868MHz 6LoWPAN with ContikiMAC for an Internet of Things Environmental Sensor Network

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***Abstract*— When deploying an Internet of Things Environmental Sensor Network (ESN), the communications range of nodes becomes a critical factor when attempting to cover a large geographic area. The 2.4 GHz radios that are commonly used for Wireless Sensor Networks do not have sufficient range for ESN applications. We investigate the performance of an 868MHz CC1120-based sensor node that incorporates a Zolertia Z1 and runs the Contiki operating system with multi-hop 6LoWPAN networking using the ContikiMAC radio duty cycling protocol. Comparisons with the commonly-used CC2420 2.4GHz radio, in terms of latency and throughput, show that the CC1120 can offer significant performance benefits for certain deployment scenarios. Brief details of an ongoing deployment are presented.**

Keywords—6LoWPAN; ESN; WSN; IoT; Contiki; ContikiMAC; Sub-GHz; 868 MHz

I. Introduction

Environmental Sensor Networks (ESN) [1] have emerged from the Wireless Sensor Network (WSN) area with a specific set of applications and hence technical challenges. Among the difficulties faced, the issue of integrating different hardware on the low power radio network is one aspect that needs addressing. Several Internet of Things (IoT) WSNs exploit the utility of an IoT operating system, such as Contiki [2], to provide standards-compliant networking in a multitasking environment with energy-efficient radio duty cycling protocols [3]. Many contemporary IoT WSNs use short-range (up to ~300 m) low-power 2.4 GHz radios that support 802.15.4 with a multi-hop capable 6LoWPAN networking stack [4,5]. This allows for end-to-end IPv6 connectivity to the sensor nodes, and the standardisation of protocols allows different hardware designs to interoperate in one network.

In contrast, recent ESNs tend to use custom communications protocols with a wide range of sub-gigahertz radios to provide communications over longer ranges (up to several kilometres) in harsh environments. The Glacsweb project has used 151 MHz radios for communications with sub-glacial sensor probes and 868 MHz radios for surface node communications [6]. Transmit-only 30 MHz radios have also been used for sub-glacial monitoring [7]. The Permasense project has made extensive use of 868 MHz radios for monitoring in the Alps [8-10] and transmit-only 433 MHz radios have been used for wildfire detection and alerting [11].

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Of these different frequency bands the 868 MHz band, or the 915 MHz band in North America, shows potential for use in IoT ESNs as it has good propagation characteristics that enable communications over several kilometres and is allowed for by the 802.15.4 standard [12]. Prior to 2012 the 868 MHz band was limited to 20 kb/s with simple modulation which was not consistent with the 915 MHz band. The 802.15.4G amendment introduced the 50 kb/s and 200kb/s data rates for both bands [13]. Low-cost radios that support 802.15.4G, such as the CC1120 [14], are also now readily available but not yet fully supported by IoT operating systems.

As part of the Mountain Sensing project, a platform consisting of a Zolertia Z1 sensor mote and a CC1120 sub-gigahertz radio running the Contiki operating system, the MS1, was produced. In this paper, we calculate the theoretical behaviour of this platform operating at 50 kb/s with a multi-hop 6LoWPAN networking stack and the ContikiMAC duty cycling protocol, test these expectations and present brief details of an ongoing deployment.

II. Expected Performance

The theoretical MAC-layer throughput can be estimated using the method used in [15] for establishing the throughput of nonfragmented packets for a 250 kb/s 2.4 GHz 802.15.4 radio in a lightly loaded network. Using a value of unity for $P_{inactive}$, the probability that the channel is available for communications, provides a means to establish the potential peak throughput which is useful for comparative purposes.

Table I shows the parameters for a CC1120 operating at 50 kb/s and results in a theoretical throughput of 24.45 kb/s for a payload of 81 bytes, the largest payload achievable in Contiki before a packet is fragmented. The multi-hop MAC-layer throughput can be estimated by dividing the single-hop throughput by the number of hops [15, 16].

