Reconfigurable Wireless Sensor Networks
New Adaptive Dynamic Solutions for Flexible Architectures

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Abstract: This paper deals with reconfigurable wireless sensor networks *RWSN* that should be adapted to their environment under user and energy constraints. A *RWSN* is assumed to be composed of a set of communicating nodes such that each one executes reconfigurable software tasks to control local sensors. We propose three reconfiguration forms to adapt a *RWSN*: (a) software reconfiguration allowing the addition/ removal/ update of tasks, (b) hardware reconfiguration allowing the activation/deactivation of nodes, (c) protocol reconfiguration allowing the modification of routing protocols between nodes. We propose a zone-based multi-agent architecture for *RWSN* where a communication protocol is well-defined to optimize distributed reconfigurations. Each agent of this architecture is modeled by nested state machines in order to control the problem complexity. The paper's contribution is applied to a case study that we simulate to show the originality of this new architecture.

1 INTRODUCTION

Wireless Sensor Networks (to be denoted by *WSN*) become today an important established technology for a large number of applications (pollution prevention (Vikram Guptay and Tovary, 2011), agriculture (Wang, 2010), military, structures and buildings health, etc). *WSNs* usually consist of many small devices called sensor nodes. Each node is able to allow local control processing and communications with remote nodes under real-time and energy constraints. Wireless Sensor Networks can be homogeneous (sensor nodes are of the same nature) or heterogeneous (with different types of nodes) (R.Saravanakumar, 2011). We are interested in this paper in homogeneous *WSN*. Several related works such as (Hnin Yu Shwe and Kumar, 2013), (Mahalik, 2009) describe the wireless sensor network (*WSN*) as a system of spatially distributed sensor nodes that collect important information in the target environment. Each sensor node has limited computation capacity, local memory, power supply (Swamy, 2003) and communication link. Each directed link connects two neighboring nodes through a network (T.-S. Chen and Sheu, 2000). The most generic model for a *WSN* is based on the data gathering (Jiping Xiong and Chen, 2013) and communication capabilities of sensors. Nowadays, *WSN* migrate to an auto-programming technology which is based on intelligent sensor networking infrastructures (Vikram Guptay and Tovary, 2011). The system can change its behavior at run-time, it is what we call a reconfigurable system. Two reconfiguration policies could be identified: static (offline: by stopping the *WSN* to make required modifications and restart it) or dynamic (online: by changing the network structures during its execution) (R.Saravanakumar, 2011). In the second case, we have also two kinds of reconfiguration: manual (executed by users) and automatic (executed by agents). The researchers define the *RWSN* (Reconfigurable *WSN*) as an adaptive *WSN*. The reconfiguration is any operation that redirects data flows when we change the state of source or destination nodes. The reconfiguration can also add/remove one/more physical elements of the network by activating/deactivating them. The reconfiguration touches first the material (allowing the activation/deactivation of nodes), second the software (allowing the reconfiguration of tasks) and third the communication protocols (allowing the adaptation of routing protocols between nodes). Many projects deal with *RWSN* such as *WASAN* (Kindratenko1 and Pointer, 2005), *ReWINS* (Harish Ramamurthy, 2005), *TWIST* project (Vlado Handziski, 2005). This definition touches one or two reconfiguration types (hardware, software or protocol) but these works do not mix all of them. Our

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problem consists in the application of these three reconfiguration types: what is the gain that we can get by using any hardware reconfiguration, or software reconfiguration or also the protocol reconfiguration? If we reduce the communication by applying reconfiguration scenarios, can we win in term of energy?

We try in this paper to answer these questions by defining three forms of reconfiguration for low power *RWSNs*. We define a new zone-based multi-agent architecture for *RWSN* where a communication protocol is well-defined for useful distributed reconfigurations. We decompose the *RWSN* to a set of zones where each one gathers a number of nodes. The radius of each zone is a parameter to be defined by users according to several characteristics of the followed technology. We define a Controller Agent (*CrA*) that handles the reconfiguration strategies of the whole network, and assign a Zone Agent for each zone (*ZA*) to control the local reconfiguration scenarios. Each node of a particular zone is controlled by a Slave Agent (*SA*) that monitors the local reconfiguration scenarios inside the node. This original multi-agent architecture combines all possible reconfiguration forms to be adapted for the environment where we minimize the energy consumption. This adaptive architecture is modeled by nested state machines in order to control the specification complexity. With our solution, we gain in term of energy to be consumed by each node and the number of exchanged messages between nodes in the network. This architecture supports the delegation between agents and controls the complexity by providing hierarchical structure of *RWSN*. We apply and simulate the paper's contribution to a case study to be assumed as a running example, and compare our results to some related works in order to show the originality of this architecture.

The paper is organized as follows: after introduction and background, Section 3 presents our position between related works. Section 4 proposes a new definition of *RWSN* to be explained on a case study. The multi-agent architecture of the *RWSN* is proposed in Section 5. Section 6 presents the coordination protocol between different agents. The simulation and evaluation of the paper's contribution is provided in Section 7 before concluding the paper in Section 8.

2 BACKGROUND

We briefly present the formalism of finite state machines to be used in the following for the modelling of *RWSN*. Finite State Machine (*FSM*) is an abstract machine that can be in one of finite number of states. It changes the behavior from a state to another by firing a transition in response to particular event. A *FSM* is an efficient way to specify constraints of the overall behavior of a system (Samek, 2003). A classic form of a *FSM* is a direct graph with the following elements: $G=(Q, \Sigma, Z, \delta, q_0, F)$ where: (a) ***Vertices Q*** is a finite set of states (Q_1,Q_2,...,Q_i) such that each state (Q_i) models a system's behavior at an instant *t*, (b) ***Input symbols*** Σ is a finite collection of input symbols or designators. This part of graph represents the finite set of initial states, (c) ***Output symbols Z*** is a finite collection of output symbols or designators. This part of graph represents the final state of the system, (d) ***Edges*** δ represents transitions from one state to another as caused by input symbols, (e) ***Start state*** q_0 is the start state $q_0 \in Q$, (f) ***Accepting state(s) F***: $F \in Q$ is the set of accepting states. We define Nested State Machines as a set of *FSM* such that a state of one corresponds to another machine. This solution is useful for the modeling of a complex system where the information should be modeled on different hierarchical levels in order to control the complexity.

3 STATE OF THE ART

Today, several researches deal with *RWSN* where a reconfiguration can be applied in three levels: hardware, software and data routing (Bellis et al., 2005), (Jie CHEN and LUO, 2009). **Hardware reconfigurations** are defined in (Bellis et al., 2005) by adding *FPGA*-based intelligent modules to nodes. In (Kindratenko1 and Pointer, 2005), the wireless autonomous sensor and networks of actors (*WASAN*) define **hardware reconfigurations** as dynamic operations that model platforms of evaluation and assistance. To model well the **protocol reconfiguration**, the existence of reconfigurable interfaces is essential; Harish Ramamurthy in (Harish Ramamurthy, 2005) presents the *ReWINS* project (Reconfigurable Wireless Interface for Networking), to manage the reconfigurability thanks to a '*Central Control Unit*'. The Reconfigurable Wireless Sensor Network for Structural Health Monitoring (M. Bocca and Eriksson, 2009), is also another project of *RWSN*. This proposition has the possibility to reconfigure the parameters of the monitoring application (**software reconfiguration**), depending on the needs of the end-user operating at the sink node. To optimize the radio transmission of data and avoid interferences (**protocol reconfiguration**), each sink node establishes a reserved communication link with each of the sensor nodes. In (Vlado Handziski, 2005), the *TWIST* project (a scalable and flexible tested architecture for indoor deployment of wireless sensor networks) defines two reconfiguration forms: **software/ hardware**. This project uses the *USB* infrastructure for the **hardware reconfiguration** and the software one is controlled by a set of interfaces to be implemented on a station.

