# ANTS: An evolvable Network of Tiny Sensors†

Daeyoung Kim[1], Tomás Sánchez López[1], Seongeun Yoo[1], Jongwoo Sung[1], Jaeeon Kim[1], Youngsoo Kim[1], Yoonmee Doh[2]

[1] Information and Communications University (ICU), 119 Munji-Dong, Yuseong-Gu, 305-714, Korea
{tomas, kimd, seeyoo, jwsung, jekim, pineland}@icu.ac.kr
[2] Electronic and Telecommunications Research Institute (ETRI), 161 Gajeong-dong, Yuseong-gu, 305-700, Korea
ydoh@etri.re.kr

**Abstract.** As a promising technology that enables ubiquitous computing and leads IT industries of next generation, sensor networks (SN) are foreseen to expand and populate the globe in such a way as the present Internet does. In this scenario, new challenges appear with such massive deployment, as the constant interaction of nodes and networks will transform them in dynamic entities that will need to evolve with their environment. In this paper, we discuss the future of sensor networks defining the concept of evolvability and its application. We also describe ANTS, a complete new architecture for wireless sensor networks, as our implementation to solve the challenges imposed by this evolvable future.

**Key Words.** Sensor Networks, Evolvability, Operating Systems, Middleware, Localization, Synchronization, Security, Network Protocols

## 1 Introduction

Small devices with integrated sensor capabilities are gaining credit by industries and institutions all over the planet. From the work started by some visionaries several years ago, research in the field leads old skeptics and new believers into a dream of potential applications for present and future. However, the track towards SN's future has several challenges to overcome. In this near future, when sensor nodes will be embedded in everyday's life, vehicles, food, clothes and any other kind of movable products will travel around interacting with each other and stationary networks creating and destroying communication bridges which will remain transparent to regular users. Living in this close tomorrow, we will witness the expansion of the ubiquitous computing, not only with the presence of sensor devices everywhere, but also with its global interconnection. Sensor networks will be born, will grow and will reconfigure

† This research has been partially supported by ITRC project of Korea Ministry of Information and Communication

autonomously, getting upgrades from the network, adapting to changes while learning from their environment and their fellow networks. But to get to this future, we have to think about the present and how this omnipresence of sensor devices should be managed by adaptability and autonomy capabilities. Here is where the concept of evolvability and the need for evolvable architectural design comes into play.

WSN applications are numerous, such as habitat [1] and health monitoring [11], environment control and actuation [2] or even parent control [6]. Some architectures have been developed as a base for this applications [3]. However, although some efforts have been done in the development of evolvability capabilities, the results are either far away from the desirable functionalities or are not applicable to the constrained WSN devices. In this paper we introduce ANTS: An evolvable Network of Tiny Sensors. ANTS is a new architecture for the development of sensor networks which functionalities are built applying the concept of evolvability. ANTS not only develops system functionalities (Section 3) but also implements application level and middleware solutions such as context aware and UPnP (Universal Plug and Play) frameworks [10]

The rest of the paper is organized as follows: Section 2 describes generally the concept of evolvability and its characteristics. Section 3 presents our specific architecture, discussing one by one all its functionalities. Finally Section 4 depicts ANTS test-beds while Section 5 concludes the paper with a summary of the introduced concepts

## 2 Evolvability in Sensor Networks

According to what has been introduced in the previous section, we could call evolvability to the capability to adapt to changes, some induced by the users according to the evolution of their needs, others provoked uncontrollably by the network nature itself and the surroundings. Evolvability support for WSN implies a series of requirements that will following be introduced. A summary also can be found in Table 1.

Indeed, the ability to adapt to changes is a key characteristic for evolvable systems (i.e. WSN), but as we will describe afterwards, a deeper view requires further considerations. Anyway, as a fundamental attribute for our analysis, we will characterize *adaptability* as the capability of a system to change or be changed to fit changed circumstances. But can a system be adaptable if it doesn't consider its interaction with other systems? For this reason we also include the definition of *interoperability*, as the ability of two or more systems or components to exchange information and to use the information that has been exchanged.

If we concentrate on the system design, we find that systems aiming to provide adaptability features must be flexible in its implementation, as monolithic approaches would require a complete redesign for any minimal change. Modular architectures, however, supply the needed looseness to address the problems of flexibility, providing well defined modules for different functionalities. We call *modularity* to the characteristic of those systems which are based in a set of interchangeable components rather than a monolithic approach. In order to guarantee a feasible modularity we also define *scalability* as the characteristic of those systems that can adapt, at any time and with the minimum cost, to a set of necessities that can be changing. Note that this definition might include configuration issues, in the sense that the highest the ease of the system to be configured to adapt to the changes, the highest its scalability. Examples of scalability and modularity applied to the SN are the support for sensor node addition or removal and the creation of modular software and hardware components.