TABLE I. Packet transmission time parameters for the CC1120 operating at 50 kb/s with a $P_{inactive}$ of one. Parameters have the same definitions as in [15]

Parameter	Symbols	Time (s)
CSMA-CA	250	0.0050
TX Packet	1064	0.0213
ACK Turnaround	35	0.0007
TX ACK	96	0.0019
LIFS	40	0.0008
Sum	**1485**	**0.0297**

A. Latency

The latency of a communications link is also an important metric in assessing its performance. The round-trip latency can be modelled using (1) where n_{BT} and n_{BR} are the number of bytes of payload to be transmitted and received respectively. n_{PT} and n_{PR} are the number of packets that the data will be split into to be transmitted and received respectively. t_{BS} is the amount of time taken to load, transmit, and read each byte. t_{PO} is the constant overhead associated with the transmission of each packet and includes radio state transition time, ACK handling time, 802.15.4 header handling time, microcontroller interrupt transition time and the time taken to transmit the PHY header. t_{CA} is the channel access time.

$$t_{Latency} = ((n_{BT} + n_{BR}) \times t_{BS}) + ((n_{PT} + n_{PR}) \times t_{PO}) + (2 \times t_{CA}) \quad (1)$$

The increased latency caused by using an RDC can be calculated with and added to $t_{Latency}$. For ContikiMAC with the CC1120, the overhead can be calculated with (2) where n_{RTX} and n_{RRX} are the average numbers of retransmissions for transmitted and received packets respectively. t_{TO} is the time taken for the radio to transition into the transmit state. t_i is the ContikiMAC inter-packet interval. n_{OB} is the number of bytes of per-packet overhead that have to be transmitted and includes sync and preamble bytes. n_{HB} is the number header bytes that are loaded, transmitted and read for each packet. R_{BR} is the transmit bitrate of the radio. n_{BT1} and n_{BR1} are the number of bytes that need to be retransmitted for transmission and reception respectively. For non-fragmented packets, where n_{PT} and n_{PR} are both equal to one, n_{BT1} and n_{BR1} will be the entire payload whereas for fragmented transmissions they are the number of bytes in the first packet. For direct communications between a border router and sensor node n_{RRX} may be zero as it is common for the border router not to be duty cycling the radio to improve performance.

$$t_{RDCOH} = (n_{RTX} + n_{RRX}) \times \left(t_{TO} + t_i + \frac{8(n_{OB} + n_{HB})}{R_{BR}}\right) + \frac{8((n_{BT1} \times n_{RTX}) + (n_{BR1} \times n_{RRX}))}{R_{BR}} \quad (2)$$

Multi-hop latency can be estimated for a network where each hop uses the same type of sensor node by multiplying the result of (1) by the number of hops. For multi-hop calculations involving ContikiMac, the latency of the first hop will need to be calculated separately from the latency of the subsequent hops as n_{RRX} is zero for the first hop only.

The latency of a connection can be determined using the Ping6 command from a Linux computer. Table II shows the parameters used to calculate the expected latencies to a node one hop away where no duty cycling protocol is used and to a node one hop away where the ContikiMAC duty cycling protocol is used. The parameters used to calculate the expected latency for a two-hop scenario where the ContikiMAC duty cycling protocol is used are also presented.

B. Energy

The average receive energy can be estimated using the amount of time that the radio is expected to be in receive and the typical receive current from the radio's data sheet. For the default ContikiMAC settings of an 8 Hertz channel check rate and two channel clear assessments per cycle, the radio will be turned on 16 times each second. For the CC1120, the total on-time is 10.08 ms in every second giving a duty cycle of approximately 1%. In the high-performance mode, the CC1120 draws 22 mA at 3.3 V giving a power consumption of 0.73 mW. In its low power mode, the CC1120 draws 17mA for a power of 0.56 mW. For comparison, the CC2420, a commonly used 2.4 GHz radio, has a receive duty cycle of less than 1% [3] and draws 0.12 mW [17].

TABLE II. Values used to calculate the expected latency of the CC1120 without an RDC and with the ContikiMAC duty cycling protocol. The parameters used to calculate the two-hop ContikiMAC latency.