We note that all related works do not address all possible reconfiguration forms together that the current paper deals with: **software, hardware and protocol reconfigurations**. We propose a new zone-based multi-agent architecture for *RWSN*. Our proposition is original and different from all others since we treat all reconfiguration forms, control the complexity of modeling by using nested state machines and optimize the energy consumption as well as the exchanged messages between nodes thanks to the zone-based solution.

4 CONTRIBUTION: NEW SOLUTIONS FOR *RWSN*

4.1 *RWSN*: Definition

We define a reconfiguration scenario as any response to a request in order to adapt the system to its environment and to improve also its performance. We consider three kinds of reconfigurations: (i) software reconfiguration allowing the addition/removal and update of Os-tasks or data, (ii) hardware reconfiguration allowing the activation/deactivation of sensor nodes, (iii) protocol reconfiguration allowing the optimization/degradation of the protocol (e.g. addition/removal/update of messages to be exchanged between nodes as well as their routing paths). We denote in the following by a *RWSN*, a reconfigurable *WSN* that automatically modifies its software and/or hardware architecture and/or inter-nodes communication protocol. Contrary to all related works, a *RWSN* is defined as a dynamic reconfigurable *WSN*, that automatically modifies at run time the architecture as well as structure of the network. This modification can touch the material (e.g. sensors), the software (e.g. OS tasks) and the data routing. Note that the *TWIST* project (Vlado Handziski, 2005) does not address the protocol reconfiguration. The *ReWINS* project (Harish Ramamurthy, 2005) does not suppose the reconfiguration of WSN as a dynamic and automatic reconfiguration. In the current paper, we extend all related works and address all possible reconfiguration forms that can be applied at run time on *RWSN*.

4.2 *RWSN*: New Architecture

We give in the following some definitions that will be used in the following.

- *RWSN*: a set of *Nbz* zones and *S* stations. A station controls the whole network, whereas each zone is composed of *n* nodes such that each node gathers *m* hardware detectors to be controlled by software tasks. Note that a communication protocol is applied between nodes of a same or of different zones. We define *Nbz* = number of the zones in *WSN* and *Zi* as the zone number *i* of the network.
- *RWSN* zone: a geographical space to be defined by all the points included in the area of this zone. This zone is fixed by a radius to be defined by the *RWSN* designer.
- *RWSN* station: a supervisor in a *RWSN* to be characterized by: (i) A memory, that should be bigger than a node memory, (ii) A bandwidth, that represents the velocity of data transmission with nodes.
- Reconfigurable node: a device to be composed with others. It runs under energy, real-time and functional constraints. A node is characterized by: (i) An identifier *(ID)* which is unique in the zone, (ii) a set of *m* detectors *DTi (i =1,2,...,m)* where each sensor is modeled by two variables: the state (*Sd*: active or not), and the value to be detected *(Vd)*, (iii) a power unit represented by two batteries (we denote by *PwBi(t)* the current value of battery's charge and *PwBiMax* the maximum load), (iv) the router *(R)* that supports the communications with other nodes.
- Reconfigurable sensor: a detector that consumes energy to provide required services for the node. We suppose that it is controlled by a unique OS-Task.
- Reconfigurable protocol: a protocol that supports the communication between nodes. We assume it as reconfigurable since we suppose that messages can be added or removed at run-time. Table 1 describes the parameters of a routing table in each node in order to characterize each communication between them.

Table 1: Node routing table parameters.

ID	Node Identifier
ID_{Zone}	Zone Identifier
ID_{Dest}	Final Destination Node Identifier
ID_{Next}	Next Node Identifier in communication path (neighbor)
Time	Execution time for communication by a node

4.3 Reconfiguration Forms

We have three forms of reconfigurations:

4.3.1 Software Reconfiguration

Modifies the behaviors of nodes at run time. The modification is made on the software architecture by: (i) adding (or removing) OS-tasks to be executed in nodes, (ii) modifying their scheduling, (iii) modifying the used data by tasks.

4.3.2 Hardware Reconfiguration

This kind of hardware reconfiguration consists of: (i) activation/deactivation of detectors, (ii) activation/deactivation of nodes. The deactivation of all detectors in a node implies its deactivation. In fact, activating only one detector in a node results in its activation.

4.3.3 Protocol Reconfiguration

Consists in modifying the data routing when software and hardware reconfigurations are applied at run-time.

4.4 Case Study

We propose as a running example a *RWSN* to be denoted by *Sys*. It is composed of 3 zones *(Z1, Z2, Z3)* where each one Z_i is composed of three nodes. These three zones are supervised by a station *(S)*. Each node $Nz_j, (j = 1..9)$ is characterized by two detectors, two batteries and a router (R_j). Each detector $DT_m, (m = 1 \; or \; 2)$ can detect the temperature (to be denoted by DT_1) and the humidity of the environment (to be denoted by DT_2). It is characterized by a state (*Sd*: {activate= 1, deactivate= 0}), and the detected value (*Vd*). The two batteries are denoted by $B_k(k = 1 \; or \; 2)$. Each battery B_k is characterized by a current value of load $(PwB_{k,j})$ and a value of maximum load $(PwBMax_{k,j})$. We suppose initially, that Nz_5 executes only DT_1(see Figure 1).

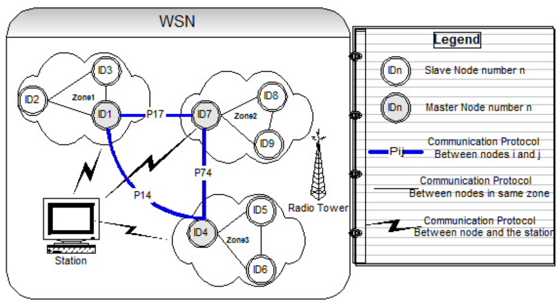

WSN
ID3
ID2
Zone1
ID1
P17
ID7
Zone2
ID8
ID9
P74
P14
ID5
Radio Tower
ID4
Zone3
ID6
Station
Legend
IDn Slave Node number n
IDn Master Node number n
Pij Communication Protocol Between nodes i and j
Communication Protocol Between nodes in same zone
Communication Protocol Between node and the station

Figure 1: A Case Study of an WSN.

