Towards Usage of Wireless MEMS Networks in Industrial Context

Pascale Minet
INRIA
Rocquencourt
78153 Le Chesnay cedex, France
Email: pascale.minet@inria.fr

Julien Bourgeois
University of Franche-Comte
FEMTO-ST Institute
UMR CNRS 6174
1 cours Leprince-Ringuet, 25200 Montbeliard, France
Email: julien.bourgeois@femto-st.fr

***Abstract*—Industrial applications have specific needs which require dedicated solutions. On the one hand, MEMS can be used as affordable and tailored solution while on the other hand, wireless sensor networks (WSNs) enhance the mobility and give more freedom in the design of the overall architecture. Integrating these two technologies would allow more optimal solutions in terms of adaptability, ease of deployment and reconfigurability. The objective of this article is to define the new challenges that will have to be solved in the specific context of wireless MEMS networks applied to industrial applications. To illustrate the current state of development of this domain, two projects are presented: the Smart Blocks project and the OCARI project.**

I. Context and Motivations

We are currently witnessing a large development of wireless sensor networks (WSNs). The first explanation comes from their ability to sense the environment in which they operate. The second one is related to their great ease of deployment: no cable installation and then no cable maintenance is needed. The third one lies in the ability of sensor nodes to move without the constraint of wires. These characteristics make WSNs excellent candidates to support applications where the network environment must be monitored, there is no prexisting infrastructure, the embedded mass is strongly constrained and node mobility is required, to name a few. That is why in the following of this paper, we focus on wireless sensor networks.

A. Advances in WSN technologies and standards

Wireless sensor networks (WSNs) consist of a possibly large amount of wireless networked sensors required to operate in a possibly hostile environment for a maximum duration without human intervention. Typically, a wireless sensor node is a miniature device that includes four main components: a sensing unit for data acquisition, a microcontroller for local data processing and some memory operations, a radio communication unit to allow data transmission/reception and finally a power source which is usually a small battery. WSNs support a wide range of applications such as healthcare applications, ambient assisted living, industrial process control, target tracking, environmental monitoring, survivors detection or exploration in unfriendly environment. These applications range from small size low industrial monitoring to large scale energy constrained environmental monitoring. All these applications require an operational network to fulfill their missions, usually without external human intervention.

Application scenarios for WSNs often involve battery-powered nodes being active for a long period, without external human control after initial deployment. In the absence of energy efficient techniques, a node would drain its battery within a couple of days. This need has led researchers to design protocols able to minimize energy consumption. Unlike other networks, it can be hazardous, very expensive or even impossible to charge or replace exhausted batteries due to the hostile nature of environment. Energy efficiency, [1] and [2], is a key issue in WSNs in order to maximize network lifetime.

There are several standards for macro-wireless sensor networks. Most of them are based on the IEEE 802.15.4 physical layer. They differ on the medium access technique and the multihop networking. Some of them are contention-based like ZigBee and ISA100 that use the IEEE 802.15.4 MAC layer. Others are TDMA based like WirelessHart. ZigBee [3], [4] is the most advanced one providing a ZigBee protocol stack. It targets transversal applications and home automation but does not meet severe constraints. For instance, routers are not allowed to sleep to save energy. No minimum throughput is ensured to time-constrained traffic. Collisions between simultaneous transmitters are still possible. WirelessHart [5] and ISA100.11a [6] are industrial solutions not yet open to designers. WirelessHart does not allow the mobility of some nodes. Network management is not yet defined. No power saving technique is specified.

Wireless nanonetworks could be integrated in distributed intelligent MEMS, allowing better communication range and better broadcasting capabilities. Some preliminary studies have defined the possibilites of such communication medium [7] within the Terahertz band and a communication paradigm based on femtosecondlong pulses has been defined. In [8], a low-weight channel coding is proposed to reduce interferences that occur in such networks and in [9] a new MAC protocol is defined for these networks. Bigger wireless devices are using the 60 GHz band [10], [11] but due to their size their integration into distributed intelligent MEMS remains complex.