Further considerations about the mechanisms for the addition, replacement or deletion of components should be taken. We define *upgradability* as the characteristic of a system which accepts hardware or software updates without being stopped, and *dependability* as the property of a system to continue its operation at an acceptable quality despite the occurrence of unexpected errors in that upgrading process.

**Table 1.** Summary of System Evolvability requirements

| Requirements | Referred To |
|---|---|
| Adaptability | Ability to change with environment circumstances |
| Interoperability | Interaction with external systems |
| Modularity | Component based architecture |
| Scalability | Ease of adaptation to changing necessities |
| Upgradability | Dynamic updating processes |
| Dependability | Tolerant to errors during the system operation |

Given the characteristics exposed previously, we can now redefine the concept of evolvability as follows: Evolvable systems are those able to adapt to its internal changes or those provoked by the interoperation with other systems. To achieve this, evolvable systems should be able to scale taking advantage of the flexibility of its modular architecture, accepting the upgrade of its components while remaining dependable under any unexpected setback in this update or failure provoked by any external cause.

## 3 ANTS

ANTS: an Evolvable Network of Tiny Sensors, is born with the consciousness that the future of the sensor networks is going to be deeply dynamic. Thus, ANTS builds all its architecture from scratch designing made-to-measure components that will interact with each other and the environment following the evolvability patterns exposed earlier. A block diagram of ANTS architecture can be observed on Fig. 1

But why ANTS? Unlike other much complex systems, insect colonies are able to develop complex behaviors as a whole while the intelligence of its individual members remains very limited. While developing the concept of evolvability and adaptability to the environment, we like to think about network nodes as kind of living creatures, where they can die, become alive or communicate with other members modifying their behavior or being modified. Very limited creatures, in the end, whose knowledge of the environment is useless without sharing it with other fellows, forging a general view of the network and whose global interpretation and reaction can deal the colony to the success or the disaster.

ANTS architecture aims to solve the paradox of most present systems in which implementation is based on present static needs rather than dynamic future requirements. Following we will present the most important ANTS functionalities.

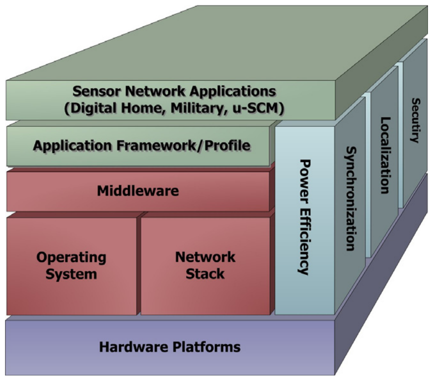


**Fig. 1.** ANTS architecture

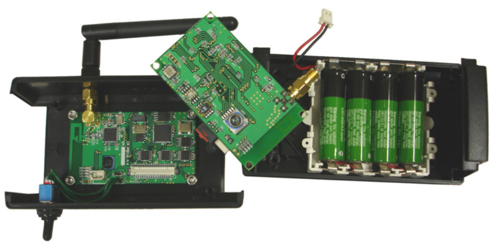

**Fig. 2.** Prototype of ANTS H2 Outdoor. The integrated single board includes ATMEGA128L μController, CC2420 Zigbee transceiver and temperature, humidity, air pressure, light and vibration sensors.

### 3.1 Hardware

ANTS architecture also includes our own hardware support. The system comprises four different hardware designs (codenamed from H1 to H4) growing in complexity depending their usability needs [Section 3.3]. This approach provides our system with the necessary *adaptability* for different SN requirements. Thus, while the lower rank devices (H1 & H2) will include less processing capacity, small memory sizes and primitive sensors, higher level nodes (H3 & H4) will integrate 32 bit microprocessors and bigger flash memories together with more complex sensors for high level applications. Furthermore, our designs include the 802.11.5.4 standard for radio communication, used in the ZigBee specification and offering promising reductions in power consumption and memory usage. Simplest nodes aim thus to sensor readings report and routing, while the higher level nodes role is for functionalities such as base station, cluster heads and localization anchors. Fig. 2 displays a prototype of an ANTS H2 outdoor node.

