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Zinonos, Zinon

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Zinon Zinonos and Vasos Vassiliou
Networks Research Laboratory
Department of Computer Science
University of Cyprus
Nicosia, Cyprus
Email: {zinonos, vasosv}@cs.ucy.ac.cy

***Abstract*—In current research studies and testbed deployments of sensor networks, individual sensor nodes are usually assumed to be static. However, recent applications require mobile sensor nodes, something that poses unique challenges in aspects like resource management, topology control, and performance. In this paper we propose a novel soft-handoff mobility protocol that provides zero handoff time and zero packet losses. The proposed solution uses cross-layer information from the MAC layer, the Topology Control, and the Performance Debugging modules of the employed architecture. Our solution was implemented and evaluated in a critical scenario inside an oil refinery.**

I. Introduction

Until recently, industries were using wired solutions to support their application requirements for monitoring and actuating operations. The use of wired-based systems has proved to be efficient, reliable and robust in critical environments. However, the high cost of deployment, maintenance, and installation of such systems increased the need of using a wireless solution. Several attempts have been done to apply wireless technology in industrial environments, but the unreliable communication protocols, noisy environments and un-stable hardware prevented industries from accepting the technology. For industries to adopt a solution using the WSN technology would result in significant savings in deployment and maintenance costs, and would be more easily reconfigured and rapidly deployed to adapt to changing business needs. In addition, performance assurances are desirable, especially in regard to timeliness and dependability. Despite the importance of the performance assurances, this topic has not received enough attention from the research community. In addition to the existing performance requirements for monitoring and actuating industrial systems, some new challenges are posed due to the usage of mobile nodes in a WSN-based system. New applications such as monitoring people and vehicles in an industrial environment require the implementation of a new mobility protocol that will be efficient and reliable. Those challenges include aspects like resource management, topology control and performance control.

Mobility can be in general approached from three points of view: the first approach is to deal with the handoff procedure locally in the Network Layer of the mobile entity (MIPv6, HMIPv6). The second approach uses information from Layer 2 to speed up the handoff process (FMIPv6) and the third solution is based on a non-evasive method known as network-based mobility (PMIPv6). In addition to the above there are also MAC-based solutions that try to provide mobility support. Examples of such solutions are the MS-MAC [1], MAMAC [2] and MH-MAC [3].

The main issue with the above IP solutions is that they cannot be directly applied to a mobile WSN due to the sensor node limitations. On the other hand, the issue with the MAC-based solutions is that there is not any real proof of their applicability to a demanding environment. In addition, there is not any implemented and tested solution that provides mobility support for moving objects (people, vehicles etc) inside a critical environment.

The work presented in this paper is part of a European project named GINSENG [4] which has the main goal to create a wireless sensor network that will meet application-specific performance targets and that will be proven in a real industry setting where performance is critical. The end user of the GINSENG project is the Petrogal oil refinery at Sines, Portugal. The Petrogal refinery is a complex industrial facility that includes a wide range of processing units that need careful monitoring and control of operations. The monitoring of the environment in a refinery provides essential information to ensure the good health of the refinery and its production processes. In the oil refinery three subsystems exist for the monitoring and control of the plant: the indicator system, the semi-automatic control system, and the automatic control system. Five types of scenarios were included in the project. These scenarios are: Production Monitoring, Production Control, Production Monitoring and Control, Pipeline Leak Detection and Personnel Safety. The Personnel safety scenario requires the use of mobile nodes and is the scenario that was used to evaluate our mobility solution.

In this paper, we present a cross-layer mechanism to efficiently support mobility in a critical scenario. The proposed mobility solution is implemented and evaluated inside the Petrogal Sines Refinery environment and the experimental results of the performance and the handoff triggering mechanisms are presented.

The paper is organized as follows: Section II presents the GINSENG project and architecture, while Section III presents the proposed mobility model. In Section IV the experimental

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evaluation and performance analysis are presented and finally Section V concludes the paper.

