DESIGNING NEXT-GENERATION LOW POWER AUTONOMOUS SENSOR NODES USING SYSTEM-ON-CHIP BASED SOLUTIONS

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As physical sensing becomes more and more pervasive, the need for accurate and efficient wireless sensors and communication nodes become important. A Wireless Sensor node is a platform which has basic components like a sensor, conditioning circuit and data communication. A set of such nodes spatially distributed in order to co-operatively sense and pass the data forms a Wireless Sensor Network (WSN).

Wireless Sensor nodes are embedded in many devices and have become a part of the environment we live in. Many of our electronic gadgets come with different sensors whose data can be harnessed for a variety of needs. For example the accelerometers in our mobile phones can track our activity and the pressure sensors in the wheels of automobiles keep the pressure at optimal levels.

Wireless Sensor Nodes are a class of emerging applications for which energy consumption is a key metric. The successful deployment of wireless sensor nodes on a large scale depends on advances in many areas such as distributed computing, networking, wireless communication, and, most importantly, low power circuit design. Some of the applications of wireless sensor network include industrial, home automation, medical monitoring, habitat monitoring, and agriculture resource management.

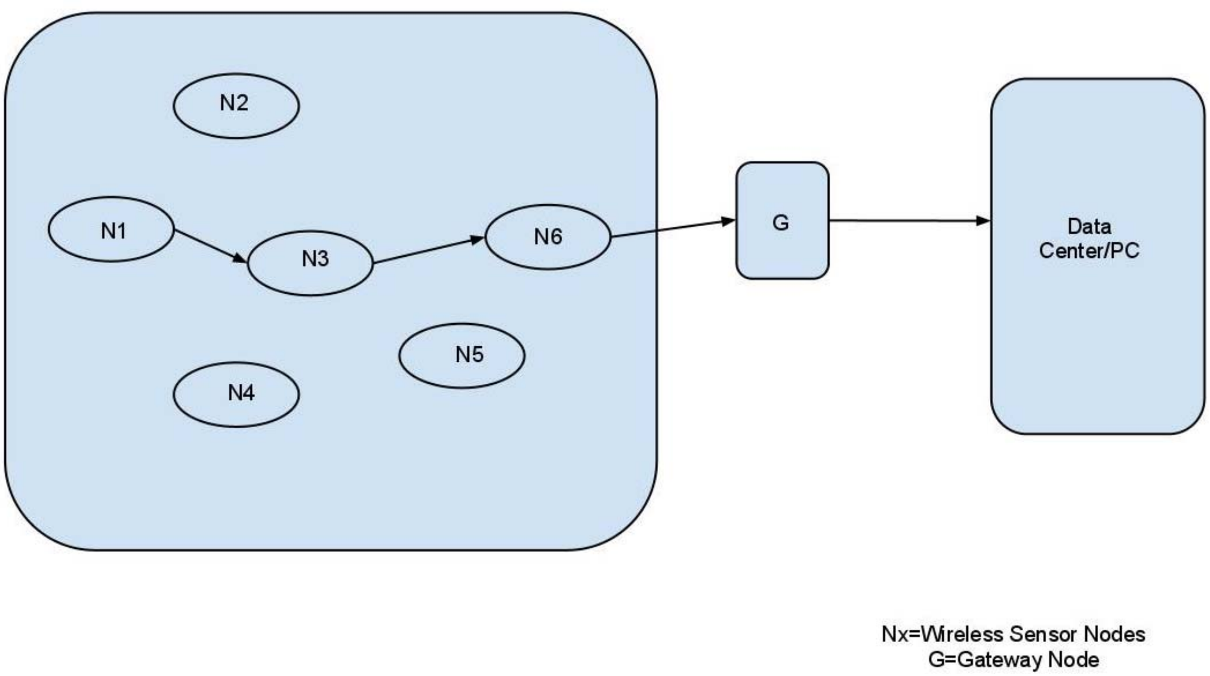

Figure 1. Representation of a Generic Wireless Sensor Network

Generic Wireless Sensor Node

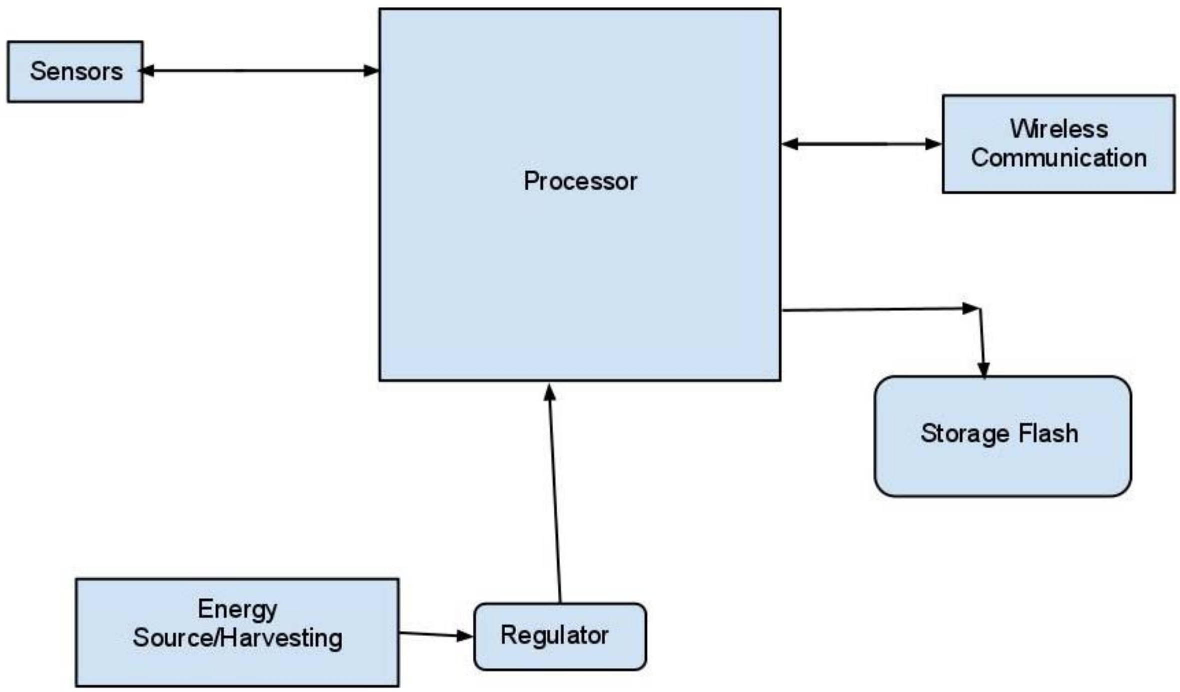

Figure 2. Block diagram of a simple generic wireless sensor node.

A generic wireless sensor node consists of a processor which is the core of the system. This controls the various sensing activities of the node as well as schedules data transmission. Features like cooperative sensing and energy management control can be incorporated in the algorithms programmed into the processor. Sensors form the acquisition system followed by processing and control by the processor. The