Parameter	**CC1120**			
	No RDC	***ContikiMAC (Average)***	***ContikiMAC (Minimum)***	***ContikiMAC (Two-hop)***
n_{BT}	94	94	94	94
n_{BR}	93	93	93	93
n_{PT}	2	2	2	2
n_{PR}	2	2	2	2
t_{BS} (ms)	0.172	0.172	0.172	0.172
t_{PO} (ms)	7.765	7.765	7.765	7.765
t_{CA} (ms)	0	34	34	34
t_{RDCOH} (ms)	0	87.480	0	303.040
n_{RTX}	-	4.7	4.7	4.7
n*rtx*	-	0	0	4.7[a]
Latency (ms)	**63.27**	**218.75**	**131.27**	**656.58**

[a.] nrtx is zero for the first hop so tRDCOH must be calculated separately for each hop

The maximum retransmission energy overhead can be calculated in a similar manner by multiplying the amount of time it takes to transmit a full-sized packet by the TX power and the average number of times that the packet is transmitted beyond the first. For the CC1120, a full-sized packet will take 21.60 ms to transmit at a total energy cost of 3.21 mJ at 14 dBM. This gives an average retransmission overhead of 15.09 mJ per packet. In comparison, the CC2420 takes 4.32 ms to transmit the same packet giving a transmit energy of 0.25mJ per packet. As expected, the transmission overhead is significantly greater for the CC1120 due to its increased transmit power and time spent transmitting.

III. METHODS & RESULTS

A. CC1120 Contiki Driver

At the time this work was carried out Contiki did not include a driver for the CC1120. As such a driver for the CC1120 was developed. Compatibility with the ContikiMAC duty cycling protocol was included and Table III shows the settings required for ContikiMAC to function with the CC1120. Not all settings that required modification were exposed as changeable parameters so minor modifications were required to the ContikiMAC source files. Table IV details the definitions that required modification and the values required.

TABLE III. ContikiMAC timing constaints for the CC1120 operating at 50 kb/s. Each parameter has the same definition as in [3] and was calculated with reference to [14].

Parameter	Description	Time (ms)
t_a	ACK turnaround time.	0.7
t_d	ACK detection time.	0.8
t_i	Inter-packet interval.	4.5
t_c	Successive CCA interval.	5.1
t_r	Time for a stable RSSI.	0.5[b]
t_s	Shortest packet TX time.	6.5
t_l	Longest packet TX time.	21

b. Calculated with reference to [18]

While the driver attempts to respect the 802.15.4 standard, limitations in the speed of processing interrupts and transitioning from pre-emptive execution to co-operative execution on the MS1 mean that it is not possible to start transmission of an ACK within the 120 µs required by the standard. Fig 1 shows that shortest time that could be achieved with the MS1 platform was 700 ms.

B. Throughput

The single-hop unidirectional MAC-layer throughput between two nodes can be determined by measuring how long it takes to transmit a set number of full-size nonfragmented packets at the fastest rate that does not result in packet loss. This was achieved by repeatedly transmitting UDP packets with a payload of 81 bytes and observing a transmission indication pin on an oscilloscope. A throughput of 19.78 kb/s for the CC1120 was determined with this method.

TABLE IV. Internal ContikiMAC parameters that need to be modified for sub-gigahertz operation. These settings are found in contikimac.c.

Internal Setting	Related Constraint	Value
SHORTEST_PACKET_SIZE	t_s	36 B
CCA_CHECK_TIME	t_r	0.63ms
CCA_SLEEP_TIME	t_c	4.8ms
INTER_PACKET_INTERVAL	t_i	0ms
LISTEN_TIME_AFTER_PACKET_DETECTED	T_{awake}	50ms

This is 4.67 kb/s below the expected value but the inter-packet interval observed during testing was 5.8ms, 5ms greater than the value used to calculate the expected throughput. Recalculating the expected throughput using this value for LIFS results in an expected throughput of 20.84 kb/s, which is similar to the achieved throughput.

The Zolertia Z1 includes a CC2420 radio which can be used, although it was not needed in the deployment. The same test was carried out with the CC2420 and the throughput was found to be 87.28 kb/s. This is 33.52 kb/s below the throughput expected from [15]. Like the CC1120 tests, the observed inter-packet interval was more than five milliseconds greater than expected. This discrepancy is likely to be due to process overheads within Contiki.