II. GINSENG Project

The GINSENG project [4] targets performance controlled networks that have strong requirements on timeliness and reliability. The functional architecture of the system is presented in Fig. 1 and it defines how the different modules should collaborate in order to have a system that could accomplish the required performance. The MAC layer (GinMAC) is responsible for providing exclusive TDMA for channel access with a pre-dimensioned virtual tree topology and hierarchal addresses (Fig. 2). It accepts packets from the upper layers, which are queued and then transmitted by the radio at the appropriate time. To successfully accomplish these tasks it must interact with Topology control, Overload control, Performance Debugging and with the Contiki rtimer subsystem. The Topology control (GinTOP) module is responsible for establishing the methods by which nodes join or leave the network (in the case of GinMAC, a tree as shown in Fig. 2), advertising the presence of empty child positions so that new nodes can join and accepting or rejecting prospective children. Functionalities such as slot allocation, transmission power decisions, tree optimizations and maintenance are also responsibilities of the Topology control module. The Performance monitoring (Perfd) module's target is to determine whether or not the wireless sensor network is meeting performance requirements. To accomplish this target, it must interface with several other elements, most notably the GinMAC protocol and Topology control. Furthermore, intra- and inter-PAN mobility, neighbour discovery, security and overload functionalities are expected to be implemented as cross layer modules using information obtained mainly from the MAC layer.

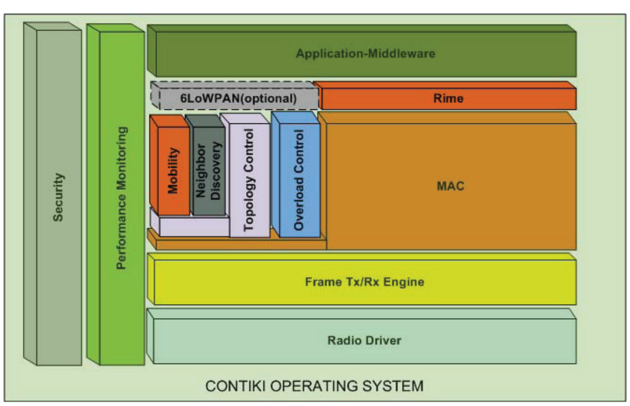

Fig. 1. GINSENG Functional Architecture

III. Mobility Solution

Mobility support in the GINSENG project, as mentioned above, has been mainly related to the Personnel Monitoring scenario. This scenario considers that there are cases when one would want to monitor personnel performing dangerous tasks, such as cleaning empty storage tanks. Moving between tanks

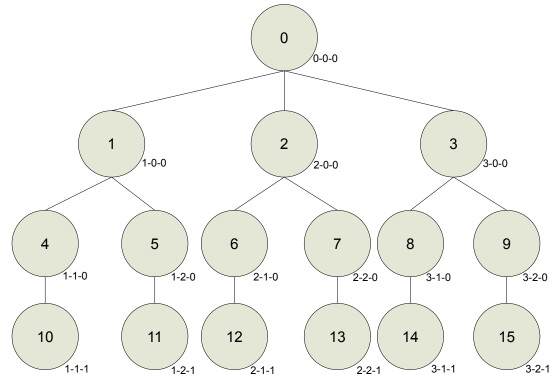

Fig. 2. GINSENG Tree

or other type of hazardous areas can cause two types of mobility: intra-PAN mobility and inter-PAN mobility. Currently, intra-PAN mobility support was implemented and evaluated inside the refinery testbed area. In intra-PAN the employee movement is within the range of the same network.

A. Mobility operation

Initially, we designed our mobility solution to support the hard-handoff operation [5]. The hard-handoff trigger was initiated based on (i) an RSSI threshold and/or (ii) a better RSSI value. The specific solution was suitable for applications with no demanding requirements in terms of packet loss and disconnection time. Based on the evaluation results of the hard-handoff algorithm presented in [5], we managed to guarantee the maximum disconnection time for the mobile node. Table I summarises the results that were obtained from the hard-handoff solution.