More generally, the myriad of potential applications supported by WSNs, the emerging standards and the technology advances have strongly motivated the research community. As a result, WSNs are now a reality.

B. Emerging distributed intelligent MEMS

Microelectromechanical systems (MEMS) are composed of mechanical parts that are controlled by embedded electronics or electrical parts. The fabrication of MEMS follows a batch process which allows them to be pretty cheap and therefore mass-produced. The mechanical part could be a sensor, an actuator or both, which changes the flow of information that has to be processed. Compared with WSNs, MEMS can sense but they can also act on the physical world, they are therefore more tied to their environment.

MEMS can be produced as single entities like accelerometers, inertial measurement units (IMU, that are now included in airbag systems as well as in most of the recent smartphones or laptops), of they can be produced as distributed systems like digital micromirror devices (DMD, technology used for projection displays).

As MEMS fabrication is a batch process, distributed MEMS can therefore be numbered in millions of units in very small space. Centralizing information from the the sensors is therefore challenging as much in the software as in the hardware part but sending back orders to actuators is even more challenging. Sensor actuators distributed MEMS needs a distributed paradigm. Each MEMS unit of the distributed system should have its own processing unit and communication capabilities: this is defined as distributed intelligent MEMS (diMEMS) [12].

diMEMS specialize the domain of sensor actuator networks because of their unique properties, roughly, scalability, high density of communication and small processing power of each unit.

C. New applications requiring a massively dense network of MEMS

The very first application of distributed MEMS was about objects conveyance. This research has developed different types of MEMS actuator arrays, based on actuators either pneumatic [13][14][15], servoed roller wheels [16] [17], magnetic [18] or thermobimoph and electrostatic [19]. More recently, sensors have also been integrated [20].

Programmable matter is the most ambitious idea using distributed intelligent MEMS. The objective is to design matter that can be programmed to change its shape. Several approaches exist, the Claytronics project proposes to use millimeter-size silicon balls that can move around each other thanks to electrostatic actuation. The software environment is particularly advanced as it includes two programming languages and two different simulators [21].

Among these two major applications, distributed MEMS are used in lots of different applications like atomic force microscopes (AFM) arrays [22], boundary layer control either on aircrafts [23] or on cars [24], flying drones [25] and smart dusts [26]. Furthermore, many distributed macro sensor/actuator arrays like active noise cancellation [27] could be applied using MEMS systems.

All these applications need communications to push further their functionalities but wired networks are not always easy to integrate at such scales. In the case of boundary layer control, it has been shown that the wiring part could cancel the benefit of using MEMS actuators that is why we think that wireless communications have to be studied in the case of distributed MEMS.

The remainder of this paper is organized as follows. Section II presents an example of a wireless sensor network in an industrial context. Section III shows how to use MEMS. The aim of Section IV is to point out the key issues in the design of MEMS networking. Finally, we conclude in Section V.

II. OCARI: A WSN IN AN INDUSTRIAL CONTEXT

Wireless sensor networks have been designed first for monitoring applications. To be used in industrial environments these networks have to cope with harsh radio conditions and the requirements of industrial applications (e.g. low power consumption, reduced and bounded transmission delays, network scalability, support of sink mobility, etc). In response to these industrial needs and challenges, OCARI has been launched in 2006 with the funding of ANR and the collaboration of 3 industrial partners (EDF (project leader), DCNS and TELIT) and 4 academic partners (INRIA, LIMOS (Clermont Ferrand university), LATTIS (Toulouse university) and LRI (Paris Sud university)). The purpose of this project is to design and prototype a wireless sensor network for an industrial environment. Targeted applications are monitoring of industrial equipments and civil engineering infrastructure, health monitoring of people working in hard conditions, predictive maintenance and environmental monitoring to detect pollution in industrial plants. OCARI aims at responding to the following requirements:

- provide time-constrained communications,
- support an optimized management of node energy and frequency band,
- support the human walking speed mobility of some particular nodes, (e.g. mobile sinks),
- be scalable and self-healing.

