MIMSY: The Micro Inertial Measurement System for the Internet of Things

Craig B. Schindler*, Daniel S. Drew*, Brian G. Kilberg*, Felipe M. R. Campos*, Soichiro Yanase†,*, Kristofer S. J. Pister*
*Berkeley Sensor & Actuator Center
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley, USA
Email: {craig.schindler, ddrew73, bkilberg, fmrcampos, ksjp}@berkeley.edu
†Azbil North America Research & Development, Inc.
Email: s.yanase.fa@anad.us.azbil.com

***Abstract*—**
The Micro Inertial Measurement System (MIMSY) is an open-source wireless sensor node for Internet of Things applications, specifically designed for a small system volume while maintaining functionality and extensibility. MIMSY is a 16mm × 16mm node with an Arm Cortex-M3 microprocessor, 802.15.4 wireless transceiver, and a 9-axis IMU. The system is fully compatible with the OpenWSN wireless sensor networking stack, which enables the straightforward implementation of standards-compliant 6TiSCH mesh networks using MIMSY motes. While the application space of MIMSY is quite vast, we present three sample implementations showcasing the opportunities afforded by a small and relatively low-cost mote with mesh networking and inertial measurement capabilities, including: high granularity areal sensing for sleep monitoring with motes embedded in a foam mattress; high reliability, low latency communication for industrial process automation and control; and long lifetime physical event detection and activity monitoring with minimal setup time.

***Index Terms*—Internet of Things, wireless sensor networks, motes, e-health, factory automation, asset tracking**

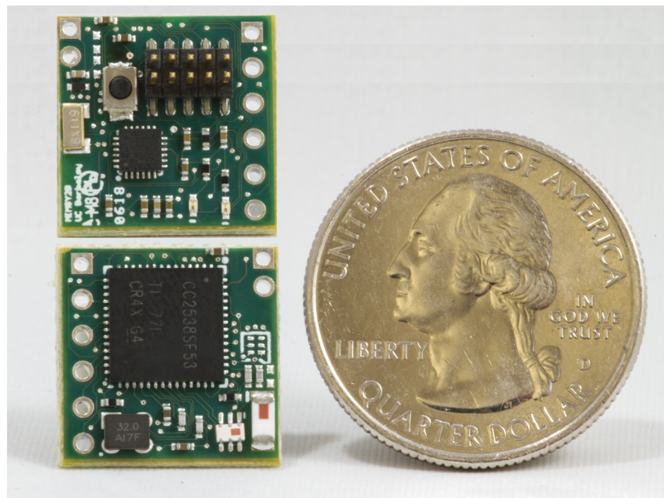

Fig. 1. Photograph of the frontside and backside of MIMSY next to a US quarter. MIMSY is 16mm tall and 16mm wide.

I. Introduction

The original vision of Smart Dust was to create micro-scale wireless sensor nodes so small, they would be "suspended in air, buoyed by air currents, sensing and communicating for hours or days on end" [1]. This dream of ubiquitous, distributed intelligence has now been a target of major academic and industrial research agendas for decades, with a "Trillion Sensor (TSensors) Movement" foreseeing significant growth in the market. With advances in microelectronics and MEMS sensors, small, capable, and relatively inexpensive wireless sensor nodes are now easily available. Combining this hardware with low-power wireless mesh networking protocols could enable a diverse set of applications in the near-term.

There are a variety of application areas where small, networked nodes could be useful. Environmental and agricultural monitoring, benefiting from the wide-area deployment capability of these sensors, have begun to and will continue to be an important sector [2]. Data-driven agricultural practice has the potential to improve crop yields [3]. Ubiquitous sensors enable high granularity (i.e. local) chemical, gas, and air quality monitoring, with potentially beneficial public health implications [4]. Infrastructure monitoring (e.g. structural health monitoring or SHM) is possible without significant capital investment in retrofitting existing systems via deployment of low cost sensors [5]. Beyond wearable fitness trackers, the notion of easily instrumenting the world around us has potential applications in health care, energy efficient building administration, and the "quantified self" [6].