4.4.1 Software Reconfiguration

We define the following three tasks {*T1,T2,T3*}: (i) *T1*: controls the temperature and detects signal when it is higher than 45 °C. (ii) *T2*: reduces the threshold from 45 °C to 30 °C. This task can be used for any detection of fire. (iii) *T3*: controls the humidity of the environment. We define 3 software reconfigurations: {*SR1, SR2, SR3*}. (a) *SR1*: a reconfiguration that allows the addition of *(T1)* to each node in a summer day; (b) *SR2*: is applied to each summer night to remove the task *(T1)* and to add *(T2)*. (c) *SR3*: updates the threshold to be taken by *(T3)*.

4.4.2 Hardware Reconfiguration

In order to minimize the dissipated energy, we apply hardware reconfigurations {*HR1, HR2, HR3*} on 3 sensor nodes (*Nz1* from *Z1*, *Nz5* from *Z2*, *Nz9* from *Z3*) (i) *HR1*: deactivates *Nz1* from *Z1* by deactivating *(DT_1(1) of Nz1* and *DT_2(1) of Nz1*), (ii) *HR2*: deactivates *DT_1(5)* for the node *Nz5*, (iii) *HR3*: activates *Nz9* from *Z3* by activating *DT_2(9) of Nz9*. The hardware reconfiguration, in this case, can change the routing information between nodes. The link of communication between *Nz1* and its neighbors is cut (the same case as *Nz5*). By using *HR3*, *(Nz9)* can be connected to its neighbors (see the modification from Figure 2 to Figure 3).

4.4.3 Protocol Reconfiguration

If we apply *HR1, HR2* and *HR3* (deactivation of *Nz1, Nz5* and activation of *Nz9*), the routing tables of *(Nz1, Nz5, Nz9)* will be changed from Table 2 to Table 3. In this case the reconfiguration of protocol eliminates 3 communication links between nodes (*Nz1, Nz5*), and adds 2 other links to (*Nz9*).

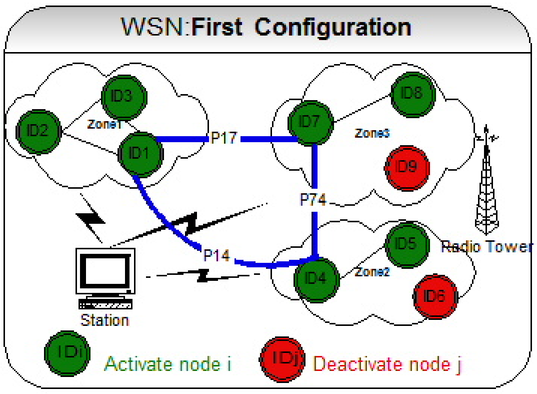


Figure 2: First configuration of (*WSN*).

Table 2: First routing table parameters.

	Nz1	Nz5	Nz9
State	Activate	Activate	Deactivate
ID	ID1	ID5	ID9
ID$_{Zone}$	Z1	Z2	Z3
ID$_{Dest}$	ID7	ID1	
ID$_{Next}$	ID2, ID3	ID4	
Time	0.02s	0.01s	

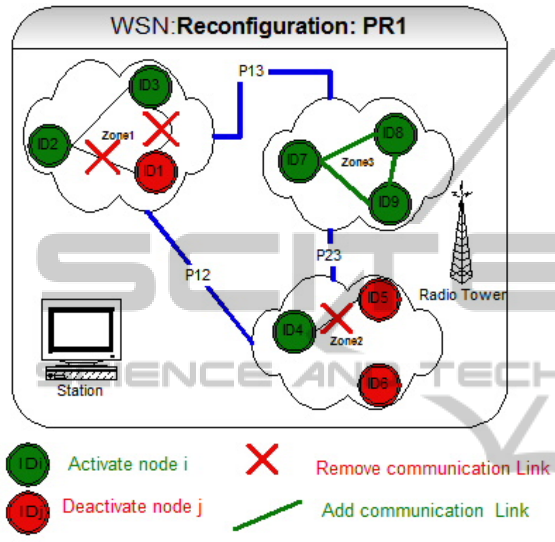


Figure 3: Protocol reconfiguration of (*WSN*).

Table 3: Second routing table parameters.

	Nz1	Nz5	Nz9
State	Deactivate	Deactivate	Activate
ID	ID1	ID5	ID9
ID$_{Zone}$	Z1	Z2	Z3
ID$_{Dest}$	ID7	ID9	ID2
ID$_{Next}$	ID2 Or ID3	ID4	ID7 Or ID8
Time			0.02s

5 NEW MULTI-AGENT ARCHITECTURE FOR (*RWSN*)

5.1 Motivation

To handle all cited forms, we propose a multi-agent architecture for RWSN. This architecture is composed of a Controller Agent (*CrA*) that controls the whole architecture, a Zone Agent (*ZA*) to be affected to each zone in order to control its nodes, and a Slave Agent (*SA*) that controls each node of any zone. All these agents handle the different reconfiguration forms that we described above. In order to control the complexity, each agent has a hierarchical architecture to be modeled by Nested State Machines. We show in Figure 4 this new multi-agent architecture of *RWSN*. We model the multi-agent architecture for RWSN as a system to be composed by one *CrA*, a set of (*ZA*) and a set of (*SA*): Sys={CrA, φZA, φSA};
φZA= set of all Zones Agents;
φSA = set of all Slaves Agents;
In one Zone = {ZA, φSA}

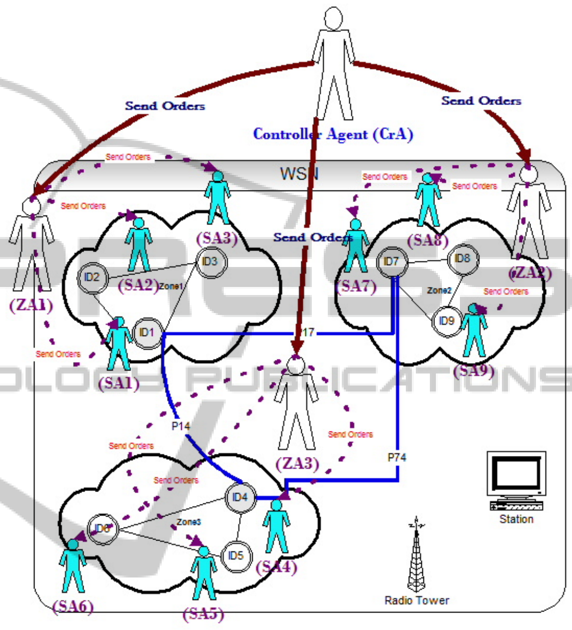


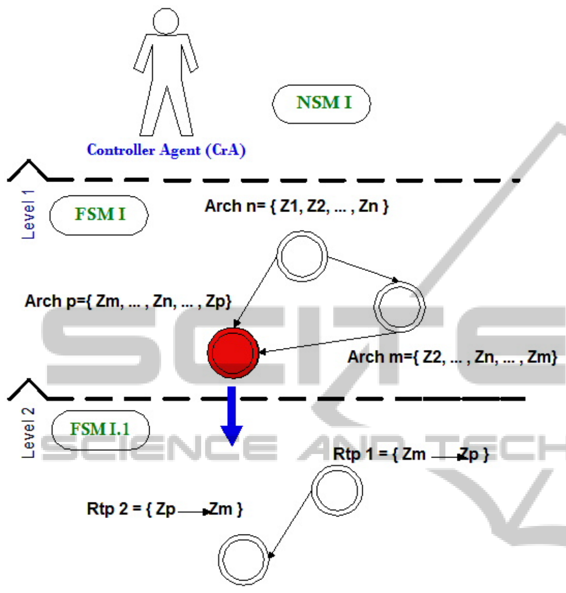
Figure 4: Multi-Agent Architecture for *RWSN*.

