Technical Report
AmICA – Design and implementation of a flexible, compact, and low-power node platform

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Abstract. Wireless sensor networks are the driving force behind many popular and interdisciplinary research areas, such as environmental monitoring, building automation, healthcare and assisted living applications. Requirements like compactness, high integration of sensors, flexibility, and power-efficiency are often very different and cannot be fulfilled by state-of-the-art node platforms at once. In this paper, we present and analyze *AmICA*[1]: a flexible, compact, easy-to-program, and low-power node platform. Developed from scratch and including a node, a basic communication protocol, and a debugging toolkit, it assists in an user-friendly rapid application development. The general purpose nature of *AmICA* was evaluated in two practical applications with diametric requirements. Our analysis shows that *AmICA* nodes are 67% smaller than BTnodes, have five times more sensors than Mica2Dot and consume 72% less energy than the state-of-the-art TelosB mote in sleep mode.

Key words: Wireless Communication, Wireless Sensor Networks, Node Platform Design, Evaluation

[1] Circuit diagrams, C libraries, software, protocol definitions, the debugger toolkit and some assembled nodes can be provided on request.

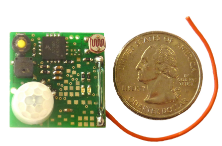

Fig. 1. *AmICA node* equipped with five sensors, two actors and a RFM12 radio module in comparison with a $0.25 coin

1 Introduction

Depending on the application, the functional and non-functional requirements of wireless sensor networks (WSNs) can be highly varying. In some scenarios, like environmental monitoring, the nodes' requirements are straightforward: they have to collect data, transmit them and save as much energy as possible. In other scenarios, data pre-processing, higher data-rates or a compact hardware design are key. For some applications single-hopping and simple protocols without a coordinator node can be used, while other applications require more complex routing protocols. This results in designs with different trade-offs adapted for specific applications.

In this paper, we present the *AmICA platform*, consisting of a novel node (see Figure 1), a basic communication protocol, and a debugger toolkit. The low-power, highly integrated design with cheap commercial off-the-shelf (COTS) components in combination with an configurable radio enables a use of *AmICA* for a wide range of WSN applications. Low duty-cycle and power-efficient applications are supported as well as applications, where in-network-processing or a compact design are required.

To ensure the communication between the nodes as well as between the network and a sink, we developed a basic communication protocol called *AmICA node protocol*. It can be easily employed in any short-distance network, where, for example, the nodes do not require time synchronization and single-hop communication is sufficient. However, the modular software stack and the flexible radio module allow also an easy implementation of other protocols, if required by a specific application.

The platform is completed with a debugging toolkit, called *AmICA node control*. In combination with an *AmICA node*, connected to a computer, it allows easy debugging of WSN applications based on the *AmICA node protocol*. It records and sends communication packets, generates network load, scans for nodes, discovers and controls them. Nodes can be re-configured and -programmed wireless, which is enabled by a bootloader.

The combination of *AmICA node*, *AmICA node protocol*, *AmICA node control* and free accessible compilers permit a fast and easy development, testing and deployment for a variety of WSN applications. To show the performance of the platform, we have chosen two scenarios, highly different in their requirements. An Ambient Assisted Living (AAL) application evaluates the use of *AmICA* for a low duty-cycle application, where power-efficiency belongs to the most important application constraints. Another scenario consist of a high duty-cycle sport application which exploits the in-network-processing capabilities, the small footprint, and the hardware robustness of the nodes.

In the next section, we provide an overview of state-of-the-art motes and describe important goals behind our design criteria. After introducing the *AmICA node platform*, we show a comparison and analysis with three other popular state-of-the-art node platforms, the Mica2Dot, TelosB, and BTnode. Finally, we briefly discuss deployment insights from the two real-world experiments with the *AmICA nodes*.