An OCARI network is organized in a cluster of cells. The cluster is managed by the cluster coordinator, called CPAN, that is also a gateway with the industrial facility backbone. Each cell has a star topology and consists of a cell coordinator with its end device nodes. The cell coordinator is in charge of coordinating its end device nodes and routing data packets. Furthermore, as depicted in Figure 1, there is also a mobile sink node or data mule, which usually represents a patrolman/maintenance operator, equipped with PDA, collecting data from sensors inside a cell.

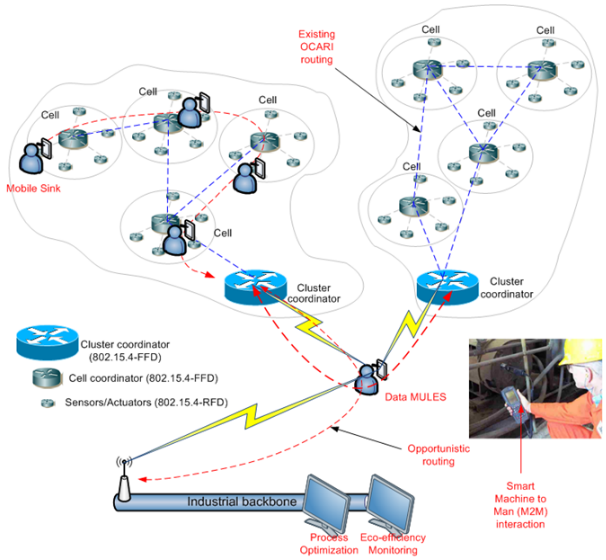

Fig. 1. An OCARI network

The OCARI project has developed a wireless sensor communication module, based on the IEEE 802.15.4 physical layer and supporting the ZigBee application layer. Thus, ZigBee application developers may quickly program OCARI applications. The MAC and Network layers have been redesigned to provide service differentiation, determinism and energy efficiency. In OCARI, there are two types of traffic: time-constrained traffic, for which a bounded delay should be ensured and unconstrained traffic. Examples of time-constrained traffic are alarm notifications and commands. Since the quantitative behavior of the OCARI network should be predicted for time-constrained traffic, determinism is required by this type of traffic. Energy efficiency means that the lifetime of the OCARI network should be maximized. Since nodes are allowed to sleep and then save energy, they stay operational for a longer period.

At the MAC layer, the solution is based on a tree rooted at the CPAN. This tree is built by the node associations. The medium access of OCARI, called MaCARI, is organized in cycles. Each cycle consists of three time periods:

- a synchronization period, denoted $[T0, T1]$, that is obtained by a beacon cascading: each cell cordinator sequentially repeats the beacon received from its parent in the tree.
- an activity period consisting of:
  - a sequential activation of cells, period denoted $[T1, T2]$. When a cell is activated, any node within the cell can send/receive data to/from its cell coordinator. Time-constrained data collected by the coordinator are forwarded toward its parent in the tree. Consequently, time-constrained traffic is relayed on the tree by the MAC layer.
  - a period denoted $[T2, T3]$ to route unconstrained traffic between cell coordinators. During this period, only cell coordinators are awake.
- an inactivity period, denoted $[T3, T0]$ during which all nodes sleep. This period is optional.

The network layer provides an energy-efficient routing, called EOLSR and a node activity scheduling based on node coloring, called SERENA. Noticing that it is expensive in terms of bandwidth, storage and energy to maintain a route toward any other network node, EOLSR maintains on each node, only a route per sink. EOLSR has two functionnalities: neighborhood discovery and route construction. The route to a sink has the smallest energy costand avoids nodes with low residual energy. It adapts to topology changes. EOLSR is active in the $[T2, T3]$ period. SERENA, with MaCARI, schedules cell coordinators activities using their colors. SERENA assigns colors to cell coordinators in such a way that two interfering cell coordinators have not the same color and the total number of colors is minimized. A time slot is assigned to each color. hence, any cell coordinator is awake in $[T2, T3]$ only in:

- the slot of its color if it has data to send,
- the slots of its 1-hop neighbors if it has data to receive.