We denote in the following by *SetZi* the set of all master and slave nodes in the zone *i*. Let we assume a node *Nzji* of the zone *i*, it is denoted by *Snji* if it is the *j*th slave node of this zone and by *Mnji* if it is the *j* master one.

5.2 Formalization of *RWSN*

5.2.1 Controller Agent (*CrA*) Logic

For the modeling of this agent, we propose two levels: (i) **First Reconfiguration Level: *CrA* Architecture:** The (*CrA*) defines in this level the set of active and deactive zones under well-defined conditions at a particular time. This level will be modeled latter with the State Machine (*FSM I*). (ii) **Second Reconfiguration Level: *CrA* Data Flows:** This level describes the different flows of data to be exchanged between the active zones that we define in level 1. For each state of (*FSM I*) that models level 1, we define in the current second level a particular state machine that defines all the possible data flows. A state of this State Machine defines a particular reconfiguration scenario that changes the routing policy software between zones. In Figure 5, the red state of (*FSM I*) defines a subset of active zones and corresponds to the state machine (*FSM I.1*) in level 2. The state *Rtp 1* represents a first routing solution between these zones and *Rtp 2* represents another routing solution.



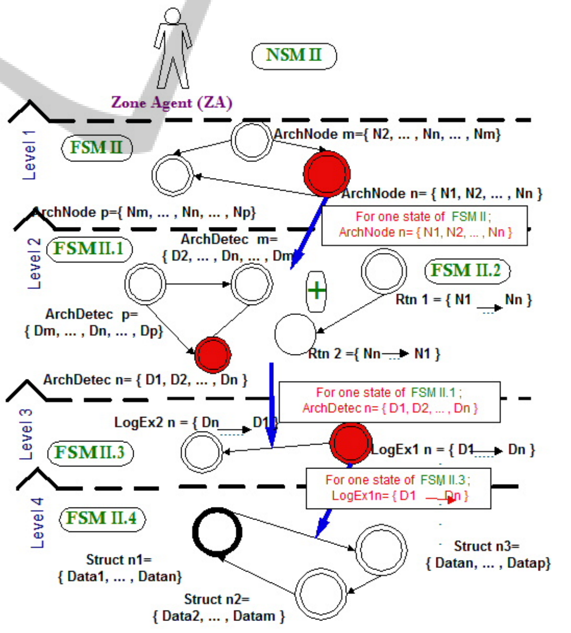
NSM I
Controller Agent (CrA)
Level 1
FSM I
Arch n= { Z1, Z2, ... , Zn }
Arch p={ Zm, ... , Zn, ... , Zp}
Arch m={ Z2, ... , Zn, ... , Zm}
Level 2
FSM I.1
Rtp 1 = { Zm → Zp }
Rtp 2 = { Zp → Zm }

Figure 5: Controller Agent architecture.

5.2.2 Zone Agent (*ZA*) Logic

We propose four levels for this agent: (i) **first reconfiguration level: *ZA* Architecture:** we describe in this level the different active and deactive nodes under well-defined conditions at a particular time. This level is characterized by a superset of nodes such that any reconfiguration scenario corresponds to the activation of a subset, (ii) **second reconfiguration level: *ZA* Data Flows/ Detectors:** the second level of the Zone Agent (*ZA*) defines the set of detectors that should be active in each node under well-defined conditions at a particular time. This second level defines also the different data flows that can be followed to exchange data between the active nodes of the zone. The activation of detectors as well as the definition of reconfiguration data flows belong to the same level since they are depending in logic, (iii) **third reconfiguration level: *ZA* Scheduling:** this level defines the different reconfigurable scheduling of OS-tasks that control active detectors in active nodes under well-defined condition at a particular time, (iv) **fourth reconfiguration level: *ZA* Data value:** This level defines the different values and structure of data to be used by the OS-tasks of active nodes under well-defined conditions at a particular time.

To handle the complexity of the problem, we use nested state machines to model the Zone Agent. In Figure 6, the red state *ArchNode n* defines the different active nodes of a zone at a particular time *t* under well-defined conditions, this state corresponds to two state machines *FSM II.1* and *FSM II.2* in level 2. *FSM II.1* defines in this zone all possible activations of detectors. *FSM II.2* represents the different routing solutions between active nodes in this zone. The red state *ArchDetect n* defines under well-defined conditions the different detectors which should be active in active nodes of the zone. *Rtn 1* defines a particular solution to exchange data between active nodes in a zone. Two states of these state machines of level 2 define a particular state machine in level 3 where a state defines a particular scheduling of active tasks. The red state *LogEx1 n* defines the execution logic of tasks and defines a new state machine *FSM II.4* in level 4. Each state in *FSM II.4* defines particular values and structures of data to be used by actives tasks. Thanks to this solution we can cover all possible reconfiguration forms while controlling the complexity of the problem.



NSM II
Zone Agent (ZA)
Level 1
FSM II
ArchNode m={ N2, ... , Nn, ... , Nm}
ArchNode n= { N1, N2, ... , Nn }
ArchNode p={ Nm, ... , Nn, ... , Np}
For one state of FSM II ; ArchNode n= { N1, N2, ... , Nn }
Level 2
FSM II.1
ArchDetec m= { D2, ... , Dn, ... , Dm}
ArchDetec p= { Dm, ... , Dn, ... , Dp}
FSM II.2
Rtn 1 = { N1 → Nn }
Rtn 2 ={ Nn → N1 }
ArchDetec n= { D1, D2, ... , Dn }
For one state of FSM II.1 ; ArchDetec n= { D1, D2, ... , Dn }
Level 3
FSM II.3
LogEx2 n = { Dn → D1 }
LogEx1 n = { D1 → Dn }
For one state of FSM II.3 ; LogEx1n= { D1 → Dn }
Level 4
FSM II.4
Struct n1= { Data1, ... , Datan}
Struct n2= { Data2, ... , Datam }
Struct n3= { Datan, ... , Datap}

Figure 6: Zone Agent architecture.

5.2.3 Slave Agent (*SA*) Logic

This agent executes the reconfiguration strategies to be defined by *CrA* and *ZA*.
Note Finally that to gain in terms of energy for example, each Zone Agent (*ZA*) controls at run-time the load in the batteries of each slave before applying required reconfiguration scenarios that can possibly re-

move tasks or also deactivate nodes in order to preserve power as much as possible. We note also that we are interested in the architecture of *RWSN* without detailing the technical solutions to add/remove tasks or activate/deactivate nodes. We are not interested also in the real-time scheduling of tasks that will be in another paper. The contribution of the current paper is dealing with the architecture of *RWSN* to address all possible reconfiguration forms while controlling the complexity of the problem.

5.3 Modeling of *RWSN*

5.3.1 Controller Agent (*CrA*) Model

We model the two levels of (*CrA*) by the following state machines.