C. Latency

The average and minimum round-trip latencies can be determined by repeatedly sending a Ping6 ICMP request from a Linux host to a node one hop from the border router once per

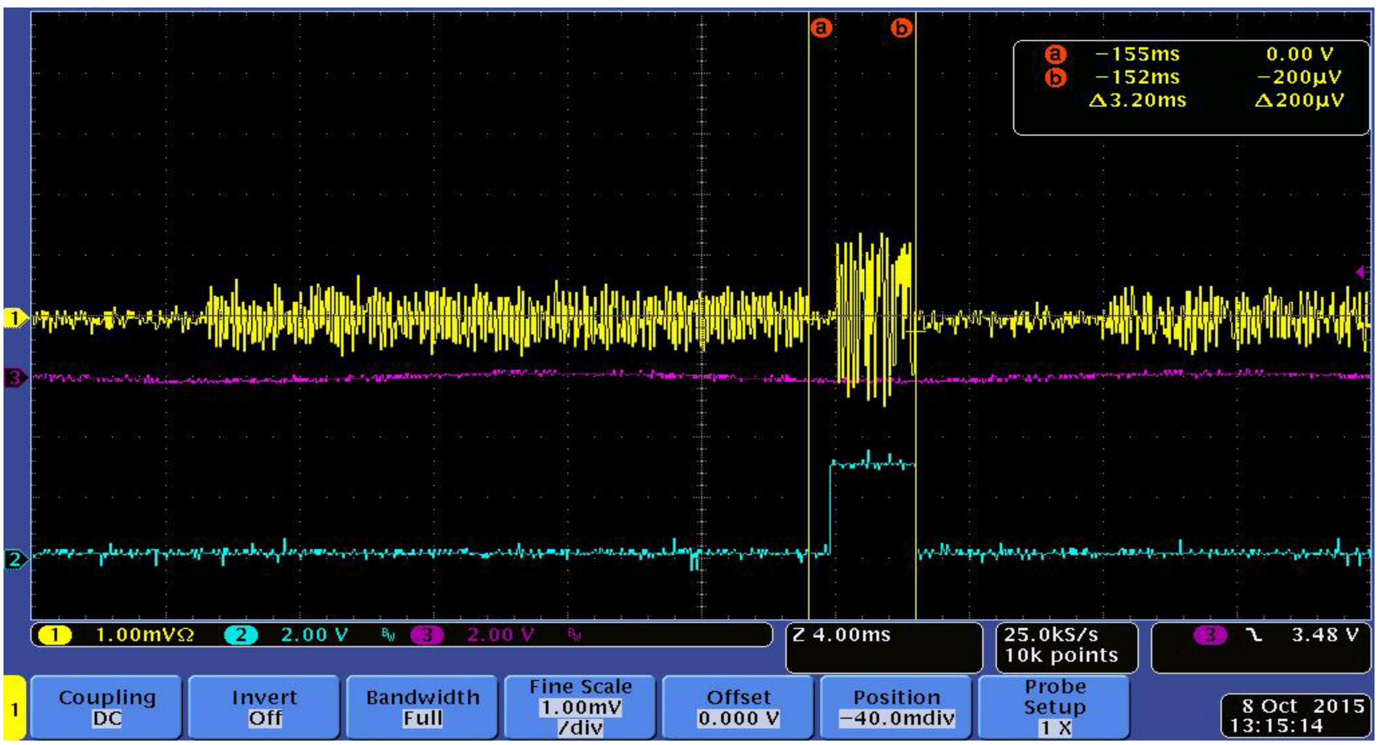

Fig. 1. CC1120 ACK turnaround time. The yellow trace shows the presence of RF signals while the blue trace shows when the node sending the ACK, the greater magnitude yellow trace, is transmitting.

second over an extended period of time. The test setup consisted of an Instant Contiki virtual machine connected to the border router by a 6-Slip interface over a USB-to-serial connection. Any pings sent to the destination node will include the latency of this connection in their results. The latency of this connection was measured by pinging the border router and found to be 21 ms.

Table V shows the results of running 43200 pings for three different scenarios for both radios. The results for the single-hop CC1120 scenarios are greater than the expected values by a similar amount that is not proportional to the latency. This implies that the discrepancy is systematic and likely to be due to the time taken to process the ICMP packets within Contiki. The result for the two-hop scenario with ContikiMAC is also greater than expected and like the single hop scenarios, this is likely to be due to processing overheads in Contiki.

