Opal: A Multi-radio Platform for High Throughput Wireless Sensor Networks

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***Abstract*—Design of current sensor network platforms has favored low power operation at the cost of communication throughput or range, which severely limits support for real-time monitoring applications with high throughput requirements. This letter presents the design of the versatile Opal platform that couples a Cortex M3 MCU with two IEEE 802.15.4 radios for supporting sensing applications with high transfer rates without sacrificing communication range. We present experiments that evaluate Opal's throughput and range when operating with one or two radios, and we compare these results with an Iris-based node and TelosB nodes. We introduce the spatial energy cost metric that measures the energy to transfer one bit of information in a unit area for comparing the performance of the platforms. The results show that Opal operating with dual radios increases the throughput compared to single radio platforms with the same data-rate by a factor of 3.7, without sacrificing communication range. Opal operating with one radio can deliver a 460% increase in throughput over other single radio nodes at reduced range. We also analyze the implications of Opal's design for multi-hop communication, showing that the dual radio architecture removes the bandwidth bottleneck in multi-hop communications that is inherent to single radio platforms.**

I. Introduction

Wireless Sensor Network (WSN) applications have evolved beyond the vision of smart dust and are now also being deployed to gather acoustic and visual data with a high demand for communication throughput. Equipment and deployment costs have proven to be a limiting factor for high spatial density deployments [1], highlighting the benefits of longer range communication. Sensor network users have also realized the higher-than-expected node cost and are moving towards deployments with more widely spaced nodes at the expense of data granularity.

Energy-efficiency has so far been a dominant design target in WSN platforms, due to the limited battery capacity imposed by the device form factor. However, recent advances in energy harvesting, such as solar, have shown networks that can operate for years [1]. While energy remains a key consideration, the focus on energy-efficiency has so far sidelined other design considerations in WSNs, such as communication throughput and range.

This letter introduces the Opal platform as a high throughput sensing module that delivers comparable energy efficiency to existing platforms. Opal includes two onboard 802.15.4 radios operating in the 900 MHz and 2.4 GHz bands to provide communication diversity [2] and an aggregate transfer rate of 3 Mbps. It embeds a 96 MHz Cortex SAM3U processor with dynamic core frequency scaling, a feature that can be used to fine-tune processing speed with the higher communication rates while minimizing energy consumption.

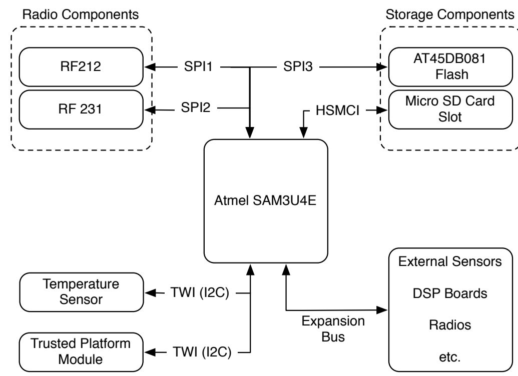

Fig. 1. Functional diagram of the major Opal components.

We conduct empirical experiments with Opal to compare its communication throughput and range against two existing single radio platforms. We introduce the spatial energy cost metric that evaluates the energy cost per transferred bit per unit area for each platform. The results show that Opal improves communication throughput by up to 3.7 times over existing platforms in long-range transmission and achieves a 460% increase in throughput for short-range single-radio transmissions. These improvements come with a reduction in the spatial energy cost of Opal over existing platforms ranging from 41% up to 78%. We also analyze the implications of Opal's design for multi-hop communication, showing that the dual radio architecture removes the bandwidth bottleneck in multi-hop communications that is inherent to single radio platforms.

II. The Opal Platform

The Opal platform was designed to strike a balance between performance and power efficiency, at a comparable cost to existing platforms. In this section, we highlight Opal's processing capabilities as well as the additional features it provides for streamlined building of secure and power-efficient WSN applications. Figure 1 provides a functional diagram of all the components contained in Opal.

