Smart Sensing for IoT Applications
(Invited Paper)

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Abstract

Large scale deployment of sensing nodes for Internet of Things (IoT) applications will be an energy constrained system. To improve the energy efficiency in such systems, making sensors more intelligent will be an important tool. In this paper, we will discuss three emerging trends for smart sensing: (1) Integration of sensing elements with low-power in-situ signal processing on the same chip or package, (2) Integration of multiple sensing modalities on the same chip or package to provide more useful data to the end application, and (3) Compressive sensing techniques to extract the useful information from raw sensor output.

1. Introduction

The vison of billions and trillions of sensors for Internet of Things (IoT) applications has been articulated by many technical and business leaders in the last few years [1]. The simplistic assumption for these IoT applications is to send all raw sensor data to the cloud so that big data analytics can be deployed to solve world's problems. However, one will quickly realize that the energy consumption of such implementation will be prohibitively expensive, rendering it impractical. Data communication has been found in many studies to be the biggest energy consumer [2]. Therefore, improving the energy efficiency of data communication is of paramount importance. Equally important is to make the sensor more intelligent so that only useful and relevant data are communicated to cloud. Approaches of making the sensors smarter will be the focus of this presentation. In particular, three specific trends for smart sensing will be discussed: (1) Integration of sensing elements with low-power in-situ signal processing on the same chip or package, (2) Integration of multiple sensing modalities on the same chip or package to provide more useful data to the end application, and (3) Compressive sensing techniques to extract useful information from raw sensor outputs.

There are two main goals of smart sensing. The first one is to reduce the overall data communication load by only transmitting the useful data to the cloud. The second one is to enable local decisions made closer to the sensor nodes. This, in turns, will reduce the latency of decision making and improve the overall energy efficiency in the system, as illustrated in Fig. 1.

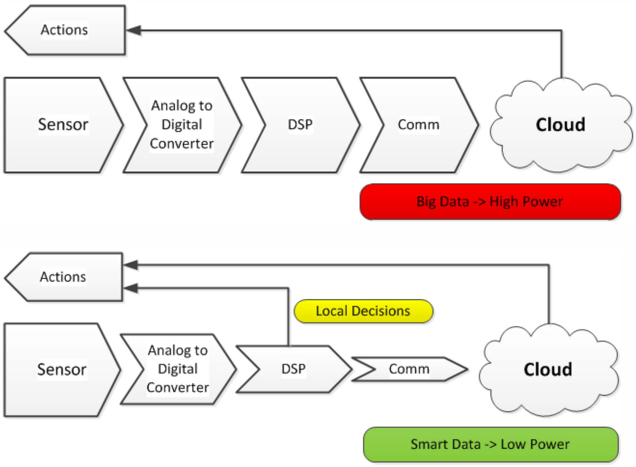

Figure 1. Smart sensing reduces energy used for data communication and enables local decision making

2. Higher Level of Functional Integration

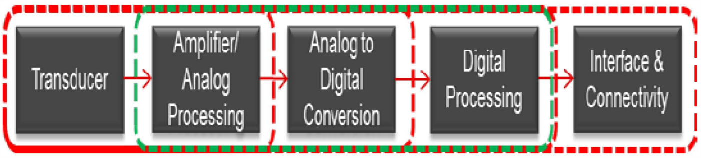

Figure 1. Integration of the sensor element with more signal processing functionalities on the same chip or package.

Figure 2 depicts the typical functional block diagram of a sensing system consisting of the sensing element, analog amplification and filtering, digital to analog conversion, digital processing, and, finally, the connectivity to the host processor or the clouds. In recent years, we have witnessed an increasing level of integration of Si-based sensors with its associated signal processing elements on the same Si die or package. Much of the progress took place in sensors used in mobile phones, where small solution size, low power and low cost are the primary drivers for high level integration. However, the higher level of integration also benefits other non-mobile-phone applications as well, like building or factory automation. In those applications, a higher precision is typically required, in addition to the reduction in size, power, and cost. High precision can be enhanced by the integration of analog to digital conversion and digital processing with sensors. With

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the local digital processing capability, we can perform linearization and temperature compensation in digital domain to achieve linearized results. Therefore, only the processed data in a more usable form are sent to the clouds, which help to reduce the communication bandwidth and to allow the cloud to focus on higher level data analytics based on the smart data. In addition, there are many situations in which Si-based sensing element is either not technically feasible or economically viable. In those cases, integrating all the analog and digital signal processing functionalities with analog-to-digital conversion on a single chip or package, as outlined in the green box here, still enjoys similar benefits as fully integrated sensors.