This use of colors allows a more efficient use of the bandwidth enabling spatial reuse and reducing interferences. It reduces the duration of the activity period and provides a better time consistency of the data collected. Energy efficiency is improved, leading to an increased network lifetime.

In December 2011, we proved the industrial feasibility of the OCARI solution by integrating all the OCARI components on the TELIT ZE51 card, based on a RF CC2420 with 8 Kbytes RAM. We will now deploy this solution in industrial plants. We wish the OCARI solution to be (i) largely used to increase the size of the user group, (ii) built by several manufacturers to ensure the diversity of supply sources and (iii) be a perenne and reliable solution.

III. The Smart Projects: MEMS in an industrial context

A. *Presentation*

The Smart projects are two projects that have been funded by the French National Agency for Research (ANR). Their aim is to study new technologies and solutions for sorting and conveying objects in production lines. The originality of these projects is to build up pluridiciplinary teams in order to study all fields related to the problem to be solved. The Smart Surface project purpose is to design and develop a surface composed of an array of cells where each cell comprises a pneumatic MEMS actuator, a sensor, a processing unit and communication capabilities. The cooperation between all these cells is leading to the recognition of the objects which then drives the conveyance task. The Smart Blocks project uses the same technologies except that each MEMS array is embedded into a centimeter-size block. This block can move by itself,

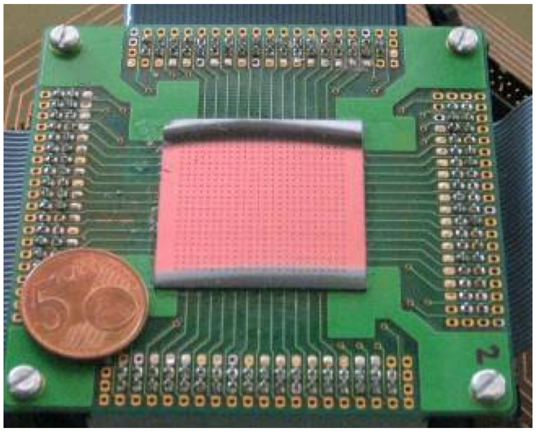

Fig. 2. Smart Surface prototype with individual control of actuators. Included with the permission of J.F. Manceau, R. Yahaoui, R. Zeggari

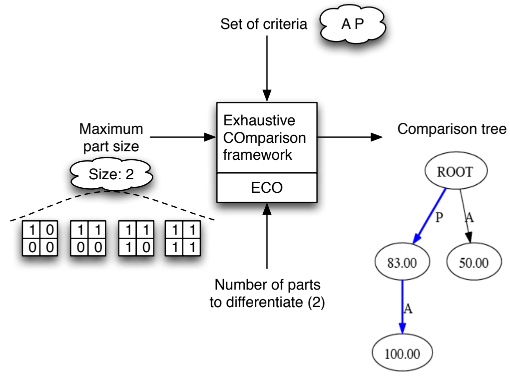

Fig. 3. Global architecture of ECO

the conveyor is therefore self-reconfigurable and modular. The blocks are linked together to form the conveying surface. Each block includes a MEMS actuator array in the upper face in order to move the objects and sensors, able to detect the object positions, are integrated also in the upper face. Each block has its own processing unit as a micro-controller, and some communication ports link it with its neighbors in order to plan global transport policies or to decide to reconfigure the shape of the conveyor in case of faulty blocks or of series change. Each block is therefore autonomous for taking its decisions but it needs to act in coordination with all the other blocks and this is the main software challenge of the Smart Blocks project. The number of actuators to control will be very important in real conditions as we could have up to 100 actuators per square centimeter, which means 1,000,000 actuators per square meter. Having a centralized control of the actuators seems too challenging both in terms of hardware and software. A decentralized control paradigm is therefore a better solution to deal with the scalability of the system. For the same reasons, sensors have to be embedded directly in the array of MEMS actuators. This will allow a decentralized closed-loop control among the blocks where sensors collect data about the shape and position of the objects. This architecture tends towards what is referred to as distributed intelligent MEMS where each block, composed of MEMS sensors and actuators, is intelligent or smart.