At the core of our platform is the SAM3U Cortex-M3 MCU from Atmel. The SAM3U can be clocked up to 96 MHz and provides ample storage capabilities and peripherals without sacrificing power efficiency. In its largest configuration (SAM3U4E), it provides 256 KB of flash, 52 KB of SRAM, and can wakeup from its stop mode in $< 10\,\mu$s, while drawing as low as $8.9\,\mu$A [3]. Two ADCs, a high-speed 12-bit ADC with up to 1 Msample/s, and a low-power 10-bit ADC with automatic sleep mode, provide the functionality necessary for a modern sensing/control system. The 12-bit ADC includes an additional programmable gain amplifier. Additionally, the USB 2.0 High-Speed interface provides a high-speed serial link to a computer. Finally, a memory protection unit (MPU) rounds up the SAM3U package. In fact, the MPU was one of the key deciding factors for selecting the Atmel SAM3U over other available Cortex-M3 based microcontrollers that had similar features. The MPU provides a way to protect the memory spaces of multiple simultaneously running threads [4]. It also allows applications to securely update system code using Deluge [5] by protecting the boot-loader's memory space.

The most interesting feature that distinguishes Opal from other mote platforms is the versatility of its radio components. Two low-power 802.15.4 compliant radios can run at bitrates between 250 Kbps and up to 2 Mbps. The outputs can be switched between two separate antennas and power amplifiers with a maximum gain of 19.7 dB can be enabled on demand to increase the communication range. For compatibility reasons, a third non-802.15.4 radio can be loaded. We use the TI CC1101 at 433 MhZ for backwards compatibility. The radio components provide significant versatility for meeting diverse application requirements. The Multiple Input / Multiple Output (MIMO) capabilities allow for high link reliability and high throughput. In our evaluation of the platform we focus on the 802.15.4 compatible components without additional amplifiers.

We have mentioned security and power efficiency as perhaps the two most important building blocks of real-world WSN applications. Opal supports stronger-than-standard secure communications, actuation, and remote attestation through a Trusted Platform Module (TPM) chip. To support long-term outdoor deployments, Opal also includes a proprietary energy harvesting input that feeds into a hardware based Li-Ion battery charging circuit. This mechanism allows the microcontroller to be put to deep sleep mode while the batteries are recharged with solar or other ambient energy sources.

We focus the rest of the letter on evaluating Opal's innovative radio interface design and show that it fills a gap in the design space of high throughput applications with low spatial energy cost.

III. Evaluation

To determine the suitability of the Opal platform for supporting high-speed applications, we report the range, throughput and energy consumption in various configurations (e.g., single and dual radio mode). For ease of comparison we propose a new metric, called Spatial Energy Cost σ (pJ/bit/m^2), that combines three performance characteristics (energy, throughput and range) into a single metric. Note that the Spatial Energy Cost metric augments the spatial capacity parameter in [6], [7] to include energy efficiency. Effectively it measures a platform's energy cost to deliver a bit of information within a unit area.

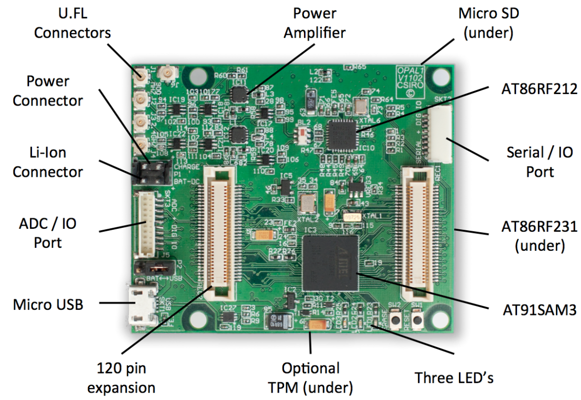

Fig. 2. The Opal platform.

A. Experimental Setup

To put things into perspective we evaluate Opal's performance relative to both the TelosB [8] and an Iris-like platform we call Iris*. The TelosB was selected because of its familiarity to the WSN research community; the Iris* was selected because of its hardware similarities to Opal. The Iris* is centered around an Atmel1281 MCU and the RF230 radio, which also featurs in the Opal design; in addition the Iris* can be extended to drive an RF212 radio, the other radio that Opal includes. Thus, by comparing the Iris* and Opal platforms we can isolate and study the impact of including a different MCU on system performance.