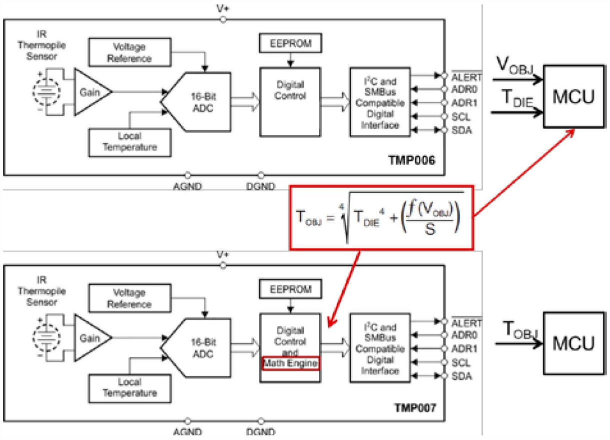

Figure 3. An example of significant savings in data communication can be achieved by the addition of local signal processing capability.

There are other benefits of integration. One recent example comes from the evolution of a family of IR temperature sensors [3][4]. These sensors detect the black-body radiation in the mid-IR frequency using a thermopile approach. This approach allows non-contact temperature measurement by simply placing the chip in front of the object of interest. The thermopile generates a voltage which is a function of the object temperature, the die temperature, and the emissivity of the object (see equation in Figure 3). The first product (TMP006) in this family integrated the thermopile detector with an analog-to-digital converter. Both the digitized thermopile voltage, Vobj, and the die temperature are sent to host processor, as shown in the top half of Figure 3. The host processor then computes the object temperature according to the formula in Figure 3. The second member (TMP007) of this family comes with an additional digital engine which performs the object temperature calculation based on the same formula. Therefore, the host processor is no longer needed for the object temperature calculation. Only the calculated object temperature will be sent to the host. Therefore, the amount of data transfer is reduced by a factor of about 2. The availability of calculated object temperature also greatly simplifies the system design. For example, one can set a lower and an upper temperature limit of the object in TMP007, which will only alert the host processor if the limits are exceeded without constantly report the temperature back to the host and rely only on host to make decision. This will further reduce the unnecessary energy consumption in data communication.

3. Multi-modal Sensing

Multi-model sensing refers to sensing with different modalities and then exploiting the interdependence of these modalities to extract more useful data. The most well-known example is the motion sensors widely used in cellular phones in which 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer combined or have their outputs "fused" together to provide a complete picture of the motion of the device.

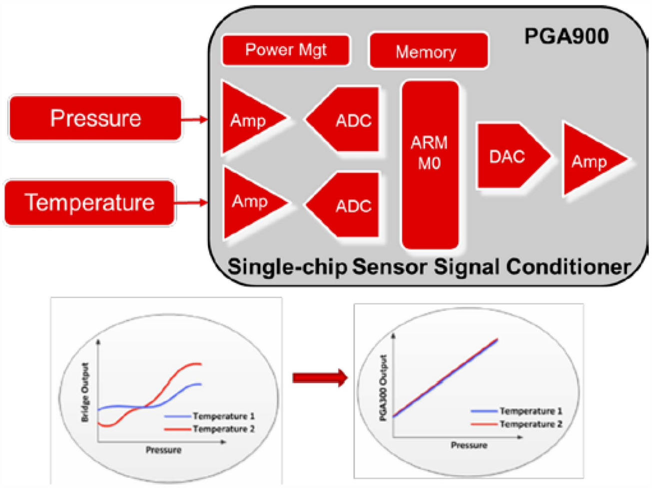

Figure 4. Local linearization and temperature compensation provide a more "usable" sensor output.