### 3.2 ANTS Operating System

ANTS Operating System (ANTS EOS) [8] is the core of our architecture and coordinates the structural design to provide evolvability services. ANTS EOS is a multi-threaded operating system offering two kind of threads (shared-stack and self-stack) that contribute to enhance the capabilities needed for a sensor network OS. These capabilities include, amongst others, a strong concurrency model, small footprint, low power consumption, robust operation and collaborative and distributed processing. ANTS EOS also includes other advanced features , such as a flexible Hardware Abstraction Layer (i.e. to accommodate different hardware nodes), a POSIX-like API set and an efficient message handling engine valid for both local and remote communication. Fig. 3 presents the ANTS EOS architecture.

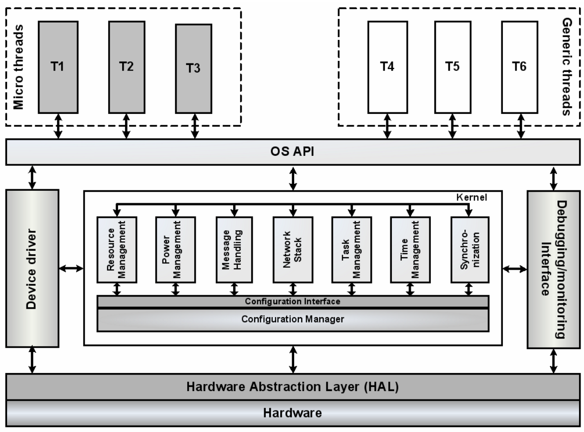


**Fig. 3.** ANTS EOS Architecture

The base of ANTS EOS evolvability is a modular design (implementing *modularity*) comprised of well defined modules that make use of a provided interface for upgrading processes. Capable of offering both kernel and user level upgrades, we foresee a dependable OS architecture, enforced by middleware, monitoring activities and dynamic updates able to take place remotely and without endangering the kernel or any other system functionalities (implementing *upgradability* and *dependability*).

### 3.3 Network Architecture

ANTS builds a two-tier, two-dimensional network architecture (NA) for optimum node communication, whose different capable nodes and different purpose network levels assure the efficiency needed for such restricted systems as sensor networks are.

On one hand, the two-tier NA is composed by two kinds of sensor nodes distinguishable by their hardware capabilities and, hence, by their potential functionalities. Together with the standard sensor network devices (micro nodes), ANTS includes more complex and powerful devices whose special resources (i.e. GPS, high bandwidth radio) make them suitable for specific functionalities such as localization anchors, synchronization cluster heads or interoperable gateways (macro nodes). This approach offers the desired *scalability* and *interoperability* needs described previously.

On the other hand, the need for specific sensor application services builds a two-dimensional NA in which the transport domain is complemented with an additional context (application) domain for exclusive context-aware services. This way, ANTS defines the existence of an overlay network on top of the transports sensor network, which using explicit network protocols (i.e. location aimed routing protocols, [Section 3.4]) can offer concrete services (i.e. Context-Awareness) out of the limitations imposed by the standard transport layer (see Fig. 4 for an example on the ANTS Network Architecture)

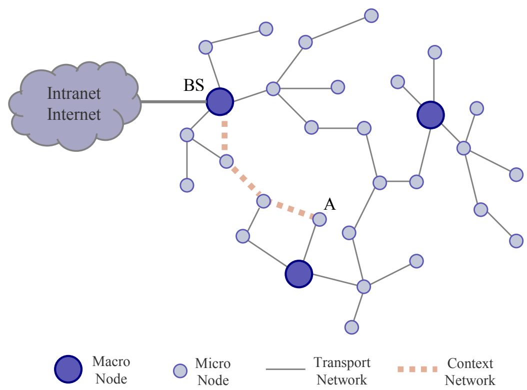


**Fig. 4.** ANTS Network Architecture example

### 3.4 Communication Protocols

ANTS develops several lightweight communication protocols that efficiently deal with delay and power consumption problems applying the evolvability concept. Table 2 shows their main characteristics. Currently we have 3 routing protocols and one mobility schema while are able to provide *scalability* (with the number of nodes) and *adaptability* & *dependability* (by supporting death of nodes and mobility)