TABLE I
Hard-handoff Mobility Disconnection Time

Threshold-based		RSSI-based	
Theoritical Handoff Delay (ms)	Testbed Handoff Delay (ms)	Theoritical Handoff Delay (ms)	Testbed Handoff Delay (ms)
2900-3100	2950	2000	2000

In the case of more demanding applications no disconnection time and no packet losses are acceptable; therefore, the hard-handoff solution is not suitable. As a consequence, a soft handoff solution was considered. The initial design and signalling of our soft-handoff proposal is presented in [6]. The initial results were obtained from experiments run in our laboratory testbed. In this paper, we move one step forward, since we enhance our mobility protocol with cross layer information obtained from the Perfd module. In addition, all the results presented in this paper are from the Petrogal Sines Refinery testbed experiments.
In order to support the attachment of the MN to a new tree position, two additional control messages must be sent. These messages are the Join and the Join_Ack that are sent/received when the MN is still attached to the previous tree position.

Therefore, the role of the Dynamic Topology Control (DTC) [7] in soft-handoff mobility is to support the re-attachment of the MN to a different tree position as a result of movement inside the testbed area. Another critical operation of the mobility algorithm is the triggering of the handoff procedure. As our main target in the GINSENG project is to guarantee the performance of the network, the proper module to decide if a MN should handoff or not to a new tree position is the Perfd module. To do so, we set some decision handoff rules in the Perfd module. By initiating the handoff procedure it does not mean that at the end the MN will handoff, since there is not any guarantee that the MN will manage to find a better attachment point. The rules that were set in the Perfd module are the following:

- *RSSI Threshold* : If the RSSI of the communication link between the MN and the current parent is below a predefined threshold H and if the last 5 packets exchanged follow a decreasing trend then it decides to handoff. This value was experimentally [6] proved to be equal to -78dB.
- *Better RSSI* : During the operation time the MN sets its idle slots to scan mode in order to receive advertisement packets from all the nodes in its communication range. If the communication link between the MN and the sender node is better by xdB then it decides to handoff.
- *Number of lost packets* : If the number of the continuous lost packets between the MN and the parent node communication is above L then the MN will decide to handoff.
- *Packet loss percentage* : If the percentage of the lost packets between the MN and the parent node communication is above N then the MN will decide to handoff. This value was set to 1% and it is application depended.

During the operation of the network it is observed that the packet loss reported is initially high when the first instance of loss occurs because there has typically been a relatively small amount of messages sent. With time, as more messages are delivered this value begins to stabilize to a more accurate representation of the actual level of packet loss experienced. Therefore, we do not perform any handoff before the MN first sends n packets. In our experiments, we set this value equal to 100 packets. The handoff triggering can be initiated using one of the above rules or any combination of them.

B. Network architecture

The testbed network architecture is comprised of three kinds of nodes: Sink Node (SinkN), Static Node (SN) and Mobile Node (MN). Each type of node is characterized by a different role in the network, and different capabilities in terms of energy, communication and mobility.

- A SinkN represents the final destination of the information generated by the WSN. Sink node is responsible using DTC to start the procedure of constructing the tree. The sink is located to the portable office and it is connected directly to the sink PC where also the Dispatcher and the Monitor applications are located. The

Algorithm 1 Soft-handoff Mobility Algorithm

```
if SN then
  Sensor Node: check the children list
  if child_num ==0 then
    No available position(s)
  else
    if child_num =! 0 then
      available position(s)  advertise
      Adv_Ctrl_Pkt=createAdv(positions(i,. . . ,n));
      sendPkt(Adv_Ctrl_Pkt);
    end if
  end if
  if join_mn then
    check if the position is still available
    if available then
      accept join, send join_ack and update children list
      JoinAck_Ctrl_Pkt = create_JoinAck(node_id, addr);
      sendPkt(JoinAck_Ctrl_Pkt);
    end if
  else
    if !available then
      do nothing
    end if
  end if
else
  if MN then
    Perform Random Walk
    if !attached then
      scan(all_slots);
      receivedPkt(advert);
      Join_Ctrl_Pkt = createJoin(node_id, addr);
      sendPkt(Join_Ctrl_Pkt);
    end if
  else
    if attached then
      set the handoff_trigger
      case 1: Five continues decreasing RSSI values and
      below RSSI threshold
      case 2: Perfd packet loss trigger
      case 3: Better RSSI trigger
      if handoff_trigger == TRUE then
        scan(idle_slots);
        search for better attachment point based on the
        RSSI value
        sendPkt(Join_Ctrl_Pkt);
        receivedPkt(join_ack);
        switch to new address
      end if
    end if
  end if
end if
```