We tested all platforms in TinyOS. Note that we have not optimized the network and serial port drivers, nor the operating system to maximize performance of any of the platforms. Instead, we focused on evaluating the standard drivers and out of the box performance of these platforms. Using compile-time directives, the Opal and Iris* nodes could be configured to use one of the two radios, or to run both of them at the same time, so three modes in total. Our experiments involved only point-to-point measurements, so no routing component was included. Instead a simple application was used that submitted packets as fast as possible and the receiving node forwarded all packets to a PC through a serial link (or a USB link in Opal's case). Missing and corrupted packets are accounted for as we report throughput, i.e. the amount of user data per second effectively received when streaming packets with 100-byte payloads.

To measure the energy consumption we inserted a 10 Ohm shunt resistor between the battery pack and the sending platform, and measured the voltage drop with an oscilloscope. The reported current draw is computed as the average value over the time interval needed to send out a single packet. Note that the baseline current drawn by the complete platform is included, so the reported numbers are higher than the raw TX numbers from the data sheets of the respective radio chip. For reference, with their radios turned off the Iris* platform consumes about 10.3 mA and the Opal platform about 16.0 mA in their default active modes.

Platform	Radio	Transmit rate (kbps)	Throughput (kbps)	Range (m)	Current draw mA	Spatial Energy Cost σ (pJ/bit/m^2)
TelosB	CC2420	250	51.2	320[1]	18.9	11.89
Iris*	RF212	250	114.2	850[11]	28.1	1.124
Iris*	RF230	250	113	850[11]	22.9	0.893
Iris*	Dual	500	110.8	850[11]	46.7	1.925
Opal	RF212	250	217.8	850[11]	31.9	0.669
Opal	RF230	250	218.2	850[11]	31.5	0.659
Opal	Dual	500	421.4	850[11]	49	0.531
Iris*	RF212	1000	160	100[11]	28.1	57.9
Opal	RF212	1000	734	100[11]	31.9	12.63

TABLE I
PERFORMANCE COMPARISON OF THE 3 PLATFORMS. ALL PLATFORMS HAVE A REGULATED INPUT VOLTAGE OF 3.3V.

B. Empirical Results

Table I compares the performance of the three platforms. Note that the theoretical upper bound on single hop communication with IEEE 802.15.4 is 225 kbps [9]. The results show that Opal's more powerful MCU enables it to achieve higher effective throughput even with the single radio configuration, with its throughput reaching around 218 kbps compared to 51.2 kbps and 114 kbps for TelosB and Iris* respectively. The relatively high difference between TelosB and Iris* is due to the different baudrates that the serial interface is set up with on the two platforms. The recent study [10] of a number of WSN platforms confirms our TelosB results with TinyOS, where they reported a 49.4 kbps average and 90 kbps maximum throughput that is generally available on existing 8-16bit WSN platforms.

Opal's improved throughput comes at the cost of increased energy consumption due to the higher processing demand. However, Opal running in the single radio configuration achieves an 18-fold decrease in σ compared to TelosB due to its much larger communication range. Utilizing a single radio on Opal also reduces σ by 25% (RF212) and reduces σ up to 40% (RF230) compared to Iris*.

For the dual-radio configuration, Iris* has the same throughput as it does in its single radio configuration, as the throughput is limited by the MCU's ability to handle packets rather than the available bandwidth. In contrast, Opal's more capable MCU can support a throughput of 421 kbps. Opal's improvement in σ is nearly four-fold over Iris*.

We also conducted an experiment on a high speed application, where Opal and Iris* use the RF212 radio with the 1Mbps setting. In this experiment, both nodes have a much shorter communication range of about 100 m. The throughput of Opal is 4.6 times greater than Iris*. The latter has a slightly improved throughput over the non-high speed dual-radio experiments because there is no need to switch between two radios. The high speed experiment results clearly have an order of magnitude increase in σ over the other experiments for Opal and Iris*, mainly due to their reduced communication range.