B. Main results

1) Hardware results: Three prototypes have been built within the Smart Surface project, the difference lies in the type of the actuators used. A first version, proposes passive cells with remotely placed actuators, a second prototype is composed of active cells that can create airflow in 2 directions but the actuators are controlled by column. Finally, the most advanced prototype (see figure 2) comprises active cells in 2D and individual control.

2) Software results:

a) Computing sensors feedback: In order to avoid a bottleneck, each cell of the surface acts independently from its neighbors. A cell embeds a processing unit, communication capabilities, an actuator and sensing capabilites. Each sensor sends a binary information to its processing unit, 1 in the presence of the object or 0 for its absence. The object could be therefore highly discretized if one cell only has one sensor.

The first work has been to study the possibility to differentiate highly discretized objects and to study the best criteria to do so. The Exhaustive Comparison Framework (ECO)[28] objective is therefore to test exhaustively the efficiency of several differentiation criteria. The criteria are then ranked, in terms of differentiation efficiency, memory and processing power needed. As it can be seen in figure 3, ECO takes as input the maximal size (in pixels) of the object, a set of criteria, and it can then generate a weighted graph (figure 4) whose vertices contain the differenciation percentage and, edges, the cost either in term of memory used or in term of processing power needed.

The second work has been to define the optimal number of sensors that have to be embedded inside the surface. The Sensor Network Calibrator (SNC) [29] is able to test different numbers and organizations of the sensors. SNC, presented in figure 5, receives as input the video from a camera which is positioned above the Smart Surface Prototype (SSP). The SSP is a macro-scale surface (10cm x 10cm) which has been used for early integration of communication and control. SNC uses the video, the models of the objects, models which must be recognized and the number of sensors that have to be tested, and it outputs the result of the differentiation. By varying the number and position of the sensors, different differentiation rates are obtained. This information can then be used to setup the best number of sensors.

b) Communications: The Smart Surface is organized to form an array of cells, where each cell is connected to its four neighbours. The network topology is then a mesh 2D. As the network topology is known and fixed, the challenges to be solved lie in the algorithmic part. A mathematical model of discrete state acquisition and several distributed

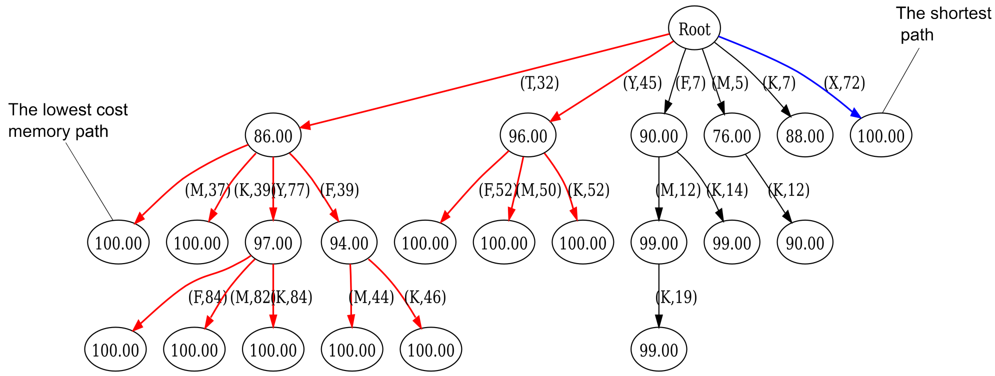

Fig. 4. ECO output as a weighted graph, here memory cost for all solutions is presented

