Architecture and Evaluation of INGA
An Inexpensive Node for General Applications

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***Abstract*—INGA is a cost-efficient and universal wireless sensor node for activity monitoring and for general applications. INGA's architecture bases on an 8-bit Atmel microcontroller and runs Contiki OS and TinyOS "out of the box". The motivation to develop INGA was driven by the need for a reasonable, cheap and expandable node for several use cases: On the one hand, in a research project, we intend to do a gait analysis of elderly persons with it, on the other hand we want to equip our student WSN lab with new nodes. For the first case none of the existing nodes fulfilled our requirements concerning assembled sensors and functionality. In this paper, we present the motivation and design for "yet another sensor node"; furthermore, we present the detailed architecture and its benefits in comparison to other nodes. The first measurement results using INGA show its characteristics and usability. INGA is completely under open-source license and all resources are provided to the community.**

I. Introduction and Motivation

Is there really a need for yet another sensor node? Ain't there enough motes in the market, to cover every thinkable use case? Well, this may be right, but let's have a short look around. When dealing with Wireless Sensor Nodes in research or education, you may have heard of the TelosB [1], which is also called TMote Sky [2] or MTM-CM5000-MSP. It is a quite universal node, easy to handle, supported by Contiki [3] and completely outdated. You may also have heard of the Atmel AVR Raven, which is also quite universal, not that easy to handle and by some reason equipped with a second (inefficient) microcontroller, an LCD and a loudspeaker (just to mention some absurdities). Furthermore many TMote Sky similar MSP-430 based nodes exist, for instance the Shimmer Sensor for human activity monitoring. On the other hand there are many high-class, -cost, and -power sensor nodes with ARM7- or XScale-processors, like MSBA2 or IMote2 [4]. Some are designed for a special purpose, some are universal, every single node has its right to exist and its benefits, but also its disadvantages. So, why another wireless sensor node? In the past we have been working with several different nodes, coming to value their individual advantages and learning about their specific shortcomings. Then, we had to master two challenges quasi simultaneously:

A. Research and Education

For research mainly the universality of a node has priority, because "if we knew what it was we were doing, it would not be called research, would it?" (Albert Einstein). A universal node for research should support every conceivable idea and thereby should be as nonrestrictive as possible. As there is sadly no way to cover every thinkable future use case, we defined some guidelines for nodes to be used in or designed for research and education:

- *State-of-the-art*: Well-known and widely supported parts are preferred, but no outdated parts.
- *Expandability*: Lead through every possible port or bus for future extensions and expansions.
- *Manageability*: No special connectors, no tiny "unsolderable" pins; normal 2.54 mm pin headers wherever possible.
- *Simplicity*: No overkill in basic functionality, as nobody should be frightened off.
- *Compatibility*: Simple adaption of existing Operating Systems.
- *Cost-Efficiency*: Be as cheap as possible, because things might fall down.

B. Human Activity Monitoring

Within the Project "Design of Environments for Ageing" [5], it is planned to monitor elderly peoples activity and by this to perform a fall detection and a fall prevention through gait analysis. In a field study more than 30 persons will be equipped with sensor nodes, that they are supposed to wear most time of the day. For human activity monitoring in the first place the right set of sensors has to be present. In most cases an accelerometer is used (e.g. in [6] and [7]); newer studies also benefit from a gyroscope [8] and a pressure sensor [9]. Secondly, power consumption is a major issue, as a long term monitoring is envisaged and the changing of batteries is unacceptable for the monitored persons. Size and weight of a sensor node is the third aspect to be addressed, when choosing or designing a node which is intended to be worn.

Both our intended use cases have in common that the designated wireless sensor nodes have to be as cheap as possible; by all means cheaper than 100 Euro, each.

The rest of the paper is structured as follows: INGA's architecture, especially its characteristics, is shown in Section II. After first evaluations in Section III, the conclusion and a link to the resources is presented in the last Section.

II. INGA's Architecture

Figure 1 shows INGA's front side; in Figure 2 INGA's overall hardware architecture is given. Some of the characteristics are detailed in the following subsections. The center of the

Figure 1. INGA's front view. The picture is nearly in original size and compared to a 2-Euro coin. INGA's physical dimensions are 50 x 39 x 7 mm.