1.1 State of the art

In 1998, the UC Berkeley introduced one of the first COTS nodes: WeC. In 2002 MICAz ([5]) and MICA2 ([3]) respectively, were presented. They were equipped with an Atmel CPU with 128KB flash, 4KB RAM, a nonvolatile storage and a Chipcon CC1000 and CC2420, respectively, radio. Two years later, TelosB was presented in [12]. The mote uses an MSP430 from TI, which consumes several times less power then MICA2, works at a lower input voltage and wakes up faster. The Chipcon CC2420 supporting the 802.15.4 protocol ([8]) was chosen again as radio. Up to three integrated environment sensors enable measurements without a seperate board. In 2004, the ETH Zürich introduced BTnode [6]. This twin device is compatible to the Berkeley motes while supporting additionally bluetooth with a Zeevo ZV 4002 radio. Each of the mentioned nodes support the free wireless sensor operating system TinyOS ([2]), introduced 1999 by the UC Berkeley.

Since TelosB a multitude of further research and commercial nodes where built. They distinguish mainly in computional performance, flash and RAM size, radios, energy consumption and size. For example, Imote2 ([9]), released in 2007 by Crossbow, runs up to 52 times faster then TelosB, but consumes orders of magnitude more power. Other nodes are specialized for specific applications like the Sensys Networks nodes ([15]), who are integrated in streets to detect vehicles.

We focus in this paper on nodes for WSN applications described in the introduction and compare our node with Mica2Dot ([4]), TelosB and BTnode, which represent the state-of-the-art in this area and are well accepted by the WSN community. We have chosen the Mica2Dot instead of MICAz, because Mica2Dot is similar to it, but works in the same frequency bands like AmICA, has a smaller footprint, and a better energy efficiency than MICAz.

1.2 Design goals

The key design goals for a WSN node are flexibility, usability, compactness, transmission range, and power-efficiency. We discuss in this section these criterias. They are the basis for the analysis comparison with the exisiting WSN platforms in section 3.

Flexibility. To support various sensors and actors, the basic board has to provide a sufficient number of different interfaces, like ADC inputs, general in- and outputs (GPIOs), two wire interfaces (TWIs) etc. For a high flexibility regarding the communication protocol, the radio has to be widely configurable and not fixed to a specific protocol. In addition, the development environment should provide a full access to the hardware and assist in a low-level programming.

Power-efficiency. Energy consumption is critical for most WSN applications, especially, when only small batteries or energy harvesting (see e.g. Enocean sensors, [7]), have to be used. Critical for low duty-cycle applications are the power consumption in sleep mode (typically a few microampere) and a fast wake-up time of the MCU and radio (together typically some milliseconds). In applications, where the microcontroller unit (MCU) is active for more time

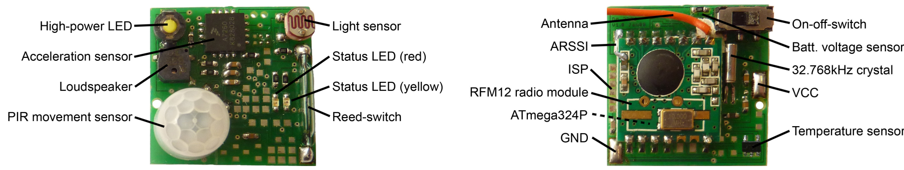

Fig. 2. Fully equipped *AmICA node*; top (left) and bottom (right) view

and more data has to be transmitted and received, the power consumption in active mode becomes an important factor. In this mode, the MCU processes data and the radio is transmitting or receiving (typically between 10 and 30mA). Special hardware accelerators or radio modules with integrated pre-processing like an automatic header recognition additionally reduce the overall node power consumption.

Usability. From the point of the developers and researchers, the development toolkits have to support all phases of an WSN application development: software implementation, debugging, analyzing, optimization, and deployment.

Compactness. For some applications, e. g., if the node has to be wearable, the node's dimensions and weight play a key role.

Transmission range. For applications, where the nodes are widely scattered or the next base station is far away, a high transmission range has to be ensured.

The described design goals are oftentimes contradicting and trade-offs have to be found. For example, a fully integrated WSN chip is very compact and has a higher energy efficiency in comparison to a node built with COTS components, but is limited relating to the integrated sensors.

2 AmICA node platform

In the following, we describe the hardware of the *AmICA node*, the properties of the *AmICA node protocol* and how the debugging toolkit *AmICA node control* supports the development of new WSN applications. A detailed comparison with state-of-the art WSN platforms is given in Section 3.