-First modeling level: *CrA* Architecture:

$GC_1=(Qc,\ \delta c,\ qc_0)$ where:

(a) **Vertices Qc**: set of states such that each state corresponds to active zones at a particular time $(Qc_1, Qc_2, ..., Qc_i)$. We denote by $Qc_i=(MN_1, MN_2, ..., MN_n)$ the set of active master nodes of *RWSN*, (b) **Edges δc**: activation or deactivation of master nodes, (c) **Start state** qc_0: a first architecture which defines the default active zones.

-Second modeling level: *CrA* Data flows: For each state $Qc_i \in$ Qc in GC1, we define:

$GC_2=(Qp,\ \delta p,\ qp_0)$ where:

(a) **Vertices Qp**: set of states where each one represents a particular routing solution between active zones $(Qp_{i1}, Qp_{i2}, ..., Qp_{ij})$. (b) **Edges δp**: the modification of data flows between active zones. (c) **Start state** qp_0: the data flows between the default active zones.

Figure 7 describes (*FSM I*) and (*FSM I.1*) that model level 1 and level 2 for *CrA*:

5.3.2 Zone Agent (*ZA*) Model

We define the following nested state machines of each (*ZA*).

First modeling level: *ZA* Architecture:

$GD_1=(Qd,\ \delta d,\ qd_0)$ where:

(a)**Vertices Qd**: set of states such that each one represents a subset of active nodes in a zone, $Qd_i=(N_1, N_2, ..., N_i)$, (c)**Edges δd**: activation/deactivation of nodes in a zone, (d)**Start state** qd_0: default list of nodes in a zone.

Second modeling level: *ZA* Data flows/detectors: For each state Qd_i of GD_1, we define two state machines GN_2 and GN'_2:

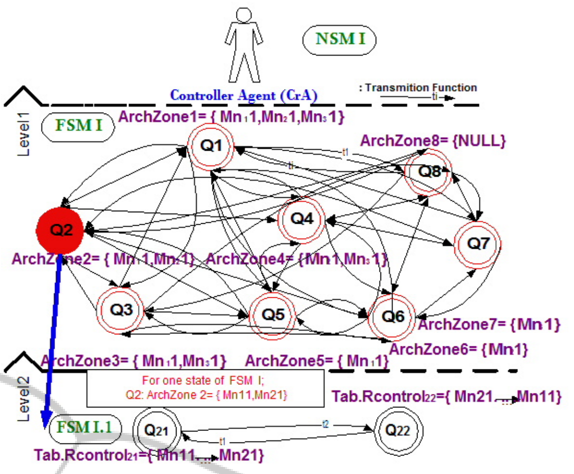


Figure 7: CrA Running Example.

$GN_2=(Qn,\ \delta n,\ qn_0)$ where:

(a)**Vertices Qn**: set of states where each one represents a particular routing solution between active nodes of a zone, (b)**Edges δn**: modification of data flows between active nodes, (c)**Start state** qn_0: data flows between default active nodes Qn_{i1}.

$GN'_2=(Qn',\ \delta n',\ qn'_0,)$ where:

(a)**Vertices Qn'**: set of states such that each one represents detectors to be active at a particular time ,$(Qn'_{i1}, Qn'_{i2}, ..., Qn'_{ij})$. We can define $Qn'_{ij}=(Detc_1, Detc_2, ..., Detc_n)$ as a set of active detectors, (b)**Edges δn'**: activation/deactivation of detectors, (c)**Start state** qn'_0: the default list of detectors in a node: Qn'_{i1}.

Third modeling level: *ZA* Scheduling: For each state Qn_{ij} in GN_2 and Qn'_{ij} in GN'_2, we define:

$GE_3=(Qe,\ \delta e,\ qe_0)$ where:

(a)**Vertices Qe**: set of states such that each one represents the scheduling of OS-tasks implementing active nodes in a zone. ,$(Q_{ij1}, Q_{ij2}, ..., Q_{ijk})$, (b)**Edges δe**: modification of the execution sense of detectors by respecting the dependence of the latter, (c)**Start state** qe_0: the default scheduling of OS-tasks Qe_{ij1}

Fourth modeling level: *ZA* Data value: For each state Qe_{ijk} in GE_3, we define:

$GS_4=(Qs,\ \delta s,\ qs_0)$ where:

(a)**Vertices Qs**: set of states where each state represents data structures and values to be used by active tasks, $(Q_{ijk1}, Q_{ijk2}, ..., Q_{ijkl})$, (b)**Edges δs**: modification of data structure or values, (c)**Start state** qs_0: the default data structures Q_{ijk1}.

Figure 8 defines the nested state machines that model *ZA1* of *Z1*. *FSM II* is a state machine that defines all possible activations of nodes in the zone, the red state Q52 corresponds to two state machines *FSM II.1* and *FSM II.2* in level 2. Q_{521} represents a particular data flow between active nodes in a zone. Q_{521} is a set of active detectors in a node. Both of the two states correspond to a particular state machine in level 3 . Q_{5212} represents a particular scheduling of OS-tasks that control active detectors in level 2. Q_{5212} corresponds to particular data structures *FSM II.4* in level 4, Q_{52121} corresponds to a particular data structures and values to be used by active nodes in this zone *Zone1*.

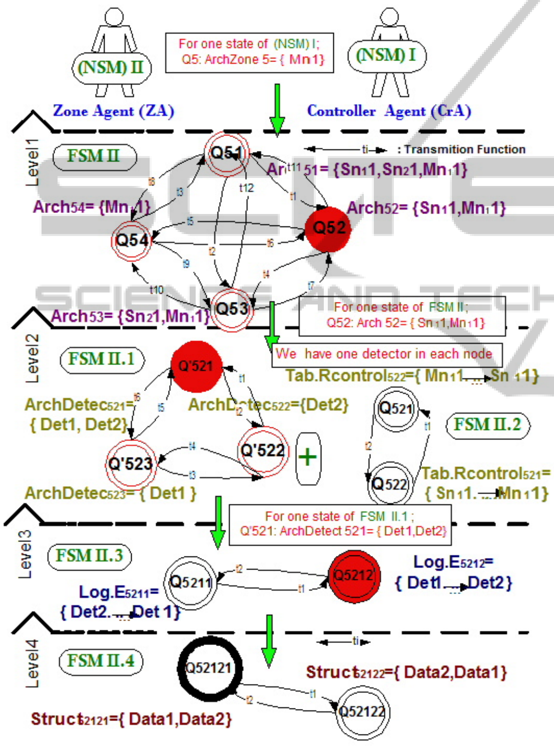

(NSM) II
For one state of (NSM) I; Q5: ArchZone 5={ Mn1}
(NSM) I
Zone Agent (ZA)
Controller Agent (CrA)
Level1
FSM II
Q54
Q52
Q54
Q53
Arch54={Mn1}
Arch52={Sn1,Mn1}
Arch53={Sn21,Mn1}
ti : Transmition Function
For one state of FSM II; Q52: Arch 52={ Sn1,Mn1}
We have one detector in each node
Tab.Rcontrol522={ Mn1...Sn1}
Level2
FSM II.1
Q'521
Q'522
Q'523
ArchDetec521={ Det1, Det2}
ArchDetec522={Det2}
ArchDetec523={ Det1 }
Q521
Q522
FSM II.2
Tab.Rcontrol521={ Sn1...Mn1}
For one state of FSM II.1 ; Q'521: ArchDetect 521={ Det1,Det2}
Level3
FSM II.3
Q5211
Q5212
Log.E5211={ Det2...Det 1}
Log.E5212={ Det1...Det2}
Level4
FSM II.4
Q52121
Q52122
Struct52122={ Data2,Data1}
Struct52121={ Data1,Data2}

Figure 8: Running Example for *ZA* Modeling.