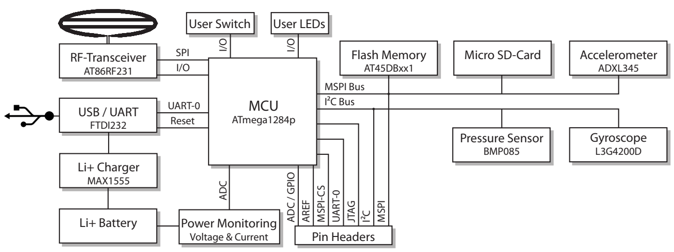

Figure 2. Block diagram of INGA's architecture.

design is the Atmel ATmega 1284p microcontroller, which was also used in the AVR Raven nodes. All communication buses are separated, which leads to a high level of robustness, because a malfunctioning or falsely programmed device only affects the bus it is attached to and not the whole system. Furthermore all relevant buses, unused I/O channels and other useful signals are lead through to a 2.54 mm pin header.

A. Power Management and Monitoring

When connected to USB, an attached Li+-battery can be directly charged through a MAX1555 Li+-battery charger. The voltage of the attached batteries is constantly monitored by a potential divider and the current of the system is constantly monitored by the combination of a Maxim MAX4372F high-side current-sense amplifier with voltage output and shunt, each connected to an ADC-channel of the ATmega 1284p. A Maxim MAX 8881 low-dropout linear regulators provides a constant voltage of 3.3 V.

B. AT86RF231 - Radio Transceiver

The RF231 is a fully IEEE802.15.4 compliant radio transceiver. In contrast to the preceding model (RF230, assembled on the AVR Raven) it also supports AES hardware encryption and some minor other enhancements. The radio transceiver is the only device connected to the hardware SPI. The PCB antenna is designed as a folded dipole, similar to the one on the AVR Raven nodes and derived from the original Atmel Application Notes.

C. MSPI-Bus

With the MSPI, realized through the second USART, a second SPI was designed as a bus, thus, communication with other SPI devices does not interfere the communication with the radio transceiver. Figure 3 illustrates that three I/0 ports are used to demultiplex the chip-select signals of the attached devices; by this way up to seven devices can share the MSPI bus. Two of these chip-select lines are lead through a pin header for individual expansions.

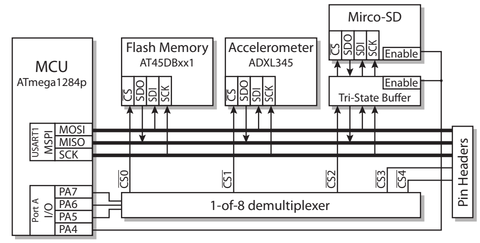

Figure 3. INGA's MSPI bus and attached components: Accelerometer, Flash Memory, Micro SD-card

1) Accelerometer: Analog Devices ADXL345.: In prior investigations [10] we compared various different 3-axis accelerometers in terms of power consumption, linearity, bit noise and correlation. It turned out that the ADXL345 was most qualified for our purposes. Its sensitivity can be set to ± 2g, ± 4g, ± 8g and ± 16g; the sampling resolution varies from 10 to 13 bit (dependent on sensitivity) and it has an adjustable sampling rate of up to 3.2kHz.

Serial Flash: Atmel AT45DBxx1 Series.: INGA can be equipped with either one of AT45DB081 (8 MBit), AT45DB161 (16 MBit) or AT45DB321 (32 MBit) serial flash devices. The dual buffer interface of these devices leads to a significant speedup in contrast to single buffer devices, because one buffer is still capable of communication with SPI, while the other writes/reads the flash memory. The benefits of this device are explained more detailed in the Evaluation Section.

Micro-SD Card.: The SD-card specification is not standardized in ISO or DIN and is only available for paying license holders. Luckily, there are open protocols that allow a free but slow operation of any SD-card via SPI, but there are some peculiarities to deal with. First of all, SD-cards can be very power consuming with a current of up to 45mA during operation. There is no easy way to just switch off the supply power, because SD Cards can draw current from the data lines as well due to its internal design.
Another major issue appears when attaching more than just the SD Card to an SPI, because the specific protocol requires some action on the clock line (SCK), without chip-select being enabled. As this happens on a bus, undefined states can occur resulting in communication problems on the whole bus. We solved this by introducing a tri-state-buffer that is able to "disconnect" all lines of the SD-card and by this there is nearly no power consumption of the SD-card while not in use.

D. I^2C-Bus

Two sensors are directly connected to the I^2C-bus. For further usage it is also lead through on pin headers. An easy expansion is e.g. realizable by an I^2C-IO-expander that allows the connection of multiple additional inputs and outputs.