2.1 Hardware

A basic *AmICA node* consists of a board with an Atmel MCU, a HopeRF radio module, a sensor for the supply voltage level, an analog received signal strength indicator (ARSSI) sensor, two status LEDs and an energy source, which are typically two AA or one lithium polymer battery. Additionaly, up to five further sensors and up to two further actors can be mounted dircetly on the board without the need of an extension board (see Figure 2 which shows a fully equipped *AmICA node*).

Processing The main criteria for choosing a MCU were a very low power consumption in sleep mode, self-wake-up capabilities, a fast wake-up time, enough and different interfaces, and a self-programming capability. The size of flash and RAM were secondary factors since they can easily be extended. We have chosen an Atmel ATmega324P running at 8MHz with 32KB flash and 2KB RAM with eight ADC inputs, 32 GPIOs, four different interfaces like TWI and various of integrated peripherals. The sleep current at 3V is under 1µA running an RTC, which can wake-up the MCU at arbitrary points in time within 7.5µs. Table 1 compares the main characteristics of Mica2Dot, TelosB, BTnode and *AmICA node*.

Communication Critical parameters for the radio are low-power consumption in sleep mode, high link budget (output power vs. receiver sensivity), fast wake-up time, and the possibility of detailed configuration. We decided to use the narrowband, low power RFM12B radio module with the RF12B from Hope RF. It uses FSK in the 433, 868 or 915 MHz frequency band, has a maximum output power of 5dBm and supports data-rates up to 115.2kbps. The maximum link budget at 2.400baud with a bit error rate of 0.1% is 114dBm. Table 2 compares the radios used at Mica2Dot, TelosB, BTnode, and *AmICA node*.

Sensors and actors A onboard temperature sensor from Dallas (DS1775) has a range between $-55°$C and $+125°$C with an accurancy of $\pm 2°$C and a resolution up to 0.0625°C. Light intensity is measured with a light dependent resistor. A acceleration sensor (Freescale MMA7260QT) can measure up to ± 6g at all three axis. A reedswitch can detect open doors, which are equipped with a magnet. A PIR movement sensor (Panasonic NaPiOn series) detects movements of warm objects, such as humans. Beside two status LEDs, a further high-power LED and a small loudspeaker can be equipped on the board.

	Mica2Dot	TelosB 2420CA	BTnode rev3	*AmICA 1.0*
Release	2002	2004	2004	2009
MCU type Flash RAM	ATmega128L 128KB 4KB	TI MSP430 48KB 10KB	ATmega128L 128KB 64KB	ATmega324P 32 / 128KB[1] 2 / 16KB[1]
Integrated sensors	Temperature	Temperature, 2x light, humidity	-	Temp., light, acceleration, reed-sw., PIR[2]
Integrated actors	1x status LED	3x status LED	4x status LED	2x status LED, high-pwr. LED, loudspeaker
Size	ø25x6mm^3	65x31x6mm^3	58x33x7mm^3	25x25x6mm^3

Table 1. Comparison of the MCU and integrated sensors and actors between Mica2Dot, TelosB, BTnode and *AmICA node*; [1]pin-compatible ATmega1284P, [2]Passive Infrared movement sensor.

	Mica2Dot	TelosB 2420CA	BTnode rev3[1]	*AmICA 1.0*
Radio type	Chipcon CC1000	Chipcon CC2420	Chipcon CC1000	HopeRF RF12B
Freq. / Mod.	315-915Mhz FSK	2.4GHz O-QPSK	315-915Mhz FSK	433-915MHz FSK
Data rate	0.6-76.8kbps	250kbps	0.6-76.8kbps	0.6-115.2kbps
Link budget	112dBm @ 2.4k[2]	94dBm @ 250k[3]	112dBm @ 2.4k[2]	114dBm @ 2.4k[2]
Antenna	wire	onboard	onboard/wire	wire

Table 2. Comparison of the radios between Mica2Dot, TelosB, BTnode and *AmICA node*, [1]only low-power radio considered, [2]@ 0.1% BER, [3]@ 1% BER

2.2 Software

Software for the *AmICA node* is written in Atmel assembler or C. The free AVR Studio from Atmel ([1]) works together with free WinAVR [16] and is a powerful development environment. C and assembler code can be implemented, compiled, simulated and flashed wired to the microcontroller with a programmer. We implemented 14 C libraries, which encapsulate the access to the sensors, actors, and the most important peripherals of the MCU. Each part of the hardware is direct programmable. All the software support and developer toolchains are available to the open-source community.