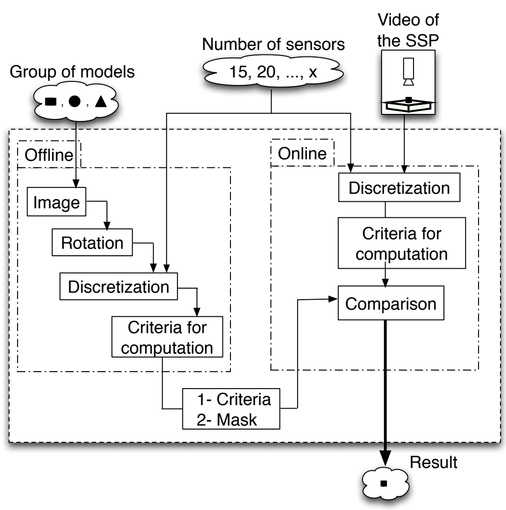

Fig. 5. Global structure of SNC

iterative algorithms have been proposed and tested [30] and it has been shown that asynchronous state acquisition methods shown better results in terms of scalability. The proposed state acquisition method presented in [31] is fault-tolerant. The faults can occur within the cell (faulty local state) or during a communication (packet loss). The robustness of the state acquisition is due to the asynchronous communication paradigm and also to a post-processing of data which can correct faults.

c) Control: Conveyance of objects with pneumatic forces is very challenging and many challenges need to be solved. Proposing an analytical model of the whole system to help controling the surface is difficult, reinforcement learning control approaches have rather been investigated. Reinforcement learning has given good results to control the Smart Surface without any prior model. The proposed reinforcement learning method is decentralized and addresses the global-local tradeoff [32]. The global problem is indeed too complex to be solved but solving merely the local problems can lead to poor global performances. An integration of sensing, communications and control has been proposed [33].

d) Modeling: Two complementary models of the Smart Surface have been proposed. The VHDL-AMS model [34] can simulate the behavior of the surface at a physical level while the SysML model [35] gives a more higher-level description of the architecture. The SysML model is derived from the VHDL-AMS one and the objective is to link the SysML description of the hardware to the UML description of the software. This will allow properties verification for the whole system and will increase the reliability of the system during the design phase.

IV. Key issues in the design of communicating MEMS

A. *Coverage, connectivity and network redeployment*

For data gathering applications, which represent the main use of WSN applications, the goal is to detect any event occurring in the area of interest and to report it to the sink. Hence, the considered area must be fully covered by sensors ensuring that any potential event will be in the sensing range of at least one sensor. In addition, the sensor network must be connected in terms of radio communication in order to forward the detected event to the sink(s). [36], [37] are the earliest papers proving that if the communication range is at least twice the sensing range, a full coverage implies connectivity among active nodes inside the area of interest.

When the sensor field is represented by a two-dimension area, the minimum number of sensors required to cover the field is obtained when these sensors are put on the vertices of a triangular lattice (or, equivalently, at the centers of regular hexagons). The asymptotic optimality was proved in [38], [39].

1) Network deployment and redeployment: Since the initial deployment can be random, the network deployment is usually far from optimal. Areas with redundant sensor nodes (i.e. not needed to ensure full coverage) coexist with areas with coverage holes. The coverage degree varies from one area to another. Redeployment is needed to ensure coverage and connectivity. It can also contribute to maximize network lifetime by allowing redundant nodes to sleep, thus saving energy. Applications may also require a network redeployment around a point of interest (e.g. an intruder, a fire) that is discovered during network lifetime. Existing redeployment algorithms can be classified according to:

- their goal: uniform deployment to ensure uniform coverage and connectivity or on the contrary a higher coverage degree close to the point of interest. Some algorithms try to minimize the duration deployment, others reduce the amount of energy consumed by this deployment.
- the assumptions made with regard to mobility. We distinguish solutions based on one or several mobile robots redeploying static sensor nodes from the solutions where all sensor nodes are mobile.
- the principles used to get the redeployment. For instance, algorithms based on the Virtual Forces principle like [40] and [41] outperform algorithms based on Particle Swarm Optimization [42]: they are simpler and achieve a faster convergence. Algorithms also differ by the initial knowledge they assume (e.g. number of nodes, target distance between neighbor nodes....).
- the centralized or distributed nature of the algorithm. In case of a centralized algorithm [40], [43], a central entity is assumed to know the position of any sensor node. This assumption is unrealistic, since even if each node knows its position, it can be impossible to forward this information to the central entity because of the lack of connectivity. Distributed algorithms [44], [45] are realistic but faced with a stability problem.

In the case of replacement of a failed sensor, cascading moves of sensor nodes achieve a higher lifetime compared to a single and longer move of one sensor [46].

B. Communication

The seminal results of Gupta and Kumar [47] show that the capacity of wireless networks scales with $\frac{\sqrt{n}}{\sqrt{\log n}}$, where n is the number of wireless nodes. This means that the network capacity increases with n.
Medium access protocols have to preserve this property. However, such protocols only rule one-hop communication. Dimensions of wireless networks are generally such that the destination is not within radio range of the source. Multi-hop communication is then needed. It requires a routing protocol able to dynamically adapt to topology changes. In data gathering applications, it is usually sufficient for any node to maintain a route to the sink. If the application has QoS requirements in terms of minimum throughput for instance, routing should be interference-aware and must be coupled with an admission control.

C. Expected properties

1) Energy efficiency: The network should stay operational without human intervention the longest as possible. It results that a main goal of WSN designers and then of any protocol running in a WSN is to maximize network lifetime. The main wastes of energy being identified and minimized, the WSN should be designed to consume energy very efficiently. Energy efficient techniques can be classified as follows:

- *data reduction* acts on the amount of data produced, processed and transmitted. Data compression and aggregation are examples of such techniques.
- *control reduction* aims at reducing the overhead induced by protocols. Tuning the transmission period of messages to network stability level or to the distance to the source of information are examples of control reduction. Optimized flooding contributes to significantly reduce the number of useless transmissions of a message broadcast throughout the network. More generally, a cross-layering approach allows protocols to optimize their performance taking into account environment constraints and application requirements.
- *energy efficient routing* minimizes the energy consumed by an end-to-end transmission and avoids nodes with low residual energy. Opportunistic routing takes advantage of node mobility or the broadcast nature of wireless communications to reduce the energy consumed by a transmission to the sink. Geographic routing use the geographic coordinates of nodes to find the next forwarder node toward the destination. Hierarchical routing reduces the overhead by organizing the network in clusters and distinguishing intra-cluster routing and inter-cluster routing. The first one is kept simple.
- *duty cycling* allow nodes to sleep to save energy. Node activity scheduling must be coordinated to avoid sending messages to a sleeping node. Node activity scheduling can be done at a high level determining which nodes are redundant and can be switched off. At a low level, node activity scheduling determines when a node is not involved in any medium access and its radio can be switched off.
- *topology control* adjusts the transmission power to the receiver distance and creates a reduced topology while maintaining connectivity.

There also a need for an energy-driven tradeoff between computation/communication/sensing. For each data acquired by the sensor, a decision has to be taken. Will it processed locally, sent to a remote processing unit or even discarded which asked for new acquisition? This choice depends on static parameters like, for example, the type of the sensed data or the type of application, but it depends also on dynamic parameters like, for example, the network connectivity, the energy level of the node, or even the energy level of the whole system.

Energy harvesting (e.g. from ambient vibrations...) is a promising research area.