Figure 3 plots σ against throughput for all the experiments. The size of the bubbles in the figure indicates the average power consumption. Note that the bottom right corner is the desirable quadrant in this figure. The larger bubbles for Opal and Iris* correspond to the dual radio experiment and reflect the increased power consumption of running the second radio. The figure clearly shows that Opal's Spatial Energy Cost σ is lower than both TelosB and Iris*, as it increases throughput by a factor of 3.7 with a modest increase in energy consumption compared to Iris*. Opal's higher throughput and range relative to TelosB reduces σ by 94% for the single radio case and by 95% for the dual radio case, despite Opal having 66% to 159% increase in power consumption in the single and dual radio configurations respectively. The Opal achieves a 78% reduction in σ for the high speed radio experiment over Iris*, where Opal achieves 734 kbps with a single radio transmitting at 1 Mbps, compared to a 160 kbps throughput with Iris*.

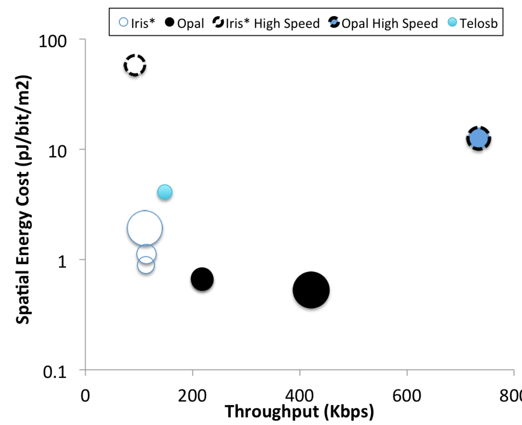

Fig. 3. Comparison of the spatial energy cost versus throughput of TelosB, Iris$*$ and Opal. The Iris$*$ and Opal results show single and dual radio results, as well as a high throughput scenario of 1000 kbps transmissions with a single radio. The size of bubbles indicates the absolute power consumption for high rate transmissions.

Overall, Opal clearly shifts performance towards the desirable bottom right quadrant, achieving significantly higher throughput to decrease the spatial energy cost. The improvements in σ and throughput far outweigh the Opal increase in average power consumption for high transfer rate applications. Such applications can use Opal's high throughput capability for transferring more content in a shorter timeframe, resulting in overall savings in energy consumption.

C. Multihop Analysis

The empirical results confirm Opal's throughput improvement for single hop communication through the combination of two 802.15.4 radios and the Cortex MCU. We now analyze

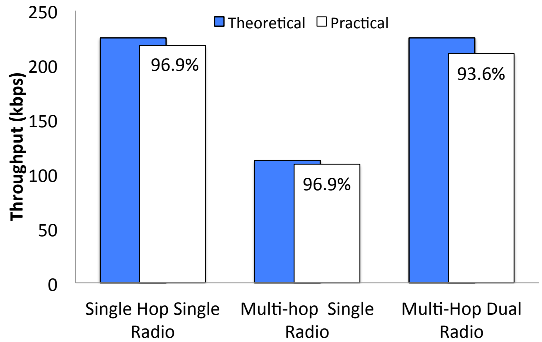

Fig. 4. Comparison of Opal multihop communication to single radio platforms in single and multihop communication. The percentage values indicate the relationship between the practical throughput to theoretical throughput. Opal's dual radio design delivers nearly the same throughput for multihop communications as single radio platforms deliver in single hop communications, thus eliminating a significant bandwidth bottleneck for multihop communication.

the implications of these results for multi-hop communication. The work in [9] had discussed the theoretical throughput limits for single and multi-hop communication with 802.15.4 radios and had proposed optimizations to approach the theoretical limits by avoiding the copying of packets when forwarding. Osterlind and Dunkels reported a theoretical limit of 225 kbps for single hop communication, and 112.5 kbps for multi-hop communication. The multi-hop communication limit is half that of single hop communication as the radio needs to duty cycle its time between transmitting and receiving, even with the multiple channel optimization that they propose.

The use of dual radios in Opal enables the use of one radio for transmission and another for receiving simultaneously. With this configuration, a node can concurrently receive packets on one radio and forward the packets on the second radio. Combining the dual radio forwarding approach with the optimizations in [9] raises the achievable multi-hop throughput with Opal.

Figure 4 compares the theoretical and practical throughput of Opal multi-hop communication to single radio platforms in single and multi-hop configurations. Our empirical results with Opal show that it achieves similar throughput in single hop communication as in [9], at about 97% of the theoretical limit. Single radio platforms can perform multi-hop communication at about half that rate, due to the need for sharing the same radio for transmission and reception. Opal's dual radio configuration, however, has the same theoretical throughput limit for multi-hop communication as a single radio platform for single hop communication. This effectively means that dual radios remove the significant throughput bottleneck for multi-hop communication in current single radio platforms. The achieved throughput of Opal for multi-hop communication is at 210.7 kbps (93.6% of the theoretical limit), as the MCU spends some time in switching between the two radios.

