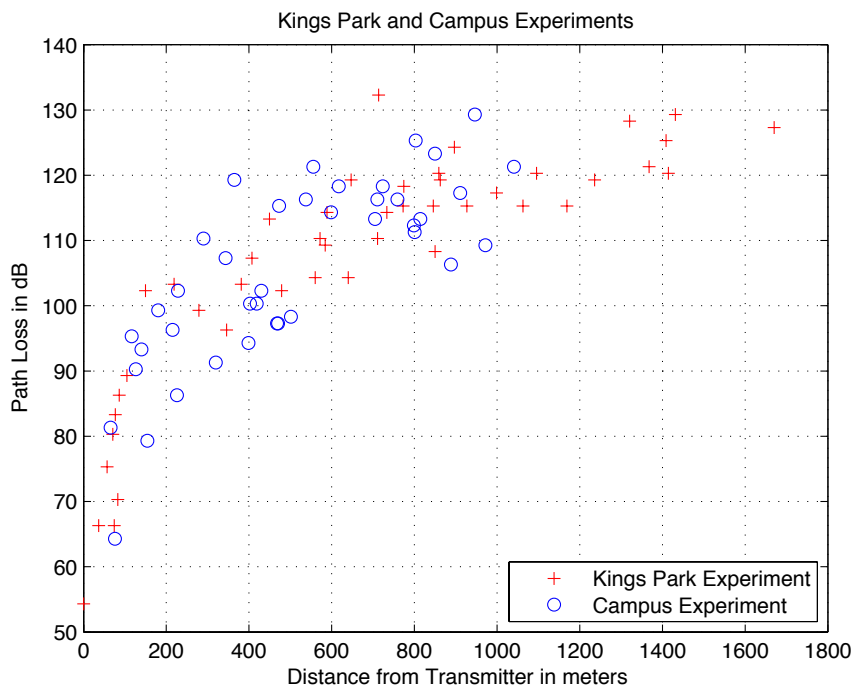


Figure 6: Path loss vs distance for Kings Park and University campus experiments

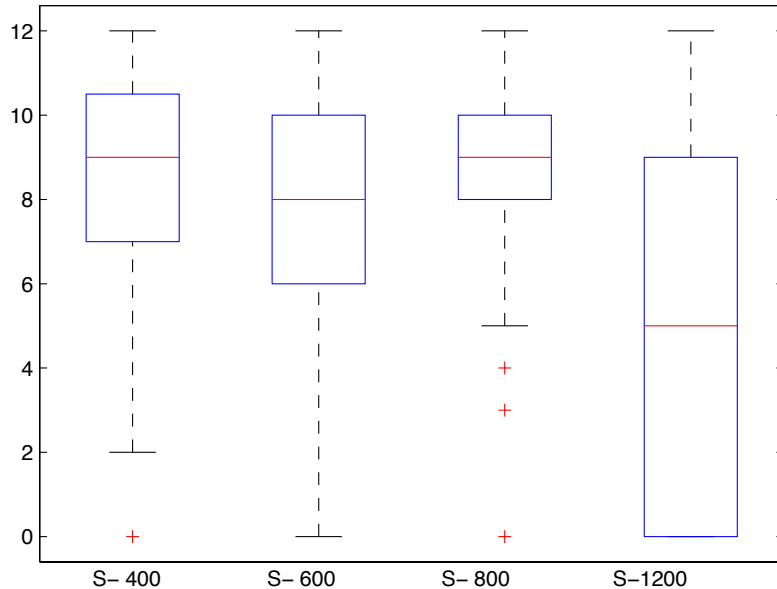


Figure 7: Variation in link quality for 4 University campus transmitters over 72 hours

of 12 received per hour. The upper and lower quartiles are shown in Figure 7 by the range of the boxes, extreme values by the whiskers and outliers by the crosses.

Table 1 reports the mean and standard deviation for the number of packets received per hour out of the 12 packets that were transmitted each hour and compares this with the link quality that would be required from a traditional multi-hop network. In previous experiments in the same environment 915 MHz nodes had a transmission distance of around 200 m. So we can compare the number of hops, and required link quality for each hop in order to achieve the same performance as the 40 MHz links. The shortest distance of 400 m requires 2

Transmitter Identifier	Distance in meters	Mean packet rate per hour	Standard deviation	Equivalent multi-hop mean packets and hops
S-400	400	8.29/12	2.95	9.97/12 (2 hops)
S-600	600	7.71/12	2.74	10.35/12 (3 hops)
S-800	800	8.56/12	2.67	11.03/12 (4 hops)
S-1000	1000	5.04/12	4.53	10.09/12 (5 hops)

Table 1: Packet delivery rate for 4 University campus transmitters over 72 hours



hops and average link quality of at least  $p = 9.97/12$  since we require  $p^2 \geq 8.29$ . Similarly, the 800m link would require 4 hops and an average link quality at least  $11.03/12$  since we must have  $p^4 \geq 8.56$ . Even to match the poor quality 40 MHz link S-1000 we would require 5 hops each with link quality of at least  $10.09/12$  to achieve  $p^5 \geq 5.04$ .