While some motes are designed with specific applications in mind, there is a long history of development behind general-use sensor motes. The TelosB mote from Berkeley and Mica series of motes from CrossBow were widely applied in research beginning in 2004, but hardware capability was very limited [7]. Newer motes like the OpenMote [8], i3 [9], Hamilton [10], and meto[1] [11] have far greater functionality, but are typically "large" (on the order of $10cm^2$ or greater) and/or "expensive" (on the order of $150). The roughly 2.5cm × 2.5cm GINA mote [12] provided wireless inertial sensing in a small package, but is now incapable of implementing the latest communication standards because it is built using

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obsolete components. The vision of this work is to specifically create a mote capable of 9-axis inertial measurement and low power wireless mesh networking with the smallest form factor possible; the Micro Inertial Measurement System (MIMSY).

Alongside the evolution of wireless sensor motes was the evolution of low power networking protocols. Protocols like Zigbee [13], although technically capable of wide-area networking [14], have largely been supplanted by reliable low power mesh networking protocols like Wireless Hart [15] and 6TiSCH [16]. Bluetooth Low Energy is actively developing a mesh networking standard for the protocol [17], with a public release in 2017. It should be noted that this is not an exhaustive list of networking implementations, and wireless sensor networks (WSN) are an area of very active research. MIMSY is fully compatible with the open-source OpenWSN [18] networking stack, which enables the straightforward implementation of standards-compliant 6TiSCH mesh networks and the applications that take advantage of them.

Our presented platform is designed as a general-purpose wireless sensor mote with a form factor and price point that makes it amenable to large scale deployments across a variety of sectors. It balances functionality and cost to deliver inertial measurement performance without unnecessary additional components. We demonstrate the ability to scale communication bandwidth, measurement functionality, and on-board computation as required by specific applications. Three applications spanning a diverse range are shown to be easily implemented using this open-source system.

Succinctly, the contributions of this work are:

- Creation of a fully open-source 16mm $\times$ 16mm wireless sensor mote, compatible with the OpenWSN wireless mesh networking stack, capable of 9-axis inertial measurements.
- Characterization of the expected single-charge lifetime for a deployed MIMSY mote for various expected functionality profiles/duty cycles.
- Three sample implementations showcasing the capabilities of the MIMSY mote in the areas of e-health, industrial automation, and environmental (e.g. workplace or home) activity monitoring.

II. Platform Implementation

MIMSY is designed as a fully open source platform: layout and schematic, detailed BOM, firmware, and complete sample applications can be found at `https://github.com/PisterLab/mimsy`.

A. Hardware

MIMSY, shown in Figs. 1 and 2, is 16mm $\times$ 16mm and has a mass of 1.24 grams. A summary Bill of Materials is shown in Table I, and typical measured current draws for various operation modes are shown in Table II. The entire system has been measured to have a current draw of 12 μA when the CC2538 is in deep sleep mode (digital regulator off, 16MHz RC oscillator off, 32MHz crystal oscillator off, 32.768kHz crystal oscillator active, power-on-reset active, sleep timer active, RAM and register retention, all other peripherals inactive) and the MPU9250 is in sleep mode. Line of sight MIMSY to MIMSY communication has been demonstrated at a range of 38 meters. To communicate around RF obstacles or long distances, a multi-hop configuration is needed.

Part	**Cost**
TI CC2538	\$7.78
Invensense MPU9250	\$5.75
Antenna and Balun	\$0.86
Button	\$0.73
LEDs	\$0.25
JTAG connector	\$0.93
Crystals	\$1.40
Passives	\$0.71
PCB Manufacturing	\$6.45
Total	**\$24.86**

TABLE I
MIMSY Bill of Materials and cost per board (Assuming 200 Boards). Note that assembly cost is not included in the total.

B. Software

OpenWSN is an open-source implementation of the 6TiSCH, 6LowPAN, CoAP, RPL, and 802.15.4e TSCH standards [18]. It is designed for low-power, high-reliability ad hoc mesh networking with Internet compatibility. Each node in an OpenWSN network has a minimum radio duty cycle of less than 1% to remain connected; this corresponds to an average current on the order of only 100μA. The communication power budget of a network node is therefore dominated by the amount of traffic that it generates, terminates, and that it routes for its neighbors. Fig. 3 shows measured current draw vs. time for a MIMSY in an OpenWSN 6TiSCH network. A 6TiSCH communication schedule consists of a repeating structure called a slotframe. The number of transmit/receive slots (active slots) in the slotframe can be tuned by the network designer, and determines battery lifetime [19]. A MIMSY with a radio duty cycle of 0.5% and a 40mAh lithium polymer battery that is smaller than itself (16mm $\times$ 13mm) would have a lifetime of more than one week; with two AA batteries it would have a lifetime of more than one year. OpenWSN and the standards that it implements are designed to be platform-agnostic — more specifically, any system is capable of running OpenWSN so long as it has a board support package, or BSP, which implements the higher level platform-agnostic code. By creating a MIMSY BSP, including the necessary Invensense MPU9250 drivers, MIMSY works “out of the box” with the otherwise native OpenWSN stack. This ease of integration with the OpenWSN software ecosystem allows the user of MIMSY to focus on writing applications that run on top of the existing stack.