The results for the CC2420 demonstrate that a significant proportion of the latency exhibited on 6LoWPAN connections is not related to the throughput of the radio as the results for the CC1120, operating at 50 kb/s, are significantly greater than one fifth of the results for the CC2420, operating at 250 kb/s.

IV. DEPLOYMENT

A deployment consisting of two dedicated routing nodes and six sensor nodes was carried out in the Cairngorm Mountains in Scotland. The nodes were deployed in two clusters in a one kilometre square area as shown by Fig. 2. The border router was situated in an estate office 3.5 km North West of Router 1 where there is permanent power and Internet connectivity. Table VI details the function of each node and the types connected sensors.

Line-of-sight RF propagation modelling for a CC2420-based 2.4 GHz deployment was carried out using Viewscheds in ArcMap. This showed that a deployment with comparable coverage would require at least 25 routing nodes with a total of 18 hops to the first closest node and 25 hops to the farthest node. Table VII shows the performance characteristics for the deployed network and the modelled 2.4 GHz deployment.

TABLE VI. Ping6 results from 43,200 echo requests for six different scenarios. The minimum and average results include the latency of the 6-Slip connection. The delta from the expected values is presented where appropriate.

Test	Minimum Latency (ms)	Average Latency (ms)	Standard Deviation (ms)	Δ from Calculated Values	
				Min (ms)	Avg (ms)
CC1120 (No RDC)	102.60	105.02	15.51	18.33	-
CC1120 (ContikiMAC)	169.50	258.33	83.42	17.23	18.58
CC2420 (No RDC)	41.86	43.00	1.73	-	-
CC2420 (ContikiMAC)	51.04	209.77	198.35	-	-
CC1120 2-hop (ContikiMAC)	-	740.13	324.23	-	62.55
CC2420 2-hop (ContikiMAC)	-	431.67	508.90	-	-

TABLE V. List of deployed nodes with their name, function and details of connected sensors.

Node	Function	Sensors
Estate	Border Router	-
Router 1	Routing Node	-
Router 2	Routing Node	-
Router 3	Routing/Sensing	Temperature spider & soil moisture
Turf	Sensing	Temperature & strain gauge chain
Lochan	Sensing	Water level & rain gauge
Hummock	Sensing	Temperature & strain gauge chain
Peat	Sensing	Temperature spider & soil moisture
Stream	Sensing	Water level & rain gauge

V. CONCLUSIONS

Our ongoing deployment demonstrates that the combination of 802.15.4G-compliant 868 MHz radio with multi-hop 6LoWPAN networking offers an effective alternative to 2.4 GHz-based networks for ESNs where nodes are spread over a large geographic area. We have demonstrated that low-power radio communications can successfully facilitate single-hop IPv6-based networking at ranges in excess of 3.5 km, over ten times what is possible with low-power 2.4 GHz radios. The deployment could support a wider geographic spread of sensor nodes than it does currently. However, it does show that despite having a lower single-hop throughput and greater single-hop latency than a network consisting of CC2420-based nodes, our CC1120-based nodes can provide a greater network throughput, lower total latency and lower energy profile in some deployment scenarios.

While ContikiMAC can operate successfully with the CC1120 and provides a comparably low duty cycle to that achievable with the CC2420, the retransmission energy overhead associated with the duty cycling protocol is substantial because the transmission energy consumption is significantly greater than the receive energy consumption. Further work is required to determine whether ContikiMAC is the most efficient duty cycling protocol for sub-gigahertz ESNs.

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TABLE VII. MAC-layer throughput and post duty cycling latency to the sensor nodes closest to and farthest from the border router for. Data is shown for both the actual CC1120 –based deployment and the modelled CC2420-based deployment. The multi-hop throughput is calculated from the single-hop throughputs determined in III.