AmICA node protocol The *AmICA node protocol* ensures a basic communication functionality between the nodes and the node network and a computer (sink). It supports up to 256 different networks with up to 255 users and one broadcast address per network. The header consists of seven bytes and a packet can contain up to 255 bytes payload. While a CRC mechanism is integrated, carrier sensing, hopping and acknowledgement mechanisms were abdicated since they belong to specific application requirements.

AmICA node control (debugging toolkit) With the help of an *AmICA node*, which is connected via USB to a computer, the debugging toolkit *AmICA node control* can be used to support the development and deployment of applications based on the *AmICA node protocol*. Compiled code from the AVR Studio can be read in and flashed to the nodes using wireless communication. The nodes settings, which are saved in the MCU's EEPROM can also be changed wirelessly. Both functions are enabled by a bootloader.

Network communication can be read along, recorded, visualized, and saved. *AmICA node protocol* compatible packets can be generated, changed and sent to the network. Also packets with bit errors, wrong checksums or non-conform structures can be sent to test the nodes' software.

3 Analysis

We analyzed the *AmICA node platform* according to the design goals described in section 1.2. We present in the following the results and compare them with the Mica2Dot, TelosB and BTnode motes.

3.1 Flexibility

The diversity of sensors, which can directly equipped on the basic node board, ensures a wide and direct use of the *AmICA node* without the need of extension boards. In comparison, the TelosB node has up to three, Mica2Dot up to one, and BTnode no integrated sensors. The *AmICA node* has beside a temperature and light sensor a PIR movement and reed-switch sensor, which enables building automation and AAL applications. A three-axis acceleration sensor can be used for further applications, e. g. for sport applications, where body movements must be recognized. While the other three nodes offer no actors except the status LEDs, the *AmICA node* can be equipped with an onboard high-power LED and a small loudspeaker. Further GPIOs and interfaces ensure the connection of further sensors and actors.

From the memory perspective, 8KB Fash and 2KB RAM are left for programs. While the other nodes have more flash and RAM (see table 1), we recognized, that for many programs the resources are enough. If more program space and RAM is needed, the ATmega324P can be changed with the pin-compatible ATmega1284P with 128KB Flash and 16KB SRAM easily. The self-programming capability of the controller enables in combination with a bootloader wireless re-configuration and -programming. Each part of the hardware is directly programmable.

The HopeRF RF12B radio is not fixed on a specific protocol open for a flexible use.

3.2 Power-efficiency

To achieve a very low-power consumption in standby mode, we have chosen the ATmega324P, which runs down to 1.8V and consumes under 1uA in so called "power-save mode" including a 32kHz RTC. In comparison to the older Atmel ATmega128L, which is used at the Mica2Dot and BTnode, the ATmega324P can wake-up itself from power-save mode. The supply voltage of all sensors can be disconnected by the MCU. The radios sleep current is 0.3uA (crystal oscillator off). The whole node consumes only 1.4uA at 3V in sleep mode. This is 72% less than TelosB, 91% less than Mica2Dot and over three order of magnitue less than

	MCU	RFM12 *TX* *RX*	Temperature sensor[1]	Light sensor[1]	Acceleration sensor[1]	Reed-switch[1]	PIR[1]	Status LED	High-power LED	Loud-speaker
Active	5.7mA	28.5mA 18.5mA	1213µA	193µA	1430µA	93µA	281µA	1043µA	4090µA	5050µA
Sleep	1.09µA	0.3µA	0µA	0µA	0µA	0µA	0µA	0µA	0µA	0µA
Wake.	7.5µs	4.1ms	-	-	-	-	<10s	-	-	-

Table 3. Current consumption of single elements of the node at 3V; [1]including the additional consumed power by the MCU, when measuring

BTnode. In transmit mode, *AmICA* consumes 85.5mW at 3V and 5dBm, which is similar to Mica2Dot (81mW) and BTnode (93mW), both using the Chipcon CC1000 ([10]). TelosB with Chipcon CC2420 ([11]) radio consumes 58.5mW, but sends only with 0dBm. The receive power consumption of *AmICA* is about one quarter lower than TelosBs and BTnodes, see Table 4 for an overview.