5.3.3 Slave Agent Modeling (*SA*)

This agent executes directly the orders of the corresponding (*ZA*). Figure 9 shows the reaction of a slave agent in Zone1 when it receives an order from a corresponding Zone Agent.

6 COORDINATION PROTOCOL BETWEEN AGENTS

We propose a communication protocol between the different agents (*CrA*, *ZA*, *SA*) of this architecture. It is based on the following operation: (i) *CrA Algorithm*: the operation that links *CrA* to any *ZA*. (ii) *ZA*

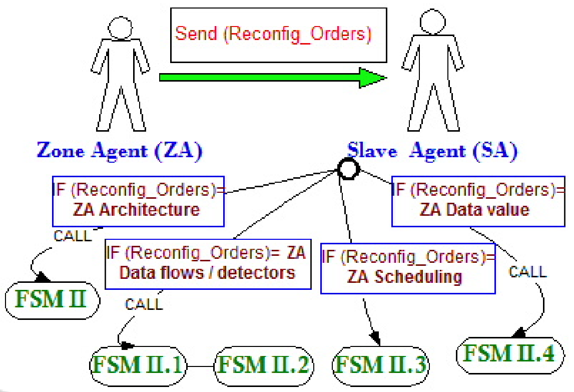

Send (Reconfig_Orders)
Zone Agent (ZA)
Slave Agent (SA)
IF (Reconfig_Orders)= ZA Architecture
IF (Reconfig_Orders)= ZA Data value
IF (Reconfig_Orders)= ZA Data flows / detectors
IF (Reconfig_Orders)= ZA Scheduling
CALL
CALL
CALL
FSM II
FSM II.1
FSM II.2
FSM II.3
FSM II.4

Figure 9: Running Example for SA Modeling.

Algorithm: the operation between any *ZA* and any corresponding *SA*. (iii) *Oper 1*: an operation allowing the activation/deactivation of nodes in a zone. (iv) *Oper2*: an operation allowing a modification of data flows in a zone (v) *Oper3*: an operation allowing the activation/deactivation of detectors in a node. (vi) *Oper4*: an operation allowing the modification of scheduling in a zone and (vii) *Oper5*: an operation allowing the modification of data structures or values in a zone.

CrA Algorithm: to apply a reconfiguration, *CrA* sends to any *ZA* an array containing the list of desired active zones with the new flow of data to be exchanged between them.

Algorithme 1 : CrA Algorithm

```
Z Zone; newArray(tabZoneActiv[nb]);
DS= Transmission Distance (threshold);
D(CrA,j)= $\alpha$, $j \neq CrA$;
D(i,j)=$\beta$ , $j \neq i$;
REPEAT
{Send new vector(activ_zones) to neighbors zones:
IF D(CrA,j) $\leq$ DS; Send (tabZoneActiv[nb], CrA, j);
FOR EACH dest j, find the next with dist_min to j;
IF D(i,j) $\leq$ DS; Send(tabZoneActiv[nb], j, i);
i+1; calculate(D(i,j));}
UNTIL D (i,j)= 0; source i = destination j;
Send(ProtoCommunic (AC, ZoneDest1, ..., ZoneDestj));
```

ZA Algorithm: Step-By-Step (ZA) sends to any (SA) a reconfiguration scenario.

Algorithme 2 : ZA Algorithm

```
We declare: VAR = orderReconfig(ZA, SA);
IF (VAR =1) Send (ReconficArchitecNode(), ZA, SA);
IF (VAR =2) Send (ReconfProtoCommNod(), ZA, SA);
IF (VAR =3) Send (ReconfArchiDetectors(), ZA, SA);
IF (VAR =4) Send (ReconfLogicExecDetec(), ZA, SA);
IF (VAR =5) Send (ReconficStructData(), ZA, SA);
IF (VAR =1) ⇒ Execute Oper 1;
We declare: Arch[]= new Array[nbNode];
FOR EACH $Z_i \in setZone^i=\{Z_1,Z_2,...,Z_i\}$;
FOR EACH $Nz_j(i)$
Arch[] = ReconficArchitecNode()
REPEAT IF (PwB → 0 ) ; $Sd(Nz_j(i))=0$;
Arch[IDj]=0;
IF $Vd(Nzj(i)) \geq$ threshold; Sd(Nzj(i))=1;
Arch[IDj]=1; j=j+1;
UNTIL j= nbNode;
RETURN Arch[]};
---------------------------------------------
IF (VAR =2) ⇒ Execute Oper 2;
ReconfProtoCommNodes(){
IF(N is an node address connected in zone)
{ Deliverdata (node, link); }
ELSE IF (The routing table contains a route for N)
{ Deliverdata (@nextnode, link); }
ELSE IF (There exists a default route )
{Deliverdata (DefaultLink);}
ELSE {Send(error-message);} }
---------------------------------------------
IF (VAR =3) ⇒ Execute Oper 3;
ArchDetector[]= new Array[nbDetector]();
FOR EACH $Nz_j(i)$
ArchDetector[]= ReconfArchiDetectors();
REPEAT IF $\forall$ $Sd(DT_k)=0$; $ArchDetector[ID_k]=0$;
IF $\exists$ $Sd(DT_k)=0$; $ArchDetector[ID_k]=1$;
IF $Vd(DT_k) \geq threshold; Sd(DT_k)=1$ ;
$ArchDetector[ID_k]=1$;
k=k+1;j=j+1; UNTIL k= nbDetector; j= nbNode;
RETURN ArchDetector[];
---------------------------------------------
IF (VAR =4) ⇒ Execute Oper 4;
ActiDetec[]= new Array[nbActiDetec]();
We declare: RandomStruct[] = new ActiDetec[]();
RandomStruct[]= ReconfLogicExecDetec()
FOR (k=0,k=j+1) REPEAT
RandomStruct[k]= RANDOM ( ActiDetec[i] );
UNTIL k= nbDetector;
RETURN RandomStruct[];
---------------------------------------------
IF (VAR =5) ⇒ Execute Oper 5;
We declare: DataStruc[]= new Array[nbData]();
We declare: RandomStruc[] = new DataStruc[]();
RandomStruc[]= ReconficStructData()
FOR (l=0,l=l+1) REPEAT
RandomStruc[l]= RANDOM ( DataStruc[l] );
UNTIL l= nbData;
RETURN RandomStruc[];
```

7 SIMULATION AND EVALUATION

In order to show the benefits of the paper's contribution, we apply a simulation of *RWSN*. We start with a theoretical simulation before presenting a practical one.