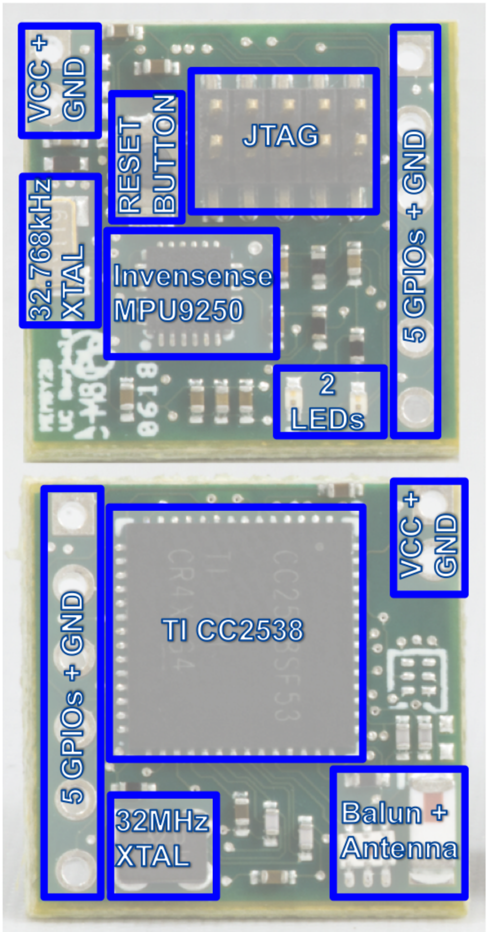

Fig. 2. System components on the MIMSY printed circuit board. The PCB is 4 layers and has edge dimensions of 16mm × 16mm.

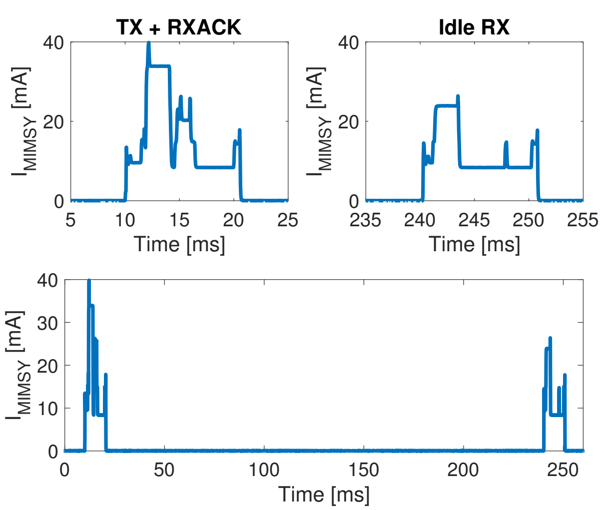

Fig. 3. Bottom: Measured current draw vs. time for a MIMSY in an OpenWSN network with a 23 slot slotframe and 1 active slot. Each slot is 10ms long. During the first active slot the mote transmits a packet with a 12 byte data payload and receives an acknowledgement. During the second active slot the mote listens idly before turning off. Top left: Close up of the first active slot. Top right: Close up of the second active slot.

CC2538	MPU9250	I_{MIMSY}
deep sleep mode (PM2)	sleep mode	12 μA
CPU asleep (PM0), RF Core enabled	sleep mode	8 mA
CPU on at 32MHz, radio off	sleep mode	13 mA
CPU idle at 32MHz, radio in TX mode at 7dBm output power	sleep mode	34 mA
CPU idle at 32MHz, radio in RX mode	sleep mode	24 mA
deep sleep mode (PM2)	6 axis (accel + gyro)	3 mA
deep sleep mode (PM2)	accel low power mode (15.63 Hz output data rate)	20 μA

TABLE II
CURRENT CONSUMPTION OF MIMSY OPERATING IN DIFFERENT MODES. ALL TESTS CONDUCTED USING A 2.5V SUPPLY AND BOTH LEDS OFF.