The power consumption of the single elements of an *AmICA node* is shown in table 3. We have chosen only low power sensors like the three-axis accelerometer Freescale MMA7260QT (consumes 1221µA itself, if active) or the Panasonic NaPiOn PIR motion sensor (consumes 101µA itself, if active). The PIR sensor current is critical, because a stablization time of up to ten seconds after switching the sensor on prohibits a pulsed mode.

AmICA nodes of the first generation have a minimum input voltage of 2.6V. To exploit two AA batteries fully, a minimum input voltage of 1.8V is necessary. That is why we designed a second generation, which can run down to 0.9V, while keeping the sleep current under 2µA.

For low-duty application the wake-up time of the MCU is important, e. g. to check, if a sensor value has changed. *AmICA nodes* wake up within 7.5µs, which is comparable to TelosB (6µs) and over 24 times better than Mica2(Dot) (see [12]).

Assuming, that a measurement of a sensor takes 0.5ms, packets contain seven byte header, four byte payload, and 30 packets per hour are sent with maximum datarate, *AmICA* will run with two AA batteries (each 2000mAh) for 171, TelosB for 150, Mica2Dot for 45 and BTnode for 0.3 months.

3.3 Usability

While Mica2Dot, TelosB and BTnode use TinyOS, software for the *AmICA node* is currently implemented in assembler or C. The main reason is that TinyOS has a very limited access to the hardware components. We implemented different C libraries which abstract from the hardware and allow a fast and “high-level” soft-

	Mica2Dot	TelosB 2420CA	BTnode rev3	*AmICA 1.0*
Input voltage range	2.7-3.3V	1.8-3.3V	0.5-4.4V[1]	2.6-3.6V[2]
Mote sleep (RTC on)	48µW	15.3µW	9000µW	4.2µW
MCU active, radio off	24mW	5.4mW	36mW	17.1mW
MCU active, radio tx	81mW[3]	58.5mW[4]	93mW[3]	85.5mW[3]
MPU active, radio rx	30mW	74.4mW	75mW	55.5mW
Energy per bit [µJ]	2.42 @ 38.4k	0.23 @ 250k	2.42 @ 38.4k	0.74 @ 115.2k
ø energy 30 pack./hr.[5]	62.1µW	18.5µW	9020.2µW	16.2µW

Table 4. Comparison of power consumption at 3V between Mica2Dot, TelosB, BTnode and *AmICA node*. Values for Mica2Dot, TelosB, and BTnode see [4], [12], and [6]. [1]also with 3.6-5.0V available, [2]*AmICA V1.1*: 0.9-5.5V and 3.8-5.5V, [3]@ 5dBm, [4]@ 0dBm, [5] each 7 byte header and 4 byte payload and 3V

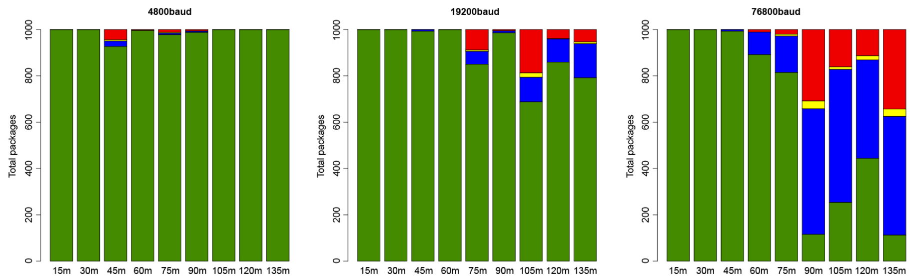

Fig. 3. AmICA node range measurements at 15-135m (line of sight) of 1000 sent packets with each 7 byte header and 23 byte payload; green: correct received; blue: 1-10 bit erros; yellow: >10 bit errors; red: packet lost

ware development. Alternatively, the developer is also free to write own hardware libraries or use assembler, hence a "low-level" access is also possible.