entire system can be powered by battery or stored harvested energy. Since different voltage levels are needed, boost conversion is needed for low voltage input, making a regulator part of the system as well. The data collected must be periodically transmitted wirelessly to a data center which is facilitated by low range RF or GSM to upload the data onto the internet.

General Requirements of a Wireless Sensor Node:

1. Low Energy Consumption- Since the deployment of a wireless sensor network tends to be large, replacement of batteries would be a difficult, if not impossible, task. Therefore, any processing the node performs has to be low power and energy efficient. Energy harvesting methods need to be used to make nodes self-sustained.

2. Self-healing Structures: A fault in one nodes should not overtly impact the operation of the network. There should be easy access to debugging and rectifying the fault through support from the other networked nodes. Communication failures should be minimal and in the event of such occurrences, back up control should take over in order to avoid losing valuable data.

3. Robust: Since these nodes are deployed under different harsh physical conditions, they need to be able to operate accurately for long periods of time without any problems.

Challenges in the Future:

- The size of the typical node has gone from a few cm^3 to sub cm^3 regime. Size is determined by energy storage and harvesters.
- Power distribution to the different part of systems needs to be efficient.
- Scaling also affects the storage element as well as harvesting sensor size which

- Puts a lot of importance on the efficiency of conversion. Battery size also tends to reduce by the same scale.
- Standby operating mode is dominant and therefore leakage/quiescent consumption becomes a crucial design parameter.
- Nodes are subjected to different non-ideal physical conditions under which these nodes should operate. The successful deployment of wireless nodes depends on the thorough characterization and investigation of operating in practical settings.