7.1 Theoretical Simulation

We propose a system (*Sys*) to be composed of 10 zones *(Z1...Z10)*, each one is composed of 100 nodes: one master node *(Mni)* and 99 slaves *(Snj)*, and a station *(S)* to control the whole *RWSN*. Each node *Nz(j)* in the same zone *Zi* is characterized by two sensors or detectors : DTn_j (n =1 or 2) to detect the temperature and the humidity of the environment. Each sensor node is equipped with a battery, thus the available energy is limited. Our system (*Sys*) is characterized as follows: (i) all the nodes *(Nzn)* are homogeneous in terms of battery and transmission range, (ii) an omnidirectional antenna is installed in each sensor node and the transmission range is defined in 15m *(DS)*, (iii) each node is identified by a unique identifier in the network, (iv) the data are transmitted without any delay, (v) the exchanged messages are with a constant size. To Apply the three forms of reconfiguration, we execute the following scenarios: (i) *(CrA)* sends the first reconfiguration to be applied: activation of all nodes (**Hardware reconfiguration**) and modification of temperature to be (45 °C) (**Software reconfiguration**), (ii) *(ZA)* of each zone receives this order and broadcasts it to each corresponding slave which applies this order, (iii) *(SA)* verifies the new routing table according to the recommendation of *ZA* (**Protocol reconfiguration**), (iv) All *(SA)* send the collected information in step by step to *(CrA)*. This scenario is described as follows:

Theoretical simulation

10 zones; CrA; DS=15m;

tabZoneActiv[10]=

Z1	Z2	Z3	Z4	Z5
Z6	Z7	Z8	Z9	Z10

tabDist[10]=

D1=D(CrA,Z1)=14m	D2=D(CrA,Z2)=13m
D3=D(CrA,Z3)=10m	D4=D(CrA,Z4)=14m
D5=D(CrA,Z5)=21m	D6=D(CrA,Z6)=26m
D7=D(CrA,Z7)=31m	D8=D(CrA,Z8)=34m
D9=D(CrA,Z9)=40m	D10=D(CrA,Z10)=42m

```
SEND STEP IF $Di \leq 15$, Di={1,...,10};
Send(tabZoneActiv[10], CrA, Z1);
Send(tabZoneActiv[10], CrA, Z2);
Send(tabZoneActiv[10], CrA, Z3);
Send(tabZoneActiv[10], CrA, Z4);
Send(ProtoCommunic(CrA, Z1, Z2, Z3, Z4));
END SEND STEP
CALCUL D(Zi,Zj); i={1,...,10}, j={5,...,10};
D(Zi,Zj)=Dj-Di;
IF $D(Zi,Zj) \leq DS$; Send(tabZoneActiv[10], Zi, Zj);
```

D(Z1,Z5)=	D5-D1	21-14=7m
D(Z1,Z6)=	D6-D1	26-14=12m
D(Z1,Z7)=	D7-D1	31-14=17m
D(Z1,Z8)=	D8-D1	34-14=20m
D(Z1,Z9)=	D9-D1	40-14=26m
D(Z1,10)=	D10-D1	42-14=28m

Send(tabZoneActiv[10], Z1, Z5, Z6);
Send(ProtoCommunic(Z1, Z5, Z6));
CALCUL *D(Zi,Zj); i={6,...,10}, j={7,...,10};*

D(Z6,Z7)=	D7-D6	31-26=5m
D(Z6,Z8)=	D8-D6	34-26=8m
D(Z6,Z9)=	D9-D6	40-26=14m
D(Z6,Z10)=	D10-D6	42-26=16m

Send(tabZoneActiv[10], Z6, Z7, Z8,Z9);
Send(ProtoCommunic(Z6, Z7, Z8,Z9));
CALCUL *D(Z9,Z10);*

D(Z9,Z10)=	D10-D9	40-42=2m

```
Send(tabZoneActiv[10], Z9, Z10);
Send(ProtCommunic( Z9, Z10);
FOR EACH $Z_i \in$ setZone;
(ZA) send to the (SA) an order of reconfig.
FOR EACH
$Nz_j(i)$; orderReconfig(ZA, SA) = 1;
VAR =1 $\Rightarrow$
Send (ReconficArchitecNode(), ZA, SA );
Arch[]= new Array[100];
Arch[] = ReconficArchitecNode()
REPEAT IF (PwB $\geq$ 0) ;
Sd($Nz_j(i)$)=1; Arch[IDj]=1;
j=j+1; UNTIL j= nbNode;
RETURN Arch[]};
New-node-archit $\Rightarrow$ orderReconfig(ZA, SA) = 2;
VAR =2 $\Rightarrow$ send ( ReconfProtoCommNodes() );
ReconfProtoCommNodes()
IF (N an address of node connected in a zone $Z_i$)
{ Deliverdata ($Nz_j(i)$, link);
ELSE IF ( $\exists$ route $\in$ routing table);
Deliverdata ($Nz_{j+1}(i)$, link);
send ( DataStructure$_j$(i)[], CrA);
```

To show the benefits of our contribution, we compare this work to the projects *TWIST* (Vlado Handziski, 2005) and *ReWINS* (Harish Ramamurthy, 2005): (i) we compute the number of exchanged messages in our multi-agent architecture of RWSN (denoted by *Arch 1*) where 10 messages are exchanged between (*CrA*) and the 10 (*ZA*) agents. We suppose that we have 50 active nodes and 50 deactive ones per zone. In this case, 50 messages are exchanged between (*ZA*) and (*SA*). The number of exchanged messages: *NbExchMgs1*= 10+10*50=510 messages. For the *TWIST* project (Vlado Handziski, 2005), the authors use the notion of Super nodes, (denoted by *Arch 2*), which is similar to our Zone Agent but without a concept of active nodes. We have 10 messages to be exchanged between the station and super nodes (10 messages are equal to the number of super nodes) plus the messages to be exchanged between the super nodes and all others= 10*1000. The number of exchanged messages is *NbExchMgs2*= 10+10*1000=10010 messages. For the project ReWINS (Harish Ramamurthy, 2005), the authors do not consider an agent-based architecture. We denote this architecture by *Arch 3*, we have, 500 exchanged messages between the station and its nearly nodes plus the exchanged messages between the rest of nodes. The number of exchanged messages is *NbExchMgs3*= $500+\sum_{i=0}^{500} i$=250750 messages. messages. (ii) If we suppose that the time of transmission of any message is 2 ms, we can calculate the transmission time of all messages for these three solutions as follows.

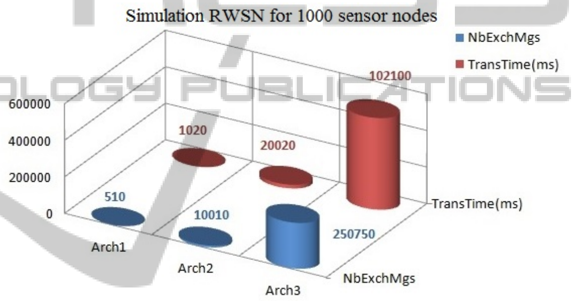


Figure 10: .Comparison between 3 architectures types:Arch 1, Arch 2, Arch 3.