While the AVR Studio support the developer in implementing software, the debugger toolkit *AmICA node control* enables a wireless re-programming and re-configuration and enables the debugging and deployment of applications based on the *AmICA node protocol*. The structure of the protocol is simple and a coordinator node is not needed.

3.4 Compactness

The base volume of the *AmICA node* is 25x25x6.0mm^3 including the MCU, the radio, an 32kHz crystal, an temperature sensor and two status LEDs. To save space, we stacked the radio module above the MCU.

Similar to TelosB we use also an integrated design, which means, that sensors and actors can be euipped directly on the basic board withouth the need of extension boards. The *AmICA node* can be direct assembled with up to five sensors and two actors (see Table 1), while the foot print of the node is 69% smaller in comparison to that of TelosB. Mica2Dots foot print is about 20% smaller in comparison to a *AmICA node*, but supports only one integrated sensor. The foot print of BTnode is 67% larger than a *AmICA node*, while it supports no integrated sensors or actors.

For applications, where size and weight is key, we recommend the use of small lithium-polymer batteries instead of two AA batteries. A 180mAh type is only 4mm high and smaller than the foot print of the node.

3.5 Transmission range

A high transmission range highly depends on transmission parameters like the used frequency band, modulation, and the physical properties of the environment. For WSNs, the 2.4GHz band is very popular, because it offers high datarates and belongs to ISM bands, i. e., it is licence-free. The disadvantages of this band are its shorter range in comparison to lower frequency bands, and very crowded wireless spectrum which includes related techonologies, like bluetooth, WLAN, but also unfair contenders, such as microwaves ovens. To achieve in general a high transmission range, different methods, like multi-hop, a high link budget or use of forward error correction codes can be applied.

AmICA node's radio uses a FSK modulation in the 433, 868 or 915MHz frequency band. In most countries at least one of these frequency bands is licence-free. For example, in Europe, the 868MHz frequency can be used. In comparison to the 433MHz band, which can be occupied without restrictions, for the 868MHz band a duty cycle between 0.1% and 1% is given, which assures significantly less interference. Assuming, that a packet needs 1.65ms to be transferred (19 bytes at 115.2kbaud), up to 21,818 packets can be send within one hour by a single *AmICA node*.

The maximum link budget of the RF12B at 2.400baud is 114dBm with a bit error rate of 0.1%. In comparison, Mica2Dots and BTnodes is 112dBm (at the same conditions) and TelosBs is -94dBm at 250kbaud and 1% bit error rate. Figure 3 shows the results of our practical measurements of the communication range (line of sight) for different datarates. It depicted, that most packet errors are caused by one to ten bit errors. Further experiments ([14]) with the *AmICA node* showed, that the range can be extended with the help of forward error correction codes. See also [13].

4 Real-world scenarios

4.1 Ambient Assisted Living

The primary goals of this scenario consist of testing the nodes outside the lab, i. e., in a real-world, low-duty cycle application, over a long period of time. We are interested in evaluating the *AmICA node protocol* and the power-efficiency of the *AmICA nodes*.

In April 2009, nine *AmICA nodes* were deployed in an apartment of an elderly person. The application was an assisted living scenario, where person's movement such entering and leaving apartment and other rooms is monitored by the WSN network. Based on this data, a flat can provide comfort and energy saving functions for its inhabitants or detect emergencies like a unconscious person and call help automatically. This experiment was running for 16 month. Figure 4 shows the floorplan of the apartment and the placement of the WSN nodes.

Results We stored over 322,000 measurement points and received over 4.4 million packets within the last 16 months. Over 99.2% of all packets were received correctly and no node failed till today. Because the receive mode emerged as highest power load, we optimize currently the algorithms with to goal to lower the receive duty-cycle down to 0.5% and below.