Dispatcher writes all data coming from the WSN to XML files and also enables multiple consumers (such as the middleware or the performance monitoring) to receive the information in different formats. The sink is a fixed node and there is not any limitation on energy since it is powered from the USB connection with the sink PC.

- The SNs are fixed nodes that are installed in pre-defined positions in a such way to measure the appropriate values (pressure, flow, temperature, etc) that the application requires. The SNs can be main-powered or battery-powered.
- The MN is carried by the mobile user in an ATEX case (with an external antenna) in its backpack. MN is powered with batteries therefore energy consumption is important.

As all the sensor nodes are installed inside Junction boxes (JB) the communication using the internal antenna is unfeasible. Due to that fact, the use of external antennas was necessary. We selected to use antennas with 9dB of gain. Figure 3 demonstrates the Sines oil refinery testbed area that was used to evaluate the GINSENG Mobile scenario.

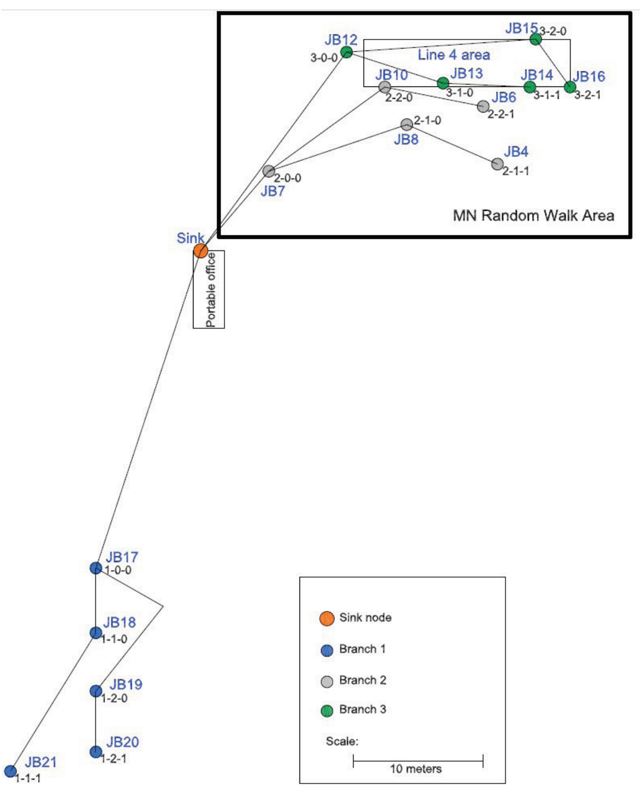

Fig. 3. Sines Testbed Area

IV. Evaluation

The GINSENG Mobile experiment uses a configuration with DTC [7] and in addition mobile nodes are supported. The configuration of different nodes are presented to Table II. The epoch duration of the TDMA-based MAC working below (GinMAC) is set to one second. In addition, we assume that the tree topology always has free positions in order to support the MN handoff. To demonstrate the support for node mobility, nodes were disconnected from the tree (nodes with JB number 6, 7, 12, 15, 17 and 20) and temporarily removed from the testbed (Fig.4). The mobile node was then introduced into the testbed and during testing the mobile user walked at a steady speed on a predetermined area (as is illustrated in Fig. 3) in a random way for 20 minutes. Since each node was configured to send one packet per 3 seconds, the total packets that were sent by each node are equal to 400.

For presenting the evaluation results, we considered one scenario where the MN was connected to the tree position with address of 3-1-1 and then it handoff to the position with the address of 2-1-1. The handoff can be triggered based on RSSI threshold or based on a better RSSI value from a possible parent (in this case the scan interval is set to 20 epochs).