III. APPLICATION STUDIES

A. High-Granularity Wireless Sensing

Nearly one out of every seven Americans suffers from a chronic sleep disorder, and only 50% of Americans get the clinically recommended seven to eight hours of sleep. Wound care for pressure ulcers cost the health care system over $200 billion annually on top of the suffering they cause the patients themselves [20]. Pressure ulcers are common issues in health care settings especially among the elderly, patients with limited or no mobility, and individuals with blood-flow impairment, and they can be treated in part through regular re-positioning [21]. Clearly, there is a huge potential for sensing technology to make an impact in the health care industry, specifically centered on the bed.

Coarse measurements of sleep quality are possible using only a smartphone placed on the bed [22], [23]. These results are largely discounted by clinicians, with proper diagnoses requiring heavily instrumented sleep studies. Attempts to integrate advanced sensor technology with the bed itself often focus on pressure sensor arrays [24], [25] in the form of a pad or mat placed on top of the mattress. Other approaches (e.g. using fiber optic sensors [26]) typically require cumbersome instrumentation setup and calibration.

We implemented a "smart mattress" capable of directly estimating body position using a 4 × 3 array of mesh-networked MIMSYs integrated within the mattress (i.e placed between two pieces of mattress foam). Each MIMSY sampled its IMU and sent back its orientation to the base station computer at 0.2Hz. The orientation was then used to determine the deformation of the mattress foam at the location of each MIMSY. A sequence of body positions is shown in Fig. 4. The 6TiSCH network used for this experiment (configured to simplify debugging) provided the MIMSYs with a lifetime of about 2 hours using 40 mAh lithium polymer batteries; with further optimization the lifetime could be extended to over one week with the same 40 mAh batteries. While we have shown that body position on a mattress can be determined using a

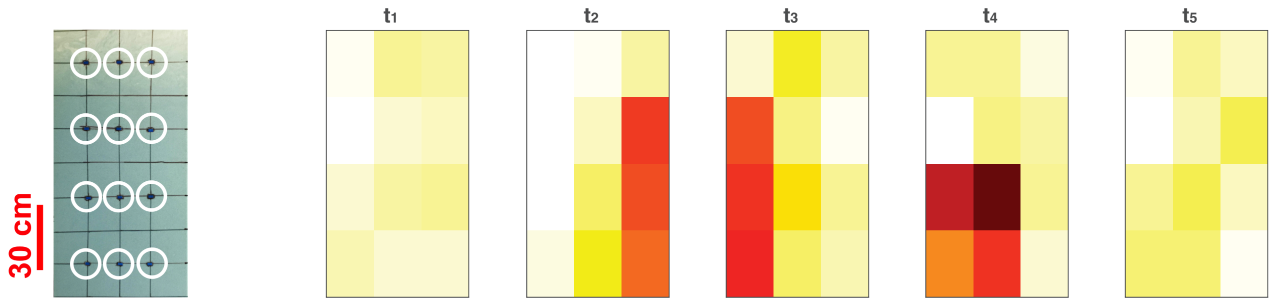

Fig. 4. Left: Mattress foam embedded with a 4 × 3 array of MIMSYS, each housed inside of a 3D printed case. The 12 MIMSYS are shown in white circles. Right: Heatmap visualization of body position on a mattress using a 4 × 3 array of MIMSYs from a real experiment. Each block corresponds to a single MIMSY in the mattress, and the color intensity represents the magnitude of the mattress gradient, calculated by measuring the MIMSY's orientation using its accelerometer and gyroscope. t_1: person is not on the mattress. t_2: person lays on the right side of the mattress. t_3: person lays on the left side of the mattress. t_4: person sits at the bottom left of the mattress. t_5: person gets off the mattress.

4 × 3 array of MIMSYs, continued miniaturization will allow thousands of nodes to be embedded, enabling inexpensive and very high-granularity sensing capabilities.

B. Latency-Bounded High-Reliability Factory Automation

Latency and reliability are paramount for the success of wireless automation of factory robots [27]. Due to high cost of failure and the inability of most wireless implementations to provide sufficient guarantees on data delivery, many critical industrial systems remain wired.