Fig. 4. Real-world AAL experiment: Floorplan and placed nodes in the flat; M.: PIR movement detector; D.: Door sensor (reedswitch and magnet); a tenth, mobile node, is not shown

Fig. 5. Real-world sport experiment: *AmICA node* and a lithium polymer battery mounted on a athlete's leg

4.2 Sport application: Rope skipping

To show the nodes pre-processing and in network processing performance, the wearing properties on a body and the usability for developers, we have chosen a sport application using a wireless sensor network. In the "speed" discipline of Robe Skipping the jumps, a athletic did within a given amount of time, has to be counted. Because there is no technical tool presently, we used *AmICA nodes*, equipped with accelerometers and small lithium-polymer batteries, which were attached to the leg, and the *AmICA node protocol* to count the jumps of up to six jumpers automatically (see figure 5). The data-rate was too low for sending the raw sensor data of all jumpers, so we were forced to pre-process the data and recognize the jumps at the node. The nodes sent only how many jumps the have counted since the last transmission.

Results The accelaration sensor provided enough information about the leg movement and the MCU had enough computation power to filter noise and detect the jumps. We measured the acceleration axis values along the feet with a 8Bit resolution and 500 samples per second. The nodes and batteries were small enough and the professional athletes were not influenced in any way. Although each seven Robe Skippers, who tested the application, jumped slightly different, all jumps were detected reliable. Some nodes had high physical stress, because they were mounted the first time too weak at the leg and flung away. Although they had no housing, they were robust enough and were not damaged.

5 Conclusion

The goal of this paper was to introduce a novel WSN platform, discuss "lessons-learned" during its design and development, and to systematically compare it with the existing work. In addition, this paper demonstrates how to create a platform while keeping a good trade-offs between oftentimes highly contradicting design objectives, such as flexibility, usability, compactness, and power-efficiency. The *AmICA platform* includes a complete toolchain supporting fast development of new applications. The *AmICA node* integrate five sensors and two actors at a 25x25mm^2 foot print and consumes only 1.4µA in sleep mode, while, e. g., BTnode's foot print is more than three times bigger and the mote consumes 3000µA in sleep mode. A link budget of 114dBm allows communication of 135m and more with no packet losses while, sending 30 packages per hour, the *AmICA node* runs 14% longer with two AA batteries than, e. g., TelosB.

References

1. Atmel. http://www.atmel.com/.
2. UC Berkeley. TinyOS wiki: http://tinyos.net/, 1999.
3. UC Berkeley. MICA2 platform: http://tinyos.net/scoop/special/hardware, 2002.
4. UC Berkeley. Mica2Dot platform: http://tinyos.net/scoop/special/hardware, 2002.
5. UC Berkeley. MICAz platform: http://docs.tinyos.net/index.php/MicaZ, 2002.
6. Jan Beutel, Matthias Dyer, Martin Hinz, Lennart Meier, and Matthias Ringwald. Next-generation prototyping of sensor networks. In *SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems*, pages 291–292, New York, NY, USA, 2004. ACM.
7. EnOcean GmbH. http://www.enocean.com/.
8. IEEE. 802.15.4 working group: http://www.ieee802.org/15/pub/TG4.html.
9. Crossbow Technology Inc. iMote2: http://docs.tinyos.net/index.php/Imote2, 2007.
10. Texas Instruments. CC1000 datasheet: http://focus.ti.com/lit/ds/symlink/cc1000.pdf, February 2007.
11. Texas Instruments. CC2420 datasheet: http://focus.ti.com/lit/ds/symlink/cc2420.pdf, March 2007.
12. J. Polastre, R. Szewczyk, and D. Culler. Telos: enabling ultra-low power wireless research. pages 364 – 369, apr. 2005.
13. C. Schlegel S. L. Howard and K. Iniewski. Error control coding in low-power wireless sensor networks: When is ECC energy-efficient? *EURASIP Journal on Wireless Communications and Networking*, page 1..14, 2006.
14. Daniel Schmidt, Matthias Berning, and Norbert Wehn. Error Correction in Single-Hop Wireless Sensor Networks – A Case Study. In *Proc. DATE '09. Design, Automation. Test in Europe Conference. Exhibition*, pages 1296–1301, 2009.
15. Inc. Sensys Networks. http://www.sensysnetworks.com/.
16. WinAVR. http://winavr.sourceforge.net/.