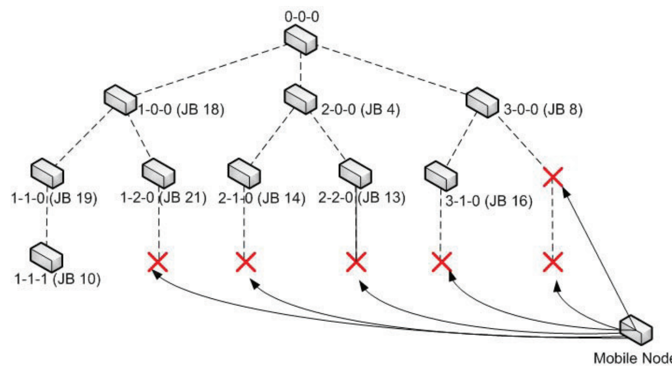

Fig. 4. Mobility Tree

TABLE II
Testbed Nodes used in GINSENG Mobile Experiments

Node Type	JB Number	Data Freq.(s)	Notes
Pressure Sensor	17, 18, 19, 20 8, 12, 15, 14	3	Nodes 17, 20,12 15 were not used
Temperature Sensor	21, MN	3	
Flow Transmitter Sensor	4, 6, 7, 10, 13, 16	3	Nodes 6 and 7 were not used

Figure 5 depicts the data packet delivery delay in milliseconds, for each node in the tree. The x axis depicts the node's tree address. The maximum packet delay is approximately 810ms whereas the minimum packet delay is 80ms. The epoch duration is 1000ms, which means that all the nodes delivered their data to the sink within the time interval of one epoch.

Figure 6 depicts the energy consumption in mW of each node in the tree. The sink node, as expected, reports the highest energy consumption. The second group of energy consumption contains the nodes attached to the first level of tree. The lowest energy consumption group includes the leaf nodes. In the case of the MN there is an increased energy consumption, which is explained by the fact that the MN changes more frequently its idle slots to scan mode in order to discover a better attachment point.