Another example of how multi-modal sensing allows smart sensor fusion is a resistive pressure sensor signal conditioner for industrial automation applications. Most, if not all, pressure transducers exhibit non-linearity between its output signal and excitation and also moderate to strong temperature dependence. Therefore, for high precision industrial pressure sensing applications, it is important to perform linearity correction as well as temperature compensation on the raw output of pressure transducers. This can be achieved by sensing both modalities: pressure and temperature, simultaneously. A single-chip sensor signal conditioner which contains two independent analog data acquisition channels and two analog-to-digital converters was developed, allowing simultaneous reading of external pressure and temperature sensors [5]. The integrated ARM based digital engine plus on-chip memories facilitate linearization and temperature compensation in digital domain, as shown in Figure 4. The linearized data can then be output in either digital formats or in the 4-20mA analog format by using the built-in digital-to-analog converter. This single chip solution dramatically reduces the overall solution size and reduces the data communication between the sensor and the host processor. .

4. Compressive Sensing and Non-Uniform Sampling

For most sensor signals, the *information rate* is actually much smaller than that suggested by the bandwidth [6] – i.e. the signals are *sparse* in a particular domain. The key concept of compressive sensing (CS) is to leverage signal sparsity and design sensing or sampling schemes that allow the useful information content to be extracted in a condensed and hence energy efficient manner.

While CS has traditionally been used in applications such as image processing, it is becoming increasingly attractive for energy efficient smart sensing. One such example is a CS-based Photo-Plethysmo Graphy (PPG) system for optical heart-rate (HR) monitoring [7] where no discernable information loss is detected despite a 30X compression in the signal acquisition.

Another example of adaptive sampling and the associated power savings can be illustrated in context of a wearable ECG acquisition system. Fig 5 shows the typical ECG signal with periodic QRS-peaks separated by long period of inactivity. For heart-rate (HR) measurement, only the detection of the R-peaks is sufficient. The conventional solution is to uniformly sample the entire ECG waveform at the Nyquist rate (fs) that corresponds to the highest frequency content in the system.

Alternately, accurate HR information can be extracted if we were to sample the ECG waveform at different rates – higher fs (fs-HI) during the QRS-peak and lower fs (fs-LOW) during the interim, longer periods of inactivity. No information is lost, but the amount of data that needs to be stored and transmitted to the cloud is significantly reduced.

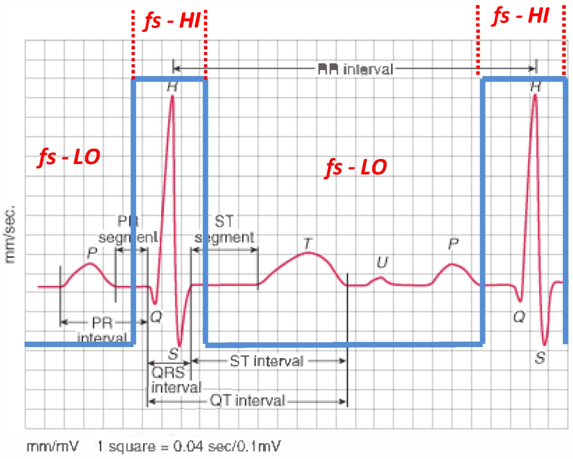

Figure 5. ECG waveform showing an adaptive sampling strategy to reduce data throughput.

In [8] and [9] researchers from TI and IMEC used a dx/dt analog feature extractor (Fig 6) to predict a-priori the onset of the QRS peaks – and therefore adapted the ADC sample rate on the fly. By employing this technique, a 7x improvement in power consumption was demonstrated since the adaptive sampling not only saved power in the analog-digital conversion but also in the subsequent DSP engine [9].

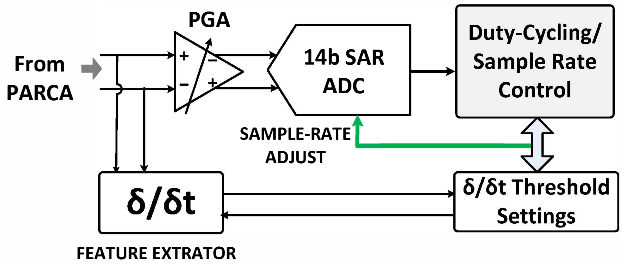

Figure 6. Adaptive sampling using a dx/dt feature extractor.

These adaptive sampling techniques plus other related compressive sensing techniques hold a lot of potentials in providing significant energy savings for smart sensing systems.

5. Summary

Putting more intelligence closer to the sensors can bring significant increase in the overall energy efficiency of many IoT applications by only transmitting data containing useful and relevant information to the host or the cloud,

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