Sensors

Sensors form the first contact to the physical environment. MEMS technology has made advances in both reduction of size as well as increasing accuracy of the sensed quantity. MEMS-based sensors that monitor temperature, voltage, humidity, photo, vibration, and gas have been part of the onboard sensor for wireless sensor nodes. These sensors result in an analog signal which further has to be amplified in order to be able to process the signal and differentiate it from noise. The external sensors can be configured or controlled by serial interfaces like SPI,I2C.

Energy Requirements and Sources

Usually the major part of energy consumption goes into the analog sensors. For instance, active sensors like metal oxide-based gas sensors consume a large amount power for heating. Next in line comes the communication link which is usually characterized by bursts of packets at regular intervals. Finally, there is the digital processor which does the sensing/conversion of the signal and low-level processing before ordering the data to be transmitted.

A typical node consists of a sensor to capture the external phenomenon, an ADC with signal processing circuitry to convert sensor information into a reliable digital form, and a radio for communication of this data. Typically, energy consumption will be dominated by the radio. Depending on the duty cycle of sensing activity, sometimes the sensor will dominate the energy consumption. Studies quote values between 1uW to 20uW for the amount of energy required for operation of a node. Some techniques like collaborative processing of data jointly by a set of nodes is done to complete computationally intense tasks.

Harvesting Ambient Energy Sources

There are numerous sources of energy in the environment which can serve as a continuous source of energy for wireless sensor nodes over their lifetime. We will concentrate on RF energy, mechanical energy and solar energy harvesting which have been shown in literature as the viable options for powering wireless nodes.

RF energy refers to the energy available through the public telecommunications system. The energy levels provided by GSM at a distance of 30-100m from the base station are between 0.1 to 1mW/m^2. This is not sufficient for any viable harvesting mechanism. WLAN, on the other hand, is a couple of orders lower compared to GSM. One possibility to harness this energy from GSM is to use a large area antenna or to have a dedicated source of RF energy. It should be noted here that these levels transmitted should be within the guidelines for the maximum amount permissible.

For harvesting mechanical motion or vibration, electrostatic, piezoelectric, and electromagnetic transduction techniques can be used. In an electrostatic transducer, as the distance between two electrodes of a polarized capacitor changes, this results in a change in voltage. In a piezoelectric transducer, a change in shape of the material results in a voltage change. In case of electromagnetic transduction, movement of magnetic mass causes a change in the flux linkages across the coil.

Thermal generators are based on principle of the Seebeck Effect where two junctions made of dissimilar materials are maintained at two different temperatures. This results in a voltage generation across the open-ended terminals of the junction. Photovoltaic energy is another important source whose efficiencies range from 5% to 30%, depending on the material used.

From Table 1, we find that power per area is reported because the thickness of these devices is typically dominated by the other two dimensions. The power available from these sources is highly dependent on the nodes' environment. We can on average, assume that 10's of microwatts of harvested energy to be available [1]. This would put a range for power consumption by the micro sensor nodes to 10-40uW to enable harvesting. Therefore, coupling energy harvesting with some form of energy storage can theoretically extend system operating lifetime indefinitely.

Table1. Characteristics of Energy from Ambient and Harvested power [1]

Source	Source Power	Harvested Power
Ambient Light Indoor Outdoor	 0.1mW/cm2 100mW/cm2	 10uW/cm2 10mW/cm2
Vibration Human Industrial	 0.5@1Hz 1m@5Hz	 4uW/cm2 100uW/cm2
Thermal Energy Human Industrial	 20 mW/cm2 100mW/cm2	 30uW/cm2 10mW/cm2
RF Cell Phone	 0.3uW/ cm2	 0.1uW/cm2

System-on-Chip Solution

The need for a complete platform comprising of analog and digital modules can be solved by moving to a system-on-chip architecture that encompasses the analog and digital peripherals suitable for implementing an autonomous sensor node. For example, Cypress Semiconductors' Programmable System-on-Chip (PSoC 3/5) are ideal processors for such system designs. PSoC Creator is the development environment for the system development. Their low power features, among various other available mixed signal programmable modules, make this architecture popular for the high demanding applications of wireless sensor networks.