We created the miniature conveyor belt system shown in Fig. 5 to emulate a factory robot on which to conduct latency and reliability experiments using MIMSYs. The conveyor belt contains a DC motor and power supply, four MIMSYs, two Azbil HP300 photoelectric sensors, and an Arduino. A computer and Analog Discovery 2 were used to monitor latency via a custom Python test harness [28], [29]. The left and right TX MIMSYs wait until they receive an interrupt triggered by the cart passing their respective HP300 sensor. The MIMSY immediately sends a ten byte packet on two different channels. The RX MIMSYs receive this packet and change the direction of the conveyor belt. While this case study did not use the mesh networking or TSCH capabilities of OpenWSN, it did borrow code from OpenWSN, specifically at the PHY level. This lower-level network control reduced latency compared to a full OpenWSN stack implementation, but resulted in higher power consumption and less network functionality.

The implementation in this case study took advantage of frequency diversity along with redundancy of transmission to provide a relatively high level of reliability. Even more capable motes (in terms of hardware) may be at the mercy of arbitrary network conditions or the network stack implementation; for the same price, we can guarantee better network reliability, either in latency or packet delivery ratio (PDR), using multiple low-cost motes. Fig. 6 shows the latency distribution of an experiment where 10,000 ten byte packets were sent — all of the packets were received.

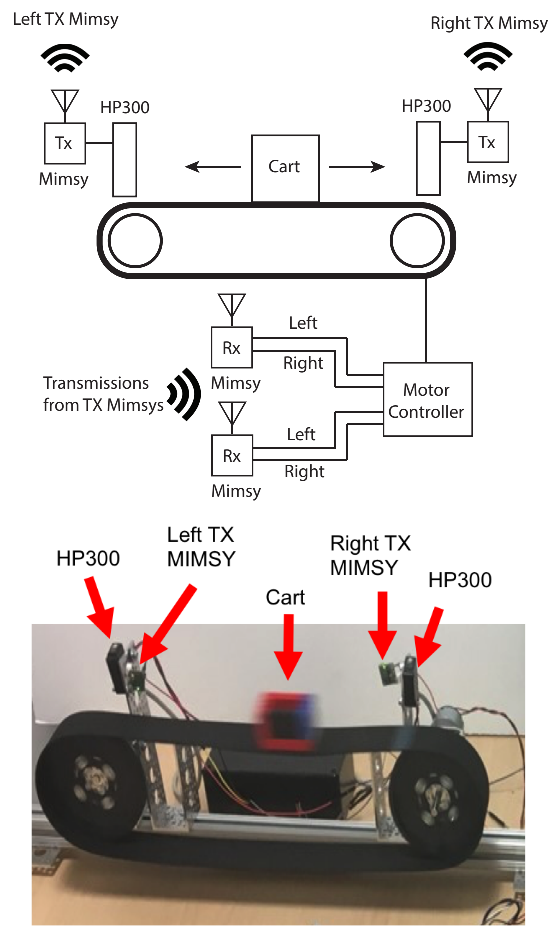

Fig. 5. Block diagram of a miniature conveyor belt control system using two transmitting MIMSYs and two receiving MIMSYs for communication. A small cart on the conveyor belt trips the photoelectric sensors as it passes by — a MIMSY then wirelessly sends a control signal to the MIMSYs connected to the motor controller causing the conveyor belt to switch directions.

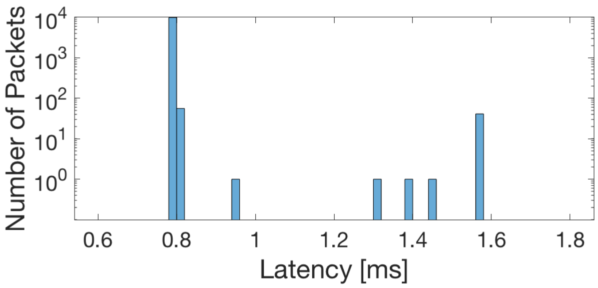

Fig. 6. Control signal latency from the conveyor belt system using four MIMSYs. A total of 10,000 ten byte packets were sent using a transmission power of 3dbm. The transmitting motes first transmitted on channel 14 (2420MHz) and then re-transmitted on channel 20 (2450MHz). The maximum latency was 1.6ms and the minimum latency was 0.8ms. All 10,000 packets were received.

C. Easily Deployable, Long-Lifetime Wireless Activity Monitoring

A movement towards "Ambient Intelligence" goes beyond embedding intelligence in our devices: it strives to bring intelligence to the world around us with environments that are sensitive and reactive to the people and things that inhabit them [30]. The modern wireless sensor network, with the potential for long lifetime distributed sensing, is an enabling technology for this vision. Key drivers include cost per mote, installation difficulty, data collection lifetime, and form factor.