**Table 2 .** Summary of System Evolvability requirements

| Protocol Name | Main characteristics |
|---|---|
| PAD [4]<br>(Power Aware Data-centric) | -Enhanced MEPG (Minimum Energy Path Graph)<br>-Able to provide mobility and self-healing<br>-Hop count and power consumption as metrics<br>-Minimizes packet delivery by being fully triggered<br>-Supports adding or removing of nodes |
| PAC [9]<br>(Power Aware Chain) | -Chain-based routing scheme<br>-Calculates transm. costs from receiving signal strength.<br>-Power-aware leader node election & better net. lifetime |
| PPVR [13]<br>(Power-aware Position Vector Routing) | -Greedy approach to minimize flooding overhead<br>-On-demand route discovery<br>-Effectively avoids out-of-range communication areas<br>-High successful rate of packet delivery. |
| SUMMA [7]<br>(Sub-network Mobility support with Multi-channel Assignment) | -Temporal packet routing to mobile attached sub-networks<br>-Gateway election & gateway data aggregation<br>-Robust interconnection and longer life times<br>-Multi-channel for interference and packet collision. |

### 3.5 Localization

ANTS also implements a localization algorithm which is based both on measured distances and hop information obtained by the use of position aware anchors. Para-LDL-EI (Parametric Learning-based Distance Localization with Evolution Improvement) [5] supports position information search of new nodes by taking profit of past network information and causing extremely low overhead. Para-LDL-EI provides the capability for new sensor nodes to obtain automatically its position without the need to run the localization algorithm again on live nodes. It shows excellent results in up to 50% of new deployed devices and, thus, presents promising results to support efficiently multiple generation sensor networks. The support of birth and death of nodes implements *dependability, adaptability* and *scalability*

### 3.6 Time Synchronization

Maintaining accurate time information in the SN does not only provide meaningful information, but also combines the system with our real physical world, allowing, for example, savings in energy or prevention of redundant information. Local clocks of inexpensive devices such as sensor network nodes are inherently inaccurate and prone to deviations of up to several seconds per week. To maintain network requirements, periodical synchronizations of sensor nodes are required, but problems with specifying reference clocks and dealing with network time forwarding inaccuracies increasing with number of hops arise. We propose a clustering based synchronization architecture in which higher level High Precision Nodes (HPN), with accurate timing information and less frequent time synchronization needs, synchronize periodically with lower level Low Precision Nodes (LPN). Our algorithm is capable of building synchronized sensor networks from a single cluster-head reference clock, transmitting its timing information to other cluster heads and defining minimum spanning trees in cluster areas for least hop count and synchronization error. Fig. 5 shows an example of sensor field clustering, where one of the cluster is detailed with cluster-level synchronization.

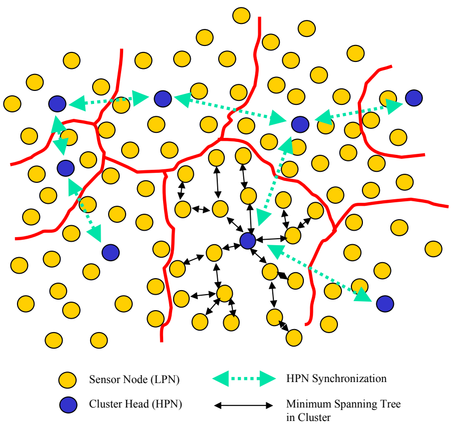


**Fig. 5.** Cluster-bases synchronization scheme in ANTS

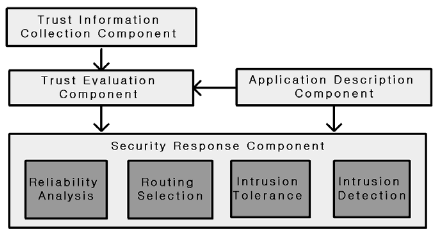


**Fig. 6.** ANTS Security Framework

### 3.7 Security

Existing approaches to SN security, which are mostly focused on cryptographic or multiple-path prevention schemes, have the problem that they just satisfy a part of the security requirement obviating other necessary concerns such as intrusion detection and certain key management techniques. We propose a trust evaluation based security framework for SN [12], which effective decisions on security scheme selection are based on an abstract node behavior coming from the network communication packets. Incoming packets are analyzed and their characteristics mapped to trust evaluation parameters, which will be computed locally or sent to the base station in order to build global and local trust relationships. Then the SN, considering all these trust values and relationships, will be easily able to make effective decisions in areas such as routing taking into account security concerns. This way we pretend to achieve the best combination of security level, performance, robustness, efficiency and deployment cost for SN. Fig. 6 presents a basic block diagram of the ANTS security framework.

By computing new trust values dependent on incoming packets our security framework achieves *adaptability*. Additionally, by allowing the introduction of new security values at application level, *scalability* and *modularity* are realized, while *dependability* is accomplished by supporting activity values for dead nodes.