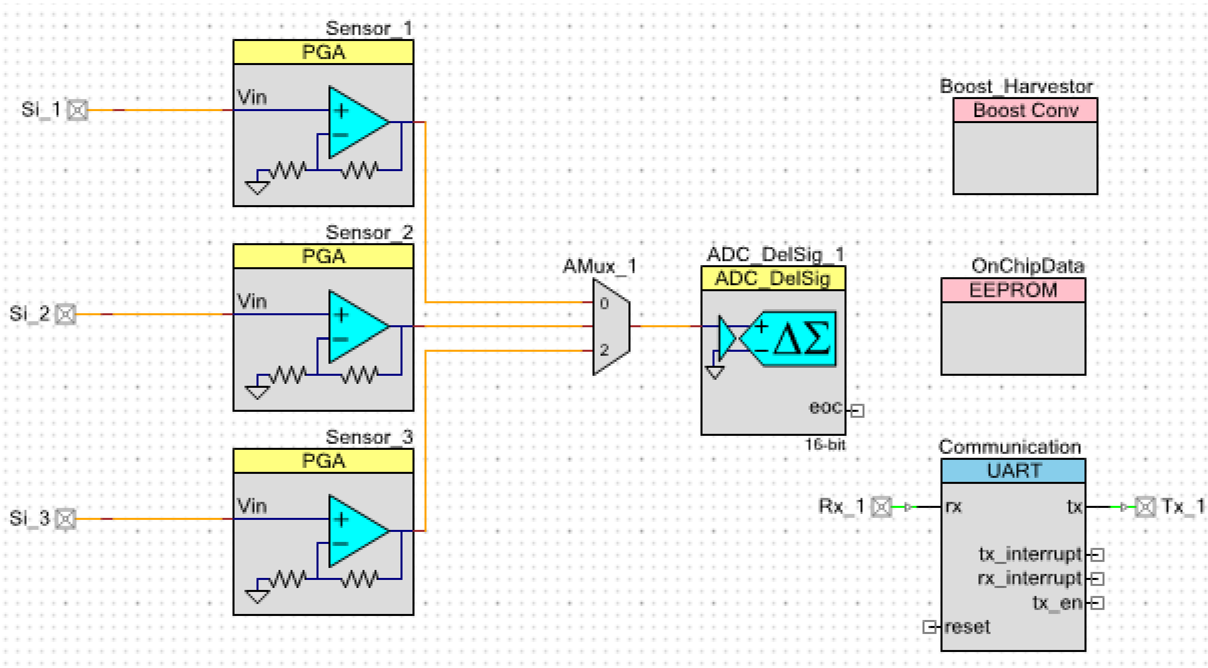

Figure 3. Schematic Capture of Design in PSoC Creator Environment

Figure 3 represents a simple autonomous system. Three different sensors are interfaced via the programmable gain amplifier. The gain is set according to the different signal level outputs from the sensors.

$$S_o = S_i(1 + R_1 / R_2)$$

The amplified signal (So) is time-multiplexed and sampled at a pre-determined rate, then converted by a Delta-Sigma ADC. The data collected is stored on-chip in Flash and then periodically transmitted via wireless communication.

Powering from Energy Harvesting Sources

An integrated boost regulator is ideal for applications where the energy supply is limited or is based on low harvesting sensors. On a PSoC device, for example, the supply can be as low as 0.5V and provide programmable levels between 1.8V to 5.25V at an average load current of 50mA. As discussed before, these boost regulators can be used to draw power from harvested sources, thus making a node self-powered. A rechargeable battery can be used too for supplying and storing harvested energy. The voltage level can be monitored and system operation can be based on the available power. For example, the entire system can go into sleep/hibernate when the battery signals that it is low. Before dropping into sleep while waiting for the battery to recharge, the system sends a signal to the nearby node/network gateway to update its status.