Radio	Number of hops to Nearest Node	Throughput to Closest Node (kb/s)	Average Latency to Closest Node (ms)	Number of hops to Farthest Node	Throughput to Farthest node (kb/s)	Average Latency to Farthest node (ms)
CC2420 (2.4 GHz)	18	5.13	4203.97	25	3.49	5757.27
CC1120 (868 MHz)	1	19.78	258.33	3	6.59	1221.93

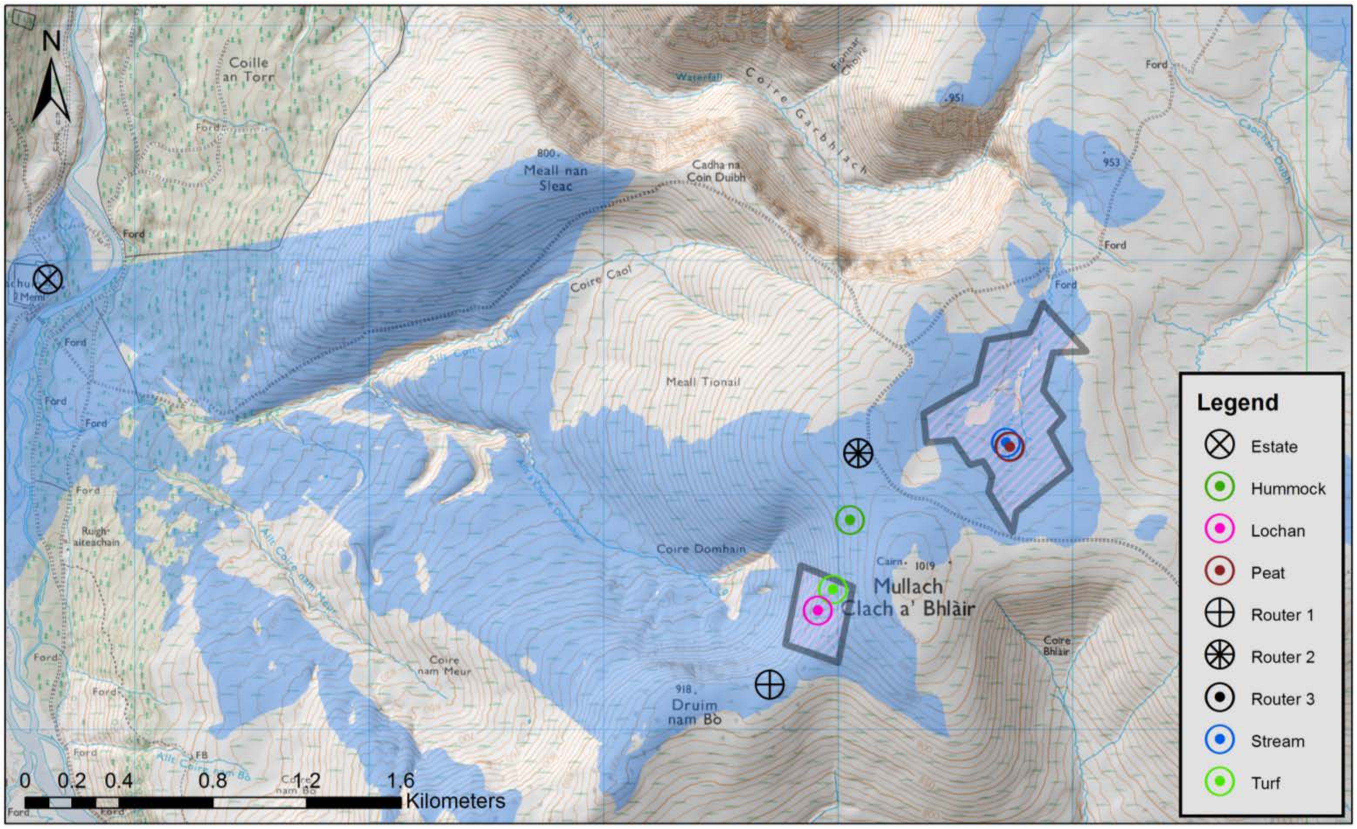

Fig. 2. Modelled coverage for the 868 MHz ESN deployment in the Cairngorm Mountains in Scotland. The outlined areas indicate the study areas. Estimated radio coverage is shown by the shaded (blue) areas. At this scale, Router 3 is co-sited with the Peat sensor node. DTM data from [19] and Crown Copyright Ordnance Survey.

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