Gyroscope: L3G4200D.: The ST-Microelectronics L3G4200 MEMS gyroscope is able to measure deviations of orientation and, thus, to determine the location more precisely. This 3-axes gyroscope is also assembled in Apple's iPhone. It is able to detect up to 2000 degrees per second in three axes

(16 bit). It allows the measurement of 3 additional degrees of freedom and thus, combined with the accelerometer 6 degrees of freedom can be sensed by INGA. The gyroscope has an integrated temperature sensor (8 bit).

Pressure Sensor: BMP085.: The pressure sensor is able to sense pressure with a resolution of 0.01 hPa and an accuracy of ± 0.2 hPa. This allows the detection of a difference in altitude in the dimension of few centimeters. Thus, for a gait monitoring, it can be easily suggested whether a person walks up- or downstairs. The pressure sensor has 16 to 19 bit resolution, depending on the selected sensitivity. Also another temperature sensor (16 bit) is integrated which enables the sensor to do a temperature compensation and by this to measure absolute pressure.

E. Bootloader and USB

INGA's Bootloader allows flashing via USB and is compatible to AVRDUDE, thus, no additional hardware is required. With enhanced drivers (provided for Linux, Mac and Windows by FTDI), also the capability of resetting the microcontroler is implemented, which again allows the flashing of multiple connected nodes quasi simultaneously. We were able to speed up the bootloader's transfer rate by the factor of 6 compared to normal and by this way e.g. flashing Contiki via USB is done in less than 5 seconds.

The bootloader is also the basis for an "over-the-air" flashing which will be implemented in software in the near future: With a bootloader present it is regardless on which memory the operating system to boot is stored. Thus, it has just to be taken care of the secure and accurate wireless transfer of the operating system, the rest can be handled by the bootloader.

III. Evaluation

The first INGA was built in August 2011 and we were glad to demonstrate it's functionality on SenSys 2011 [11]. We evaluated INGA in real world measurements in our lab with other 2.4 GHz hardware present and in the countryside with most likely no other radio traffic in the considered frequency spectrum.

A. Communication Range

In a first evaluation, we compared INGA's communication range to the original Atmel AVR Raven node. In a line-of-sight setting on a field with no other interfering radio transmissions in the designated frequency, we measured UDP/IP packet loss at increasing distances. The tested nodes acted as sender, sending 6 Byte of payload every 20 ms and a PC with a AVR Raven USB-stick acted as receiver.
It turned out that there is no significant difference between INGA and AVR Raven, as both had only randomly occurring single packet losses along the track. We defined a UDP packet loss of greater than 50 percent as breakpoint where no further communication is possible. This breakpoint was reached after 194 m for INGA and 219 m for AVR Raven. The increase of packet loss happened in short period of only few meters from nearly zero percent to greater than 50 percent. Thus, INGA's radio-frequency (RF) part is fully working and comparable to the AVR Raven.

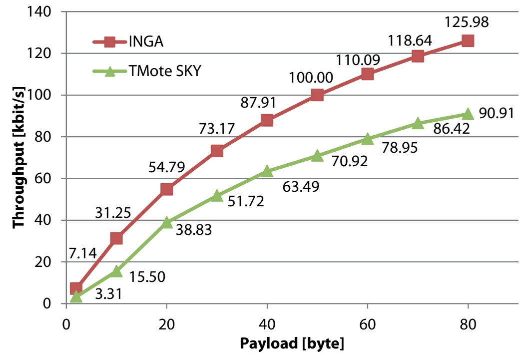

Figure 4. The throughput of UDP/IP traffic at a varying payload size.

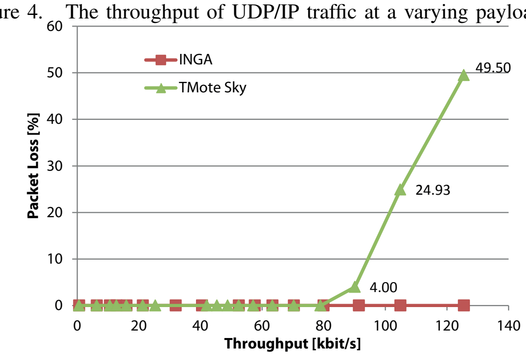

Figure 5. Performance of writing received UDP data directly to external flash memory.