## 4 ANTS Test-Beds

The ANTS team has developed two different application platforms as test-beds for our work: ANTS Smart Home and ANTS Surveillance. A graphical representation of the ANTS Surveillance test-bed is shown at Fig. 7: A helicopter deploys micro and macro sensors nodes in a target area aimed to detect the presence and movement of vehicles. The SN, aerial vehicles and other devices connect via an AODV (Ad-hoc On-demand Distance Vector) based network, forwarding the information and obtaining other services such as accurate GPS information (DGPS station).

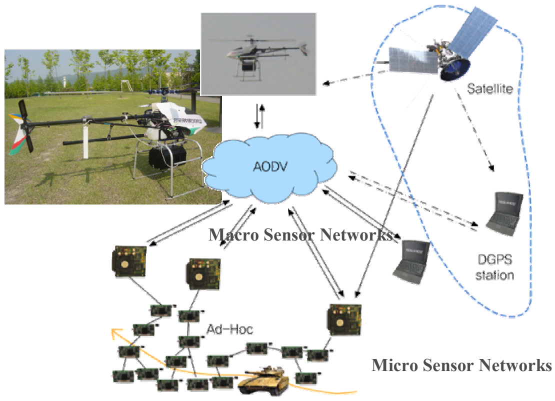


**Fig. 7.** ANTS Surveillance application platform

## 5 Conclusions

We have presented the concept of evolvability, and how the new emerging WSN technologies will need to apply it to fulfill the needs for their future prospected applications. Our particular project, ANTS, collects these ideas and builds a complete architecture distinguishable by its adaptability and flexibility, becoming the first WSN system to truly evolve with its environment and its changing needs.

## 6 Acknowledgements

We would like to thank: from ICU, *Mr. Sungjin Ahn*, *Mr. Bui Duy Bach*, *Mr. Seungki Hong, Ms. Junghyun Kim, Mr. Hyunhak Kim, Mr. Sangsoo Lee, Mr. Jihoon Park, Mr. Noseong Park, Mr. Long Minh Pham, Ms. Do Thu Thuy, Mr. Hyungjoo Song* and *Ms. Zhiying Yao*; from ITRC *Prof. Joongsoo Ma*; from Samsung *Mr. SeungRyong Park* and *Mr. K.S Chang*, and from ETRI *Dr. J.S. Jang, Dr. Jaedoo Heo* and *Mr. S. Park*.

## References


1. A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler and J. Anderson: Wireless Sensor Networks for Habitat Monitoring, WSNA'02, September 28, 2002, Atlanta, Georgia, USA.
2. D. Wang, E. Arens, T. Webster and M. Shi: How The Number And Placement Of Sensors Controlling Room Air Distribution Systems Affect Energy Use And Comfort, Center for Environmental Design Research, University of California, Berkeley.
3. J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler and K. Pister: System Architecture Directions for Networked Sensors, ASPLOS IX, November 2000, Cambridge, MA, USA
4. N. Park, D. Kim, Y. Doh, S. Lee and J. Kim: Power Aware Data-centric Routing Protocol for Sensor Networks, Submitted to SCCI'05
5. D. Bach and D. Kim: A Localization Algorithm Extension for The Evolvable Sensor Network, PDCS 2004, Cambridge, MA, USA
6. M. Srivastava, R. Muntz, M. Potkonjak: Smart Kindergarten: Sensor-based Wireless Networks for Smart Developmental Problem-solving Environments, SIGMOBILE 7/01, Italy
7. J. Park, D. Kim: SUMMA: Sub-network Mobility support using Muli-channel Assignment in wireless sensor networks, Master Thesis, School Engineering, ICU 2005
8. T. Do, D. Kim, T. Sanchez, H. Kim, S. Hong, M. Pham, K. Lee, S. Park: An Evolvable Operating System for Wireless Sensor Networks, IEHSC, Singapore, May 10-13, 2005.
9. M. Pham, D. Kim, Y. Doh, S. Yoo: Power Aware Chain Routing Protocol for Data Gathering in Sensor Networks, ISSNIP 2004, , Australia, Dec. 14-17, 2004.
10. H. Song, D. Kim: Sensor Network Management System using UPnP, KISS Fall Conference, Oct. 2004.
11. Victor Shnayder et all.: Sensor Network for medical care, Technical Report, Harvard University, 2005
12. Z. Yao, D. Kim, I. Lee, K. Kim, J. Jang: A Security Framework with Trust Management for Sensor Networks, IEEE/CREATE-NET SecQoS 2005, Greece , September 9, 2005
13. S. Lee, D. Kim, S. Ahn, N. Park, " Power-aware Position Vector Routing for Wireless Sensor Networks," To appear in USN'2005, Nagasaki, Japan, 6-9 December 2005