2) Auto-adaptivity: All the applications share the same requirement: the wireless network should remain operational the longest as possible without external human intervention to fulfill the application missions. Such an autonomous network will survive, like any biological entity only if it is able to adapt to the dynamicity of its environment, the hazards of failures.... As a consequence, such a network should be auto-adaptive, able of self-healing in case of failures or energy depletion, able of self-optimizing by for instance selecting the most energy efficient paths to reach the sink... In a mobile wireless sensor network, sensor nodes have no (or a very limited one) initial knowledge of the network topology and obstacles, they progressively acquire this knowledge by exchanging messages with their neighbors and sensing their environment. The accuracy of decisions taken by mobile nodes increases with their knowledge degree. Wireless sensor networks have also to dynamically adapt to the detection of points of interest as expected by the application, with for instance the tracking of an intruder.

3) Real-time constraints: While WSNs only sense data, diMEMS can also act on real world and therefore they could need coordinated control. The coordination between the actuators can either be local or global, meaning that only some actuators from a neighborhood will act all together or that all the actuators of the system have to act together. Distributed control has therefore to be used in such systems but the usage of wireless communication adds uncertainty for the control. Control is very sensitive to delay, and even more to jitter, and to packet drop out. Integrating wireless communications in a control system is therefore challenging and many improvements and certainly co-designs between the control and the communications, will be needed.

4) Mobility: Mobility is the concern of diverse networking fields ranging from ad hoc networking with low mobility, to Vehicular Ad hoc NETworks (VANET), with high mobility. Mobility causes topology changes which can disturb the logicial topology. Mobility have also an effect on the quality of transmissions as messages are more commonly lost whe the communicating nodes are mobile. In the case of diMEMS systems, the relative mobility of nodes is quite low, which means that it has to be taken into account but it is not a major parameter of diMEMS systems.

D. Design and performance evaluation

1) Cross-layer design: Cross-layering approaches are very useful to meet the application requirements in resource constrained networks; we can distinguish [48]:

- *Top-down approach*: where the higher layers decide strategies and select parameter values for the lower layers.
- *Bottom up approach*: where lower layers report resource status like the bandwidth to the higher layers.
- *Application-centric approach*: where bottom-up and top-down alternate to optimize the parameters of the lower layers.
- *MAC-centric approach*: where the MAC layer is in charge of deciding which flow should be transmitted with which quality of service level.
- *Integrated approach*: where an optimal solution to the global problem is found. This approach is the most complex one.

We can also use less radical cross-layering approaches, which take advantage of the information provided by the higher layers concerning application requirements and by the lower layers concerning the status of resources to optimize network resources use while meeting the application requirements. For instance, the QoS perceived by the user is improved when routing uses only links of good quality, this quality being known from the MAC layer. Furthermore, a larger bandwidth will be available to the application if in data gathering applications, routing maintains only a route toward the sink.

In the case of nano-wireless communication, the right cross-layer approach is application-centric as the environment and the application changes the strategies for lower layers but in the mean time lower layers could also feedback information to upper layers.

2) Performance evaluation: experimentation, simulation and modeling: Performance must be predictible. A performance evaluation should preexist to network deployment. This evaluation can be done by experimentation, simulation or by modeling. Precise simulation is currently limited to hundreds of nodes (thousand nodes in the best cases), whereas some modeling can reach thousands of nodes without any problem in the case of asymptotic analysis for instance. Simulation of diMEMS will require to scale up in number while maintaining an acceptable precision level. Number of nodes is likely to number in millions which will need innovative simulation frameworks. Experimentation is required to provide parameters that are representative of both the application and the environment considered. These parameters can be used to calibrate the simulation tool. Simulation results can then serve as input parameters to the models that will allow the designers to know the behavior of the network.

V. Conclusion

This paper presented the use of wireless MEMS networks in industrial context. WSNs in industrial context raises many challenges that come to extreme in the case of wireless MEMS networks. The possible applications of wireless MEMS networks are huge, since due to their size, they can be integrated almost everywhere and can embed not only sensors but also actuators which increases their utility.

VI. Acknowledgments

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