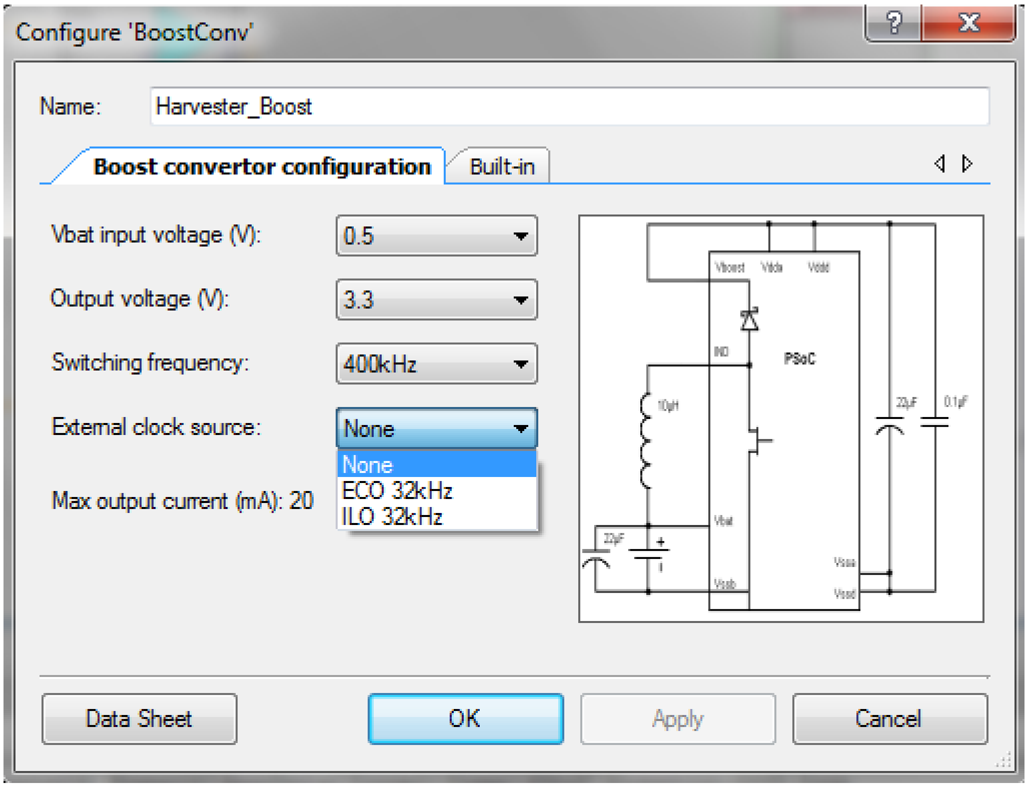

Figure 4. Configuration window of Boost Converter for the application

The boost converter is configured by adjusting the values of the capacitors and inductors as shown in Figure 4. The input and output voltage can be specified depending on the requirements of the harvester and the end application. The switching frequency can be controlled based on the allowed size of inductor (inversely proportional to switching frequency) and switching losses (proportional to the frequency).

$$f_{sw} \uparrow = [(V_{out} - V_{in} + V_D)(1 - D)]/(i_{load} * L \downarrow)$$

Features of Low Power Design targeted to vital battery operated systems

Severely energy constrained systems need to have a long battery lifetime due to the inherent difficulty in physically accessing them to replace batteries as well as the sheer scale of deployment. With shrinking sizes of the nodes, this becomes a challenge both in terms of storage and harvesting area available to the node. Low power design is very important in energy constrained mobile applications, and therefore SoCs must be designed to ensure the lowest quiescent energy is consumed during idling states where the node spends most of its time.

Many processors offer multiple operating and low power modes to improve power efficiency. For example, there are four modes available in PSoC3. Active mode is the primary mode where the CPU controls specific modules to be operational. Alternate active powers only specific sub systems while the CPU is halted. Sleep mode is where all modules and CPU are disabled except some supervisory systems like the Watch Dog Timer. Finally, the lowest energy consumption is hibernate mode where all modules including supervisory modules are turned off and consumption is less than 200nA. The device only wakes upon a hardware pin interrupt. These different operating modes are very useful, depending on the state in which the wireless sensor node is operating. This could be dependent on external environment, time of day, or the activity levels/Frequency to be sensed. This kind of software-based state machine control is useful for the end user to choose the right mode and easily change power consumption based on the application's current requirements.

Some other techniques can be used in order to avoid unnecessary power consumption like leaving I/O unused which could be driving a load. Instead, have a default high impedance on such I/O pins at the top level. Also, using a higher frequency than needed for a certain application is sub-optimal. Similarly, use of a PLL with source clock at a low frequency is more optimal than running the main clock frequency at higher cycles.

Wireless Sensor nodes continue to become more sophisticated as well as more computationally intensive. Features like low power as well as integration of modules in a single chip are vital for a rugged and efficient node development.

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