Fig. 5. Data Delivery Delay

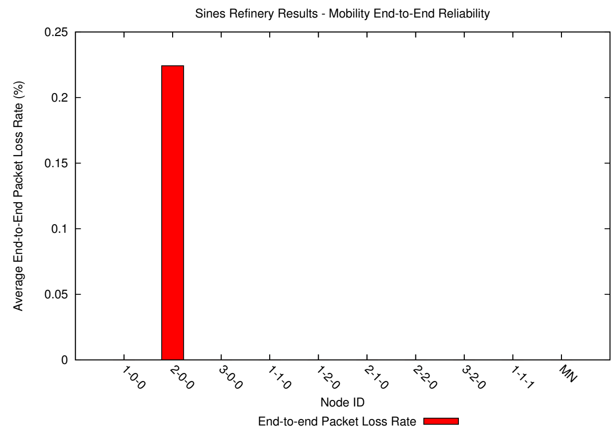

Fig. 7. Packet Loss

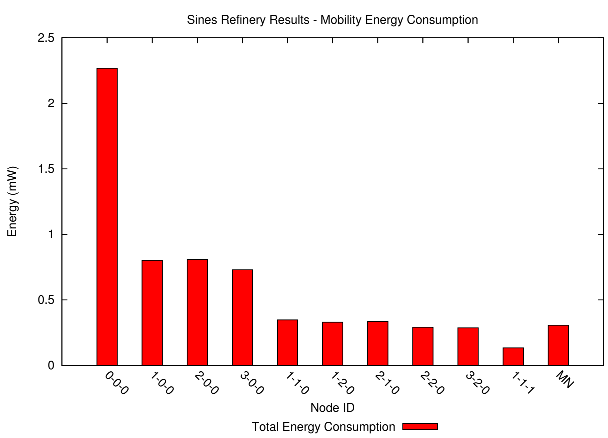

Fig. 6. Energy Consumption

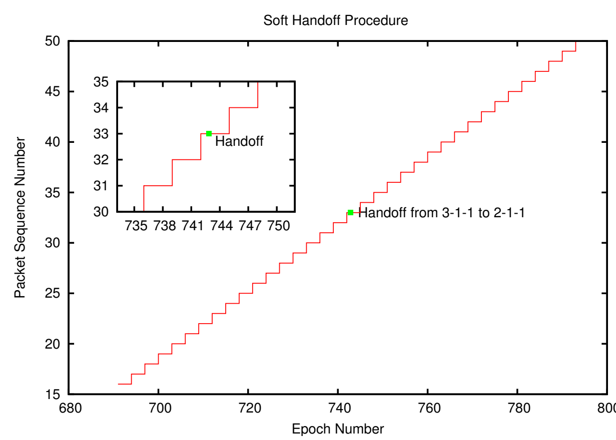

Fig. 8. Handoff Procedure

Figure 7 shows the percentage packet loss for each node in the tree. In all cases the packet loss is equal to zero except in case of node 2-0-0. Comparing these values with the values that were reported by the dynamic topology evaluation [7] we can observe that in mobility evaluation packet loss are decreased. This can be explained by the fact that in mobility evaluation we constructed the tree using fewer nodes than in DTC case. The important observation of Figure 7 is that the MN reports zero packet losses.

During the MN's walk, we monitored the data that the MN was sending to the sink node. In addition, we monitored the slot numbers where the mobile node disconnected and connected again to the tree. The received packet sequence numbers and the handoff events are shown in Figure 8. Based on the results, the disconnection time and the packet losses during the handoff procedure are equal to zero. By switching the tree address at the beginning of the next epoch, we can achieve a smooth handoff (where no packet is lost). Figure 8 also shows, in zoom, the packet sequence numbers during the handoff events where it is clearly indicated that there is no packet lost during the handoff events.

Table III presents the number of extra control messages that are required in order to achieve the zero downtime. Only two extra messages are needed for each handoff event.

TABLE III
MOBILITY OVERHEAD

Number of control messages per handoff	MN downtime	
	Disconnection slot	Connection slot
2	74284	74284

As shown in Figure 6, the MN presents an increased energy consumption comparing with other leaf nodes. Figure 9 depicts the energy consumption breakdown of the different components of the MN. The increased total energy consumption of the MN is due to the scanning interval that was set by the MN in order to trigger the handoff.

Based on our evaluation results we managed to avoid any disconnection time introduced by movement and the handoff of the MN. In addition, the soft handoff can provide us with zero packet loss during a handoff procedure but it introduces additional signalling packets (two extra packets per handoff) to the normal operation of the network. Finally a possible extension for the soft handoff solution will be to consider the current parent node or the sink node to be responsible to

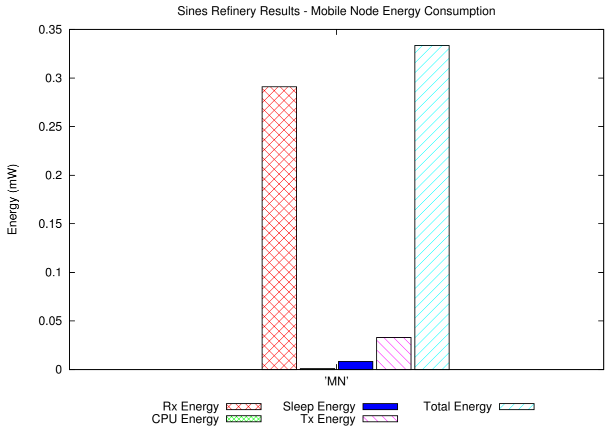

Fig. 9. Energy Breakdown

monitor the MN performance; therefore, we can reduce any overhead in the MN.

V. Conclusions

In this paper, we proposed a soft mobility solution that provides zero handoff time and zero packet losses for a network operating in a critical environment, like the Petrogal Sines refinery. We used experimental testbed evaluation to prove the performance of our solution. We also considered the overhead of the proposed solution in terms of communication and energy consumption. In the future, we aim to further test our model using combinations of handoff triggering rules. In addition, we will study the relation of the mobility model with the number of necessary free tree positions.

Acknowledgements

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