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Controlling the Handoff Procedure in an Oil Refinery Environment Using Fuzzy Logic

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Abstract—Mobility is one of the most important challenges in a wireless sensor system. Usually, continuous connectivity of a Mobile Node (MN) is achieved by supporting handoff from one connection point to another. In order to guarantee reliability and seamless communications to a MN, it is important to avoid unnecessary handoffs occurring during a short period of time. In this paper, we present a mobility management solution that is applied to a network operating in an oil refinery environment. The proposed mobility solution is supported by fuzzy logic techniques in order to keep the number of handoff triggers to low values and at the same time to provide high reliability. The performance evaluation of the proposed fuzzy-based solution and the conventional Received Signal Strength Indicator (RSSI) based method shows that the proposed solution manages to increase the reliability of the system and at the same time reduce the handoff overhead.

I. INTRODUCTION

Wireless sensor networks (WSNs) have been a very active research area in the last decade. The majority of the wireless sensor applications used assume the presence of static nodes in order to perform monitoring missions in the region of interest. However, the assumption of static nodes is generally not valid anymore, since many new applications require the existence of mobile sensor nodes. In order to support high network performance, in addition to the mobility requirements, carefully designed handoff strategies are required. Properly executed mobility management actions are needed to be able to achieve minimum packet losses and disconnections due to the mobility of the node. As with any mobile system, a handoff in WSNs consists of three main phases: (a) measurement phase, dealing with the mechanics of measuring important parameters, (b) decision phase, dealing with the algorithm parameters and handover criteria and (c) execution dealing with radio resource allocation and handover signaling. The importance of the triggering decision is high, since it affects the overall performance of the system. For example, if the handoff is triggered too early or too late this could affect the link quality between the Mobile Node (MN) and the receiving node. In addition, the number of the triggers contributes to the overall overhead and complexity of the system, especially when having devices with limited capabilities like sensors. Thus, one of the objectives is to keep the number of triggers

low and at the same time to provide high reliability.

In this paper, we present our mobility management protocol that has been used to support the operations of mobile workers in a real industrial environment where performance requirements are critical. In order to achieve this, we use an intelligent mobility controller that is based on fuzzy logic principles. The main idea of using fuzzy logic control (FLC) is that if it is designed with a good (intuitive) understanding of the system to be controlled, the limitations due to the complexity introduced by the system's parameters on the mathematical model can be avoided.

This work has been implemented in the context of an FP7 European project named, GINSENG [1]. The general aim of the GINSENG project was to develop a performance-controlled Wireless Sensor Network system that is well suited for situations in which dependable and deterministic performance is needed. GINSENG provides novel software components (for example, Operating System and TDMA Medium Access Control) and algorithms (