Note that the minimization of exchanged messages between nodes reduces the total energy consumption in a RWSN. We can compute the complexity of our coordination protocol that we compare to related works (Vlado Handziski, 2005) and (Harish Ramamurthy, 2005). Let n be the constant size of data to be exchanged between nodes, and N be the number of operations in the communication protocol (Oper 1, Oper 2, Oper 3, Oper 4, Oper 5), Nb(oppj) the number of sub-operations in the operation oppj, j=(A,..5), *Size(n)*: the algorithm size or the total number of sub-operations in the protocol. The complexity of our protocol is compared to related works (Vlado Handziski, 2005) and (Harish Ramamurthy, 2005) as follows: (a): For our architecture (*Arch 1*): $Size(n) = \sum_{j=1}^{5}(\sum_{i=0}^{n} Nb(oppj)) =$ $5(2n[log_2 n]) = 10n[log_2 n]$ and the complexity is $\mathbf{O(10n[log_2 n])=O(n[log_2 n])}$. The *Size(n)*=recursive equation. (b): For TWIST (Vlado Handziski, 2005) architecture (*Arch 2*), we have: *Size(n)*= $n(2n[log_2 n]) = n^2[log_2 n]$ and the complexity is $\mathbf{O(n2[log_2 n])}$. (c):

For ReWINS (Harish Ramamurthy, 2005) architecture (*Arch 3*), we have: *Size(n)* = n^3 and the complexity is $\mathbf{O}(n^3)$.

7.2 Practical Simulation

We are interested in the exchange of signals between nodes when the temperature is between 30°C and 50°C (30°C ≤Temp≤ 50°C). Our major goal is to keep all nodes of the network on live as much as possible. We assume that if the number of dead nodes (node with battery charge = 0, *PwB*=0) reaches 30% of the original number of nodes (in order of 300 nodes) then, the network collapses. We apply our contribution to this case study by using WSNet (Wireless Sensor Network simulator) (Elyes Ben Hamida, 2007). Figure 11 shows the network topology [1].

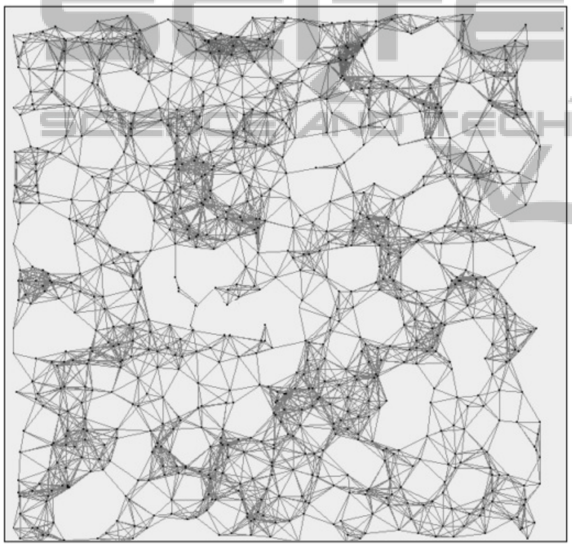


Figure 11: Simulated RWSN topology.

We assume two simulation strategies: (i) First case (*SIM1*): We suppose that we do not apply the paper's contribution. Each node sends periodically the temperature information even it's higher than 50°C, (ii) second case (*SIM2*): We apply our contribution by assuming that each node stops any emission of temperature information if it is higher than 50.

Figure 12 shows the benefits of our contribution that we tested with WSNet.

We note that without the reconfiguration (*SIM1*), the network performance is low, since it collapses much faster than in (*SIM2*). Figure 13 presents additional results of our simulation by using WSNet. The red nodes are deactivated nodes (*PwB*=0), the brown

[1]We thank Ms. Zeineb Gueich for collaboration to prepare this experimentation

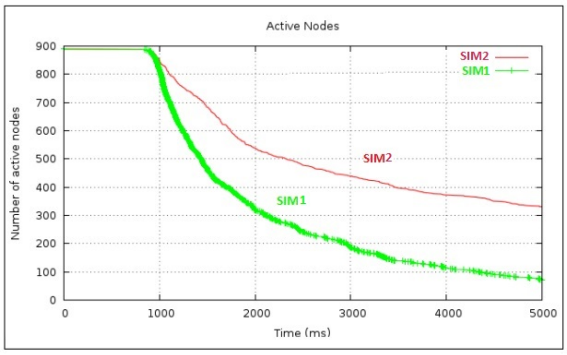


Figure 12: .Comparison between two simulation cases.

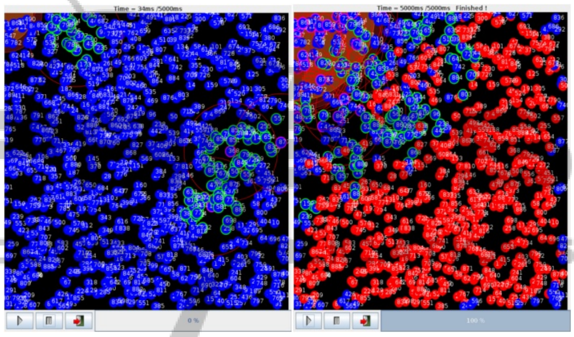


Figure 13: The start and end of simulation.

area shows the high temperature zone, the nodes with a purple outline are active in the process of transmitting data and those in green are in their neighborhoods and participating in routing.

According to our theoretical and practical simulation, the advantages of the paper's contribution :(i) a gain in transmission time of messages to be exchanged between nodes. This gain includes a decrease of transmission times, (ii) a gain in terms of energy since we gain in transmissions of messages, (iii) a hierarchical architecture of *RWSN* in order to control the complexity of the problem and to increase the flexibility of reconfiguration.

8 CONCLUSIONS AND PERSPECTIVES

This paper proposes new solutions for reconfigurable wireless sensor networks to be composed of communicating nodes which execute reconfigurable tasks. The reconfiguration is assumed to be any operation allowing the adaptation of the network to its environment under different constraints. We define three forms of reconfigurations to increase the flexibility of the network: (i) software reconfiguration allowing the addition/removal and update of tasks, (ii) hardware reconfiguration allowing the activation/deactivation of sensor nodes or detectors, (iii) protocol reconfiguration allowing the modification of data flows. Nowadays, many projects deal with RWSN such as WASAN and TWIST(Vlado Handziski, 2005). Nevertheless no one addresses all these forms together.

We propose a zone-based multi-agent architecture for *RWSN* where hierarchical agents are defined for a more flexibility of the network. We use nested state machines as a modeling solution to cover all these forms and control the complexity. A coordination protocol is defined between agents for their feasible coordination. We present in the paper a theoretical and practical simulation that proves the paper's contribution.

The applicability bound of our proposed solution is the modelling complexity when the number of zones increases. Moreover, the system that we treat is real-time, but it is critical to meet all real-time constraints while handling different reconfiguration scenarios. The third applicability bound is the critical management of reconfiguration requests on the medium between the nodes especially when the number of zones increases.

We plan in the future work to verify functional and temporal properties for the formal validation of *RWSN*. The real-time scheduling in nodes as well as the functional safety will be possible future trends to be also followed. A real industrial case study will be considered for more evaluations of our contribution.

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