### 4.3 Data Fidelity

Our experiments demonstrate that the average packet reception rate for the best 3 links over the 40 MHz channel up to 800 m distance is in around 8 packets out 12 received per hour. There are a number of techniques that can be used to improve this. For example, the decoding process used for these experiments is not optimal, although sufficiently stable for our feasibility study. Also, the ratio of data received versus data collected can be increased by transmitting each packet more than once. For example, since packet losses are largely independent, transmitting each packet twice should result in nearly 100% data collection. However, before investing network energy and complexity to increase the data collection ratio, we should consider the fidelity of the currently collected signal. That is, how much *information* about the observed temperatures has been lost? We measure fidelity by using a simple repair strategy to estimate missing data. Temperature observations are sent by each node once every 5 minutes. For any gaps between received observations, if the gap is less than 30 minutes, and the trend of the data series before and after the gap is the same, then we can estimate the missing values using linear interpolation. In the case that the trend direction has changed, then we have missed a local minimum or local maximum and so can not estimate the missing data reliably. Similarly, for gaps between observations of more than 30 minutes, we can not reliably estimate the missing data. Using this simple repair scheme gives an additional 1 packet per hour over the received data. This ratio could be further improved by the transmitting nodes simply sending high priority observations, such as local maxima and minima 2 or more times. In this way, we can deliver data with a high information content even without a feedback channel.

Table 2 shows how repairing the received data can result in high fidelity without the requirement of using acknowledged communication. The fidelity was estimated over the same 72 hours period used for link quality observation. We were able to repair over 1 packet per hour for the received data from transmitting nodes at 400m, 600m and 800m. This represents around 9% increase in the mean packet rate. The farthest node presented the lowest fidelity with 0.46 packets per hour. The use of a simple repair strategy for temperature monitoring corroborates the high fidelity of the received data, even with no retransmission or acknowledgements. If the transmitter nodes were programmed to retransmit high priority data (for example, daily maximum and minimum temperatures and unusual changes)

Transmitter Identifier	Distance in meters	Mean packet rate per hour	Mean fidelity per hour
S-400	400	8.29/12	9.39/12
S-600	600	7.71/12	8.69/12
S-800	800	8.56/12	9.40/12
S-1000	1200	5.04/12	5.50/12

Table 2: Fidelity of data delivery for 4 University campus transmitters over 72 hours

then the delivered data would be fit for purpose, and at a much lower cost than for a traditional multi-hop sensor network.

## 5 Conclusion

In this paper we presented a design and experimental evaluation for a new wireless sensor network for environmental monitoring and agricultural applications. It is based on a low-cost transmit-only single-hop structure where information flow is unidirectional from many nodes to a sink. Acknowledgements are not possible leading to a limited probability of packet loss which is acceptable for many applications. The outstanding feature is the long range which is possible due to very low data rates of the sensors and a sensitive software defined receiver at the base station which is not energy limited.

Our experimental results demonstrate the feasibility of an asymmetric arrangement with ultra low-cost transmitters and a sensitive software defined radio receiver with multichannel capability. Experimental radio range measurements in two different outdoor environments demonstrate a single hop range of up to 1.8 km. The reliability and fidelity of communication is demonstrated using an experimental deployment for distributed temperature measurements. These results support the proposition that 40 MHz sensor networks with transmit-only nodes will be significantly cheaper and simpler to build as well as being more reliable than a traditional multi-hop sensor network using higher frequency radios.

## 6 Future work

In this work it was demonstrated that the basic idea of a sensor network consisting of long range, transmit-only sensors is feasible. In future work it is necessary to improve the encoding at the transmitter side, e.g. using forward error correction. The automatic multichannel reception with the software define radio receiver can also be improved. The hardware for a low-cost software defined radio receiver for

the 40 MHz band will be developed. It might be even possible in the future to implement a low cost software defined radio receiver on each node and therefore achieve full transceiver capability. The 40 MHz band is also very interesting for underground wireless sensor networks. Though this is also possible at 2.4 GHz [3] the attenuation is very large and prohibits deep installations. So lower frequencies are preferred [2]. Preliminary experiments indicate that a 40 MHz transmitter placed below the plough depth on an agricultural field has many hundred meters of range and can be permanently installed.

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