IV. Conclusion

We have presented the new Opal sensor node platform that supports high throughput applications. Employing a 32-bit high speed SAM3U MCU at its core enables Opal to take full advantage of two available 802.15.4 compliant radios. We have shown that using the dual radio configuration can increase the maximum throughput by a factor of 3.7 compared to typical 8-bit MCU-based and single radio platforms, e.g. TelosB. Even in single radio operation, traditional MCUs typically become a bottleneck for high throughput. Using the SAM3U, the Opal platform can stream data at up to 734 kbps continuously, 4.6 times faster than a comparable hardware platform equipped with an 8-bit MCU.

We proposed a new metric called the Spatial Energy Cost to empirically compare different hardware configurations. This metric combines energy, throughput and range into a single value that measures the energy cost to deliver a bit of information within a given area. Opal provides significantly lower spatial energy cost, and these improvements justify any increases in power consumption for high data rate applications. Our analysis extends empirical single hop results and shows that Opal's dual radio design removes the inherent multi-hop bandwidth limitation of single radio platforms.

Overall, Opal's design achieves high throughput and improves the spatial energy cost over existing platforms in order to support higher bandwidth sensing applications. Even for low data rate applications, more content can be transferred in a shorter amount of time, resulting in significant overall energy savings. The versatility of Opal in particular, and SAM3U-based platforms in general, positions them as strong candidates for future sensor network deployments.

References

[1] Peter Corke, Tim Wark, Raja Jurdak, Darren Moore, and Philip Valencia, "Environmental wireless sensor networks", *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1903–1917, 2010.

[2] Branislav Kusy, Christian Richter, Wen Hu, Mikhail Afanasyev, Raja Jurdak, Michael Brünig, David Abbott, Cong Huynh, and Diethelm Ostry, "Radio diversity for reliable communication in wsns", in *IPSN*, 2011, pp. 270–281.

[3] Atmel Corporation, "AT91 ARM Cortex-M3 based Microcontrollers: SAM3U Specifications", 2009.

[4] K. Klues, C. J. Liang, J. Paek, R. Musaloiu-E, R. Govindan, A. Terzis, and P. Levis, "TOSThreads: Safe and Non-invasive Preemption in TinyOS", in *SenSys*, Nov 2009, pp. 127–140.

[5] J. W. Hui and D. Culler, "The dynamic behavior of a data dissemination protocol for network programming at scale", in *SenSys*, Nov. 2004.

[6] J. Foerster, Evan Green, Srinivasa Somayazulu, and David Leeper, "Ultra-wideband technology for short or medium range wireless communication", *Intel Tech. J.*, 2001.

[7] Raja Jurdak, Cristina Videira Lopes, and Pierre Baldi, "A survey classification and comparative analysis of medium access control protocols for ad hoc networks", *IEEE Communications Surveys and Tutorials*, vol. 6, pp. 2–16, Jan. 2004.

[8] Joseph Polastre, Robert Szewczyk, and David Culler, "Telos: enabling ultra-low power wireless research", in *Proceedings of the 4th international symposium on Information processing in sensor networks*, Piscataway, NJ, USA, 2005, IPSN '05, IEEE Press.

[9] Fredrik Osterlind and Adam Dunkels, "Approaching the maximum 802.15.4 multi-hop throughput", in *Proceedings of the Fifth ACM Workshop on Embedded Networked Sensors (HotEmNets 2008)*, June 2008.

[10] Peter Trenkamp, Markus Becker, and Carmelita Gorg, "Wireless sensor network platforms - datasheets versus measurements", *SenseApp'11*, 2011.

[11] Mikhail Afanasyev, Damien O'Rourke, Branislav Kusy, and Wen Hu, "Heterogeneous traffic performance comparison for 6lowpan enabled low-power transceivers", in *Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors*, New York, NY, USA, 2010, HotEmNets '10, pp. 10:1–10:5, ACM.