B. Application Layer Throughput

In our lab we compared the UDP throughput of INGA to the T-Mote Sky nodes using the UDP/IP communication stack of Contiki. Packets of varying payloads were sent in each case between two identical nodes, which were placed in a distance of one meter. We measured the exact time for 100 packets with an oscilloscope. In Figure 4 the UDP throughput is plotted for different payloads. INGA's throughput is higher at any payload size. A maximum throughput of 131,386 bit/s (16.423 Kbyte/s) was achieved for 90 byte payload size by INGA.

C. Memory Performance

In contrast to the MSP430 based architectures, the ATmega based architecture of INGA has separated interfaces for memory and radio access. To expose this feature we evaluated a simple scenario were other nodes begin to fail: UDP traffic of increasing throughput shall be received and then be written into the external flash memory. Using common nodes like the TMote Sky one would expect an increase of packet loss or a decrease of throughput, because writing data is time consuming and at some throughput the microcontroller is busy writing data. But, INGA's dual-buffer flash in combination with the designated second SPI was able to write any received packet directly to flash without any losses. In Figure 5 you can see INGA's performance in receiving data packets and writing them to external flash memory at varying rates of throughput in comparison to the TMote Sky. The TMote Sky begins produces packet loss at a throughput rate of 90 kbit/s. As TMote Sky itself was not able to send packets at such high data rates, we used another INGA as sender.

When SD-cards are connected to low-power mircocontrollers, always the slow SPI mode for communication is

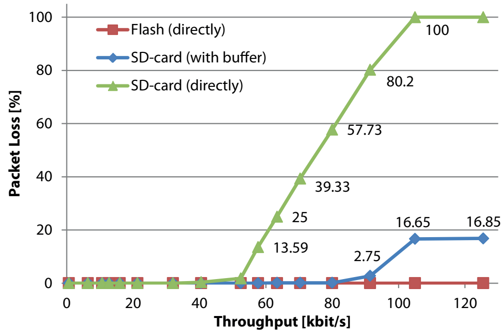

Figure 6. INGA's performance of writing received UDP data to flash memory and to SD-card (with and w/o SRAM buffer).

used instead of the more powerful proprietary interface. To demonstrate the effect of this slow interface, received data was directly written to the SD-card. In Figure 6 these results are shown. It can seen that at a higher rate of throughput packets get lost and, thus, the SD-card limits the throughput of this scenario. An obvious optimization is to introduce an SRAM buffer and with that to write whole pages instead of every single packet to the SD-card. It can be seen, that with such an buffer, still data rates of more than 80 Kbit/s are possible, whereas without such an buffer a maximum of 40 Kbit/s can be reached.

In case of expected burst traffic it would also be a suggestion to first write all received data into the external flash and copy from there to SD-card afterwards. Copying one flash page from external flash to SD-card takes 24 ms; the throughput from flash to SD-card is 21.33 Kbyte/s.

D. Power Consumption

INGA has the capability of online current and voltage monitoring. The processor, the radio, the sensors and the memories all have different power saving states, which leads to numerous possible evaluations of power consumption. In a small setup INGA's overall power consumption was measured in comparison to the TMote Sky. Table I shows that at maximum transfer rate and TX power of 0 db, INGA's energy consumption is short compared to TMote Sky; per throughput as well as absolute.

Table I
CURRENT AT MAXIMUM TRANSMIT RATE AND TX POWER OF 0 DB.

	INGA	**TMote Sky**
I_{cc}	18.69 mA	19.69 mA
Max. transmit rate	125.98 kbit/s	90.91 kbit/s
Electric Charge	0.15 mAs/kbit	0.22 mAs/kbit

IV. Conclusion

INGA is an acronym for "Inexpensive Node for General Applications" – and this is what we wanted it to be: INGA costs in any case less than 100 € – the concrete costs depend on quantity and configuration. Although it is easy to handle, because it is equipped with standard connectors and interfaces, it is still quite small and by this way fulfills the requirements of our second use case, the activity monitoring of elderly people. We have shown the advantages of INGA's architecture which is superior to the MSP430 architecture by design. We have also shown that INGA performs better than TMote Sky, while consuming less energy and we claim INGA being very useful in the area of research and education, as it is widely supported and very cost-efficient.

A. Resources

INGA is completely open source. You are free to adapt or change anything you like. We provide schematics and EAGLE-files in the download section of INGA's website. In addition all hardware drivers for Contiki will be provided in a SVN/GIT-repository. Additionally, as our WSN lab is just starting, we will also provide teaching materials and tutorials at http://www.ibr.cs.tu-bs.de/projects/inga.

Acknowledgments

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