There is a large amount of research in the related concepts of "smart homes" and "smart buildings," which often utilize sensor networks to analyze activity and usage patterns of occupants [31], [32]. Tapia et al. introduced ubiquitous "tape on and forget" sensors (each about 4cm $\times$ 4cm) for activity monitoring, however there was no wireless data transmission through a network, and all data analysis was performed offline and asynchronously [33]. Although Van et al. demonstrated a large wireless network of in-home sensors, each new node had to be manually paired with the network, the network was a star network (and not a more reliable mesh), and nodes had a larger form factor ($\sim$10cm^2 before attaching the actual sensor) [34]. For researchers looking to study "smart homes" and related domains without prior WSN experience, the required effort and cost of an installation often outweighs the benefits; many will opt for sensors wired to a central hub instead [35].

We present MIMSY as a solution to some of the challenges with prior work on instrumented environments. MIMSY is only 16mm $\times$ 16mm, and can be placed unobtrusively on practically any surface (see Fig. 7 — MIMSYs were placed on a microwave, cabinet door, and refrigerator, and monitored their usage). Motes automatically joined the wireless mesh network once turned on, eliminating the need for manual pairing and connectivity maintenance. The mesh shown in Fig. 7 was a two-hop network consisting of three MIMSYs recording inertial events, a relay mote to extend the range of the MIMSYs, and a root mote connected to a computer. The events were detected using the IMU's low power motion detect mode, which triggered a GPIO interrupt on MIMSY when a sufficient acceleration was detected. Packets were

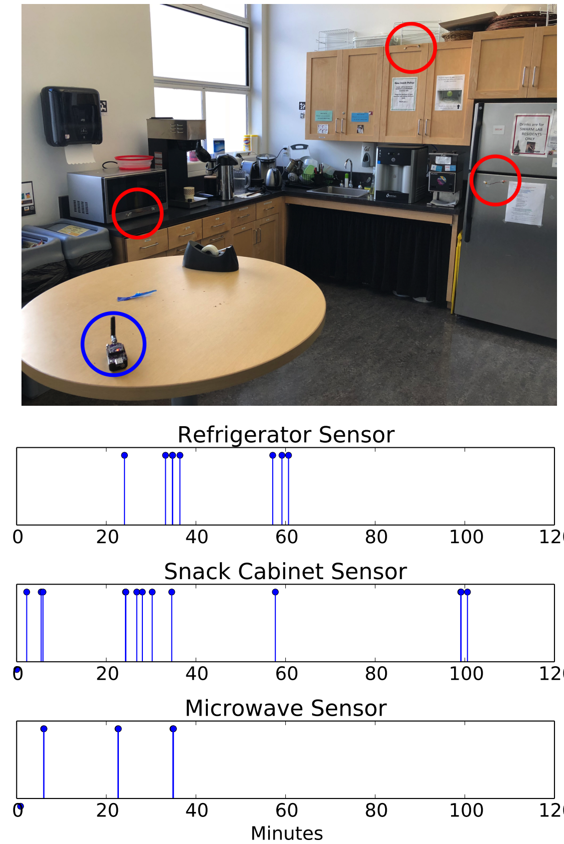

Fig. 7. Top: Activity monitoring in a kitchen with a two-hop network. When any of the three MIMSYs (shown in red) senses motion, it sends an alert back to the host computer (not shown) via an OpenMote (shown in blue). Bottom: Alerts sent to the host computers by the three different MIMSYs.

sent whenever MIMSY was triggered by this interrupt. Fig. 7 shows two hours of this event-based transmission behavior. Leveraging the power-saving properties of OpenWSN, the maximum lifetime of one of these motes was 12 hours on a 40 mAh battery; lifetime would be increased to about a month using two AA batteries. Extending this case study further, an entire building or home could be outfitted with dozens of easy to deploy activity monitoring wireless sensors.

IV. Conclusions

Future wireless sensor applications in areas such as environmental and agricultural monitoring, health care, and infrastructure could be enabled by small, power efficient, and inexpensive platforms. We have presented a new 16mm $\times$ 16mm mote built specifically for inertial sensing, and taken advantage of an open-source mesh networking stack to demonstrate three sample deployments. We hope that by making this system fully open-source we will lead others to do research using the same (or similar) motes; the continued miniaturization of microelectronic components will lead to even smaller motes in the future (e.g., the 4mm^2 single-chip μmote [36]), and we should be actively investigating use cases for when they get here.

ACKNOWLEDGMENT

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