On the convergence between Wireless Sensor Network and RFID: industrial environment

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***Abstract*—The convergence between Wireless Sensor Network and RFID technology enables the development of flexible and integrated architectures that could currently represent a competitive solution for several application scenarios. This paper proposes an advanced heterogeneous wireless network designed for industrial environments: typical sensor applications (personal and environmental parameters monitoring), RFID based services (e.g. objects identification) and convergent applications (localization and tracking) are merged. Several research topics are addressed (resource optimization, low power communication within hostile environments, etc). Proposed model would be a generalized solution that assures high performance in terms of reliability, robustness, and flexibility: main architecture component, Multi-Modal Wireless Sensor Node (MM-WSNode), is provided with multiple sensing, communication and data process resource that allows several working modes in function of environmental conditions detected.**

Keywords: Wireless Sensor Network; RFID; Localization and Tracking, Network design.

I. INTRODUCTION

Commercial opportunities around both active and passive RFID technologies are constantly increasing. In the last few years, passive RFID technology (Figure 1) was progressively affirming taking advantage by its no energy supply requirements, really reduced size, great life-time and low cost manufacture [2]. Application field of passive RFID technology is really extended. The major disadvantages of a passive RFID TAG are the short detection range (the TAG can be read only at very short distances, typically a few feet at most), the impossibility to include sensors that can use electricity for power and the peculiar work mode (the TAG remains readable for a very long time, even after the product to which the tag is attached has been sold and is no longer being tracked). On the contrary, an active TAG needs power supply and can so be read at great distance; it has the capability to perform independent monitoring and control, the capability to initiating communications (so it can be active actor in autonomous networks) and of performing diagnostics; it is capable of highest bandwidth communication and can have other sensors that use electricity for power. Respect to passive TAG, it is considered to be more expensive for both manufacture and maintenance (batteries supply implies higher human intervention); it usually to be physically larger than a passive TAG. Active RFID technology is emerging, probably with the contribution of advancements in replaceable batteries technology that, however, actually enable really long life-time. Some active TAGs are sealed units and others can be connected to external power sources providing a truly complete technologic set for advanced application design.

Probably, the next generation of RFID development and commercial opportunities will be determined by the creative use of sensors on the active RFID TAGs [2].

On the other hand, during last years, sensors have been increasingly adopted in the context of several disciplines and applications (military, industrial, medical, homeland security, etc.) collecting and distributing observations of our world in everyday life. Sensors progressively assumed the critical role of bridge between real world and information systems, through an always more consolidated and efficient sensor technology [1] that enables advanced heterogeneous sensor grids. Current sensor networks are able to detect and identify simple phenomena or measurements as well as complex events and situations.

The paper proposes an integrated architecture featured by the optimized coexistence and cooperation between WSN and RFID infrastructures. This solution is also optimized for high density networking: high accuracy localization, as well as complex heterogeneous sensor systems, typically requires a great number of nodes. Considering potential hostile environments, the framework guarantees, through advanced wireless sensor nodes, high reliability and robustness: main architecture component, Multi-Modal Wireless Sensor Node (MM-WSNode), is provided with multiple communication and data process resource that allows several working modes in function of environmental conditions detected.

Addressed research issues can be resumed as in the follow points:

- *Coexistence* between several technologies, especially in the field of wireless communication.

- *Cooperation* between several actors developed according several technologies in order to achieve common goals or performing cooperative tasks.
- *Competition* between intelligent actors which, according an adaptive approach, are able to perform their behavior and role within the system in function of detected conditions and constraints. This last aspect could have a strong impact in hostile environments.
- *Optimization* of resource according a green approach; this is directly or indirectly related with each one of previous issues.

The paper is structured in three main parts: the first part (Section 3) proposes a technical description of the overall architecture; Section 4 is focused on the description of the main architecture component (MM-WSNode) that proposes the great part of key issues; finally (Section 5), an application case (industrial environment) is proposed.

Figure 1. Examples of RFID passive TAGs.

II. Related Work

Proposed architecture is the result of the optimized integration between WSN [1] and RFID [2] technology; RFID-based applications are actually object of a great commercial interest as well as sensors are assuming an always more critic role within several systems and environments. Research interest is providing a key feedback that is enabling a continuous process of technologic improvement and techniques refinement.

Proposed framework would be an attempt of improving performance, robustness and dynamism of systems in which sensor based applications coexist and cooperate with RFID systems. Proposed framework assumes advanced (even if low cost) wireless nodes, ah-hoc designed for multi-hop networking [1], provided with parallel processors and multiple communication capacities.

Moreover, the enabling of resulting applications into Virtual Organization context [3][6] makes proposed architecture easy to be integrated into preexistent Control Centers and able to remote work in accordance with the typical hierarchical organization that actually characterizes the great part of real work environments.

III. Overall Architecture

Proposed architecture provides an optimized communication infrastructure for the simultaneous support of the following applications:

- *Environmental monitoring* (e.g. temperature, humidity, noise, etc.). Considering industrial environment, this class of sensor is assumed to be fixed and not necessarily critic respect to power consumption.
- *Personal sensors* (e.g. biomedical parameters). All sensors associated to persons. They are useful in the most modern industries in order to monitor parameters of interest for the health of workers. They are mobile actors within the architecture.
- *Identification, localization and tracking*. The subsystem is designed in order to localize into the interest area RFID readers able to detect and identify objects; details will be provided further in this section and in the section 5.

The overall capture system (Figure 2) is based on a novel WSN that, on one hand, acts as common sensor systems (capturing environmental data) and, on the other hand, provides a multi hop communication infrastructure for all mobile nodes (personal sensors and RFID readers).

The most interesting architecture component is the localization and identification sub-system. In the current prototype, a set of RFID readers, able to detect and read passive TAGs, communicate through a WPAN (RF 868Mhz/FFDs MAC and RF 2.4Ghz/FFDs MAC) with MM-WSNode devices; these last devices are able to locally elaborate and integrate received data that is sent to Base Station (BS) through a ZigBee network (IEEE 802.15.4, 2,4Ghz, RFDs MAC) [4]. As showed (Figure 2), proposed framework does not impose any predefined topology that is an open parameter in function of concrete deployments and localization algorithms.

Communication with personal sensor devices is managed according the same infrastructure but nodes simply transmit information generated; they are not localized in the space.

Proposed architecture is composed of several functional components (Figure 3) that can be resumed in two main layers: Service/Application layer and Local Infrastructures. Service/application layer includes typical application and middleware functions; it is composed by several sub-layers:

- *Service-level infrastructure*. Context-aware support for integration of the system within complex Virtual Organizations [3][6].
- *Control System*. It is the user level platform for enabling final user to application access and configuration, monitoring and control.
- *Information System*. As in the common mean.
- *Localization Engine*. It implements a localization algorithm that provides the final application with the ability of positioning active TAGs within the area. Its inputs are detected RSSI values and prefixed positions in which values are detected (anchor nodes).

An exhaustive description of middleware and application layer is considered an interesting topic but out of paper scope. Local Infrastructure is described and analyzed in the next sections.

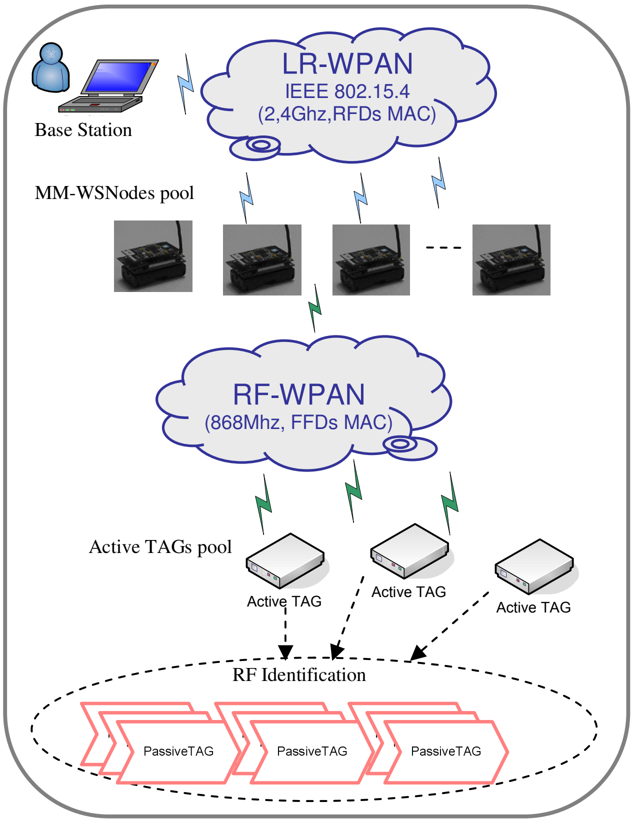

Figure 2. Schematic representation of overall capture system.

If required by coverage area requirements and/or network scale, density or topology, local infrastructure can work on the top of an overlay layer that mainly introduces dynamic cluster partitioning of the whole network according the model proposed by [7].

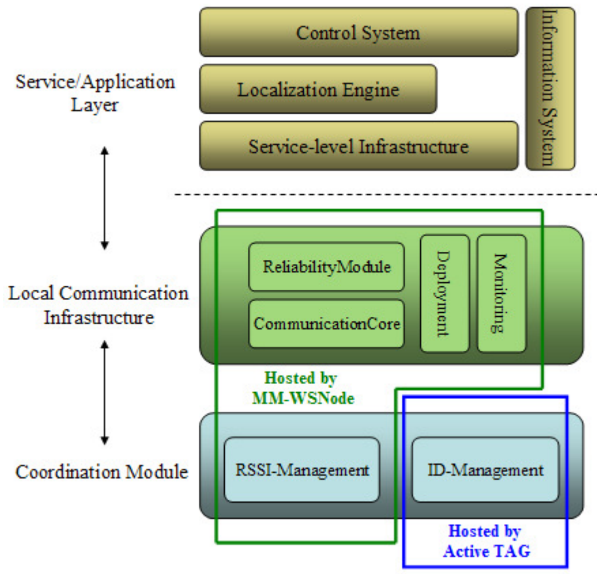

Figure 3. Logic modules of architecture.

IV. MULTIMODE WIRELESS SENSOR NODE (MM-WSNODE)

The main goal of the section is providing an overview on MM-WSNode and on the features that differentiates it respect to common low-cost commercial wireless sensor nodes.

MM-Node proposes an advanced node model that can support the development of intelligent systems based on low-cost WSN, as well as autonomous networks, multi-mode communication networks, fault-tolerant networks, adaptive networks and neuronal sensor networks.

MM-WSNode is a complex and advanced wireless node featured by the coexistence and cooperation of two potential independent active components, each one provided with its own computational, storage, sensing and communication resource. Active components can interact, in order to provide a global behavior, in accordance with a master-slave or peer to peer approach.

A device, called Coordinator, is provided with higher communication capabilities. Active actors communicate between them through a physic interface; intercommunication API is built over the standard RFC1662; this API, on a hand, allows physical communication between devices, and, on the other hand, provides an abstract support for suitable design and implementation of distributed cooperative behaviors. The behavior of the node is the result of cooperation between the behaviors of single devices. Software platform for both devices is TinyOS [12].

The following part of section proposes a brief but exhaustive description of node hardware, of related resource management model and, finally, of protocol stack.

A. *Hardware*

Typical smart low cost wireless sensor node, designed for multi-hop networking, is featured by advanced, small in size, low consumption processors and transceivers according wireless technologies oriented to low rate communication (little amount of information and low power transmission). Modern devices can be provided with in-board or on-board sensor components. Software platforms can be reduced versions of generic purpose operative systems (e.g. Linux) or, alternatively, embedded operative systems (e.g. TinyOS [12]) oriented to maximize power management efficiency through advanced event-driven management models.

MM-WSNode hardware is composed by three main devices (Figure 4): the main component (Host), the Coordinator and the Adapter. Host and Coordinator are active components because provided with autonomous processors; Adapter is simply a passive component that allows physical communication between 51-pins expansion connector of Host and 10-pins expansion connector of Coordinator. Host is a MicaZ device [5] provided with Atmel ATmega128L and with an IEEE 802.15.4 compliant RF transceiver (2.4Ghz, 250Kbs, RF power range included between -24dbm and 0dbm). Host is considered the main component because it provides energy supply for both devices. Coordinator is similar to Host relatively to processor features and memory size but differs by Host for communication capabilities: it assumes frequency (between

868Mhz and 2.4Ghz) and higher RF power (included between 5dbm and 15dbm). Both can mount sensor devices.

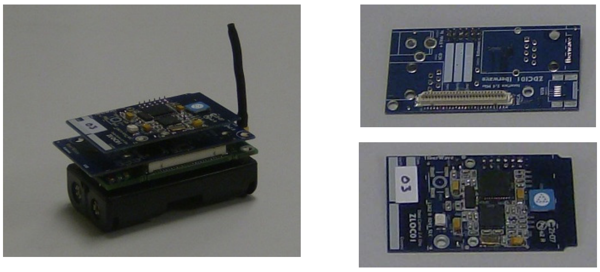

Figure 4. MM-WSNode (on the left); Adapter (up on the right) and Coordinator (down on the right).

More than a concrete device, MM-WSNode would propose a family of devices: hardware features could significatively vary in function of concrete application domain and environment that can propose requirements and constraints significantly different among them.

B. *Resource Management Model*

The design of wireless sensor nodes usually to take into account the following issues:

- Application life-time is considered, both with robustness and reliability, the most relevant commercial key issue for wireless sensor systems. The great part of sensor nodes are battery powered. Human intervention is typically considered as an expensive and not always suitable task.
- Also sensor devices not battery powered could work as embedded sensors; several hosts could be featured by limited resource also in terms of available power.
- A constantly increasing number of sensor devices work within green systems; this advises a design oriented to resource optimization.

Common wireless sensor nodes are designed in order to work according an event-driven Sleep/Operate model: the natural state for a node is “sleep”; in this state its energy consumption is next to be zero and, so, not relevant; an external (message receiving, active sensor notification) or internal (timeout expiring) event makes node state as “operate”; in operate mode, power consumption is considered to be important; at the end of operations, the state becomes sleep.

This is a simplified view of node activity because, really, operate state should be divided into a number of sub-states (two as minimum): transmission/reception (high energy consumption) and data process/information capturing (limited energy consumption).

Proposed node is really different respect to a common low-cost wireless sensor node because composed by two active intercommunicating components, each one provided with its own computation, sensing and communication resource. Because two active components, proposed node really works in accordance with a Sleep/Operate model significantly more complicated respect to common models. As showed in Figure 5, there are really several states in which the energy consumption is relevant: Full Operation (both active components in operate state), Host_op (Host in “operate” state and Coordinator in sleep state) and Coordinator_op (Coordinator in operate state, Host in sleep state). Direct transitions between the states Sleep and Full Operation (and reverse) are absolutely theorist transitions. Each state, characterized by relevant energy consumption, is really composed by a certain number of sub-states independence by activity of each one of active components: transmission/receiving or data process. Moreover, Coordinator usually communicates with a power notably higher than Host. A quantitative evaluation of MM-WSNode power consumption is out of paper scope. However, industrial environment assumes power supply by batteries only for mobile nodes. MM-WSNode should be adopted as anchor node that does not change its position during application lifetime.

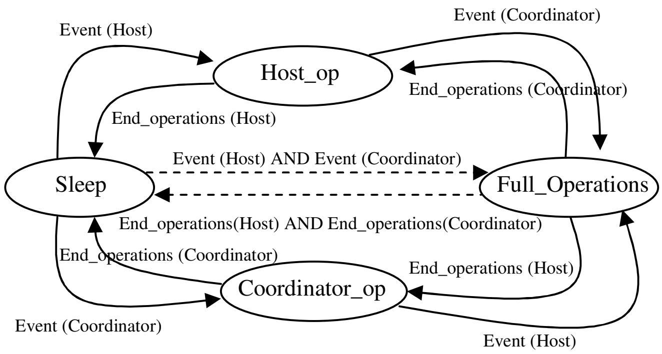

Figure 5. Resource Management Model for MM-WSNode.

C. *Intercommunication API*

Each one of active module (Host and Coordinator) that composes MM-WSNode is absolutely independent respect to behavior implemented and resource management. However, MM-WSNode fundamental idea is the active cooperation, in accordance with a certain interaction model (e.g. peer-to-peer or master-slave), between the two components in order to provide a global behavior. Considering that each one of components is separately programmed, a well-defined two side API is provided in order to guarantee suitable intercommunication of active messages and peer resource access. Proposed API provides an abstract view of peer resource, implementing Packet/Frame level functionalities over RFC 1662 standard (Table 1). Maximum payload (data) size, at this level, is limited to be 36 bytes. Resulting API is provided as TinyOS module and allows generic iteration (active message sending/receiving) and specific purpose operations. For example, the Host could detect the unavailability of communication with the whole network and could use Coordinator communication resource (higher RF power) to discover a reliable communication path. Developer can so design behavior software including a standardized peer resource access capability. The module is designed in accordance with most common software principles: it implements a communication interface and it is provided with a background engine that manages reception events. Moreover, the API extension is really suitable: new complex events can logically generate an added trigger that notifies, through an active message, correspondent tasks and related data or parameters to the peer engine; the engine reacts in function of detected trigger and input data; performed task can be ad-hoc implemented extending the engine.

TABLE I
RFC 1662 STANDARD RESUME

Byte#	Field	Description/Value
0	Synchronization byte	Always 0x7E
1	Packet type	There are 5 admitted values (types): • P_PACKET_NO_ACK (0x42): packet with no ACK required • P_PACKET_ACK (0x41): packet with ACK required; it includes a prefix byte; receiver has to send a P_ACK response with prefix byte as contents. • P_ACK (0x40): ACK response that includes prefix byte. • P_UNKNOWN (0xFF): Unknown or generic packet.
2…n-1	Payload data	Data message
n	Synchronization byte	Always 0x7E

D. *Protocol Stack*

Wireless nodes implements two layers of global protocol stack (Figure 3):

- *Coordination Module*: it is composed by two cooperative sub-modules: the first one, ID-Management, is implemented by active TAGs and has the main role of managing passive TAG detection and identification according one of the multiple supported work modes (periodic, event-driven or on demand); furthermore, detected information is elaborated and sent to MM-WSNodes; the second logic sub-module, RSSI-Management, is implemented by MM-WSNode and provides support for detecting the Radio Signal Strength Indicator (RSSI), organizing and integrating (with local node data) information sent by active TAGs. Coordination module is really limited respect to communication functions: active TAGs just broadcast detected information (mono-hop communication). On the contrary, it includes several functionalities for information detecting and management at different levels of integrated architecture.

- *Local Communication Infrastructure*: this module is implemented by MM-WSNode; it manages application level data and has the main role of assuring reliable communication from nodes to Base Station. Architecture is not constrained to work according a predetermined topology and, so, a self-deployment mechanism is required. Furthermore, considering that multi-hop communication usually to be required within potentially hostile environments, sensible to unpredictable condition changes, the improving of communication robustness is the real critical issue for WSN performance. In order to supply these QoS requirements, three logic sub-modules are provided: CommunicationCore (lack of protocols that implements a flexible and scalable routing mechanism), DeploymentManager (mechanism that adaptively guarantees correct configuration and refresh of communication paths from each node to Base Station) and ReliabilityModule (set of reinforcement mechanisms, such as information redundancy, able to guarantee reliable communication into hostile environments). Optionally a MonitoringManager for resource monitoring can be integrated.

Multimode communication allows the WSN to provide a multi-hop, reliable and scalable communication infrastructure among nodes; communication modes differ for RF power and frequency. This adaptive approach enables low power communication as favorite option but, at the same time, provides an alternative option if topology constraints, physical obstacles or interferences make WSN temporally or permanently unable to guarantee reliable communication in hostile environments. An optional functional module enables fault tolerance mechanisms in order to detect and manage software/hardware failures. Because parallel architecture, a relevant number of partial failures can be successfully managed (node is able to correctly guarantee all functionalities implemented by its global behavior).

V. AN APPLICATION SCENARIO: INDUSTRIAL ENVIRONMENT

Complex industrial environments imply a great number of specialized people that (frenetic) work in order to realize specific and, in the great part of cases, interdependent tasks.

Objects of different size are used by different people improving the probability of loosing some of them (especially if small in size) causing a productivity decreasing or, some times, safely problems.

The concrete application scenario is an industrial area in which aircrafts are produced (Figure 6); a great number of objects are used during industrial tasks that, even if organized and synchronized, imply the cooperation of workers into different part of main industrial area. A considerable amount of time is typically spent to reorganize the objects inventory and, eventually, searching for no present objects that are very hard to find especially if small in size and dislocated into (large) work areas. A technologic support for this process could represent a significant improvement of industrial tasks efficiency. Furthermore workers employed in critical tasks are provided with biomedical sensors in order to monitor their health status. Also environment is constantly monitored; sensors able to capture temperature, humidity, light and noise are adopted.

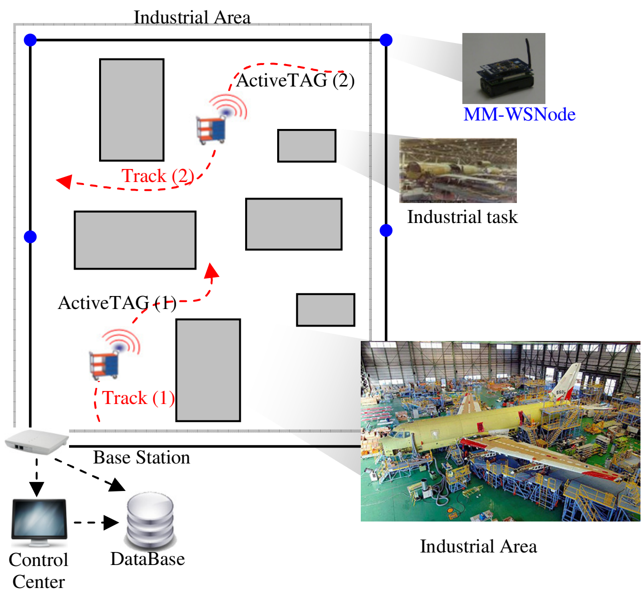

Figure 6. Schematic view of reference industrial area.

Proposed integrated solution provides an industrial area with the ability to identify and localize objects, randomly dislocated into considered area, with a considerable precision; a variable number of human-driven boxcars are dislocated into the area (Figure 6); they usually to spent the great part of the time stopped near work areas (in which aircraft parts are separately produced) and so they are moved really slowly; the first function provided by the framework is the real time localization and tracking of these boxcars that will be considered as active actors; moreover, each boxcar has to be able to detect and identify all pre-marked objects (passive actors) that are into its capture range; each object is preliminarily related to one or more boxcars and so, the boxcar, has automatically to detect the object, determining its identity. These requirements are the logic consequence of the extreme facility of loosing small in size objects during the construction of the different aircraft parts and of the necessity of monitoring the activity of boxcars. Comparing the schema showed in Figure 6 with the picture of Figure 2, MM-WSNode devices are strategically dislocated into the border of the area in order to guarantee correct capture of information needed by localization engine; at the same time they provides a communication infrastructure for any mobile node dislocated into the area as well as a sensor system for detecting environmental conditions. In dependence of required accuracy and concrete environments different approaches can be adopted in order to estimate the active TAG location using detected RSSI (Received Signal Strength Indicator) information samples provided by sensor network. Localization algorithms are really interesting but an exhaustive state of art is out of paper scope. Typically a localization algorithm provides a mathematic elaboration of RSSI detected in prefixed points (called anchor nodes). The performance of a RF localization system depends by device sensibility for RSSI detected, by number and position of anchor nodes and by localization algorithm, eventually reinforced by mechanisms (as calibration or memory able). The proposal of a concrete localization technique is out of paper scope that is mainly focused on communication infrastructures.

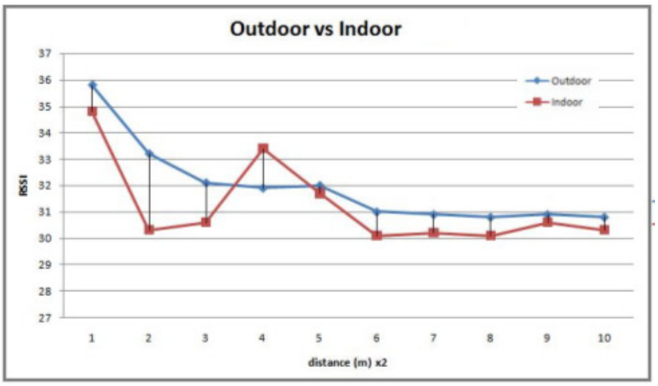

Figure 7. Average RSSI values detected in function of distance for indoor and outdoor environment.

Detected RSSI values depend by hardware sensibility and by environmental parameters; in the ideal case, it should regularly decrease in function of distance; during experimental tests of prototype, average RSSI detected results as next to be ideal (regularly decreasing in function of distance) in outdoor environment, but, as expected, really more irregular within indoor environments (Figure 7); each reported point is the average value of 100 samples; these results are in accordance with results provided by [11]; in indoor environment only relevant distances are really characterized by regular difference [11] implying a lower accuracy of algorithms respect to outdoor environments in which good results can be obtained adopting relatively simple approaches [10]. Accuracy into indoor environment can be sensibly increased by preliminary calibration that can provide a robust reference for environment characterized by not too much variable conditions; memory can limit errors in environment characterized by slow movements of active actors (as in proposed scenario).

VI. Conclusions and Future Work

The paper proposes an integrated architecture resulted by the convergence between WSN and RFID. The main architecture component is an advanced multi-mode, low cost wireless node provided with parallel processors that could considerably increase performance, robustness and flexibility of applications at the time of effectively working into real-world in the context of no dense heterogeneous sensor networks. The coexistence and the optimized cooperation and competition between heterogeneous actors allow advanced application working on the same communication infrastructure.

In the next future proposed architecture will be optimized through mayor experimentation and the prototype will be particularized in order to improve the safety and health of workers within industrial environments. Also middleware infrastructure will be improved integrating a machine interpretable semantic support in order to introduce new interaction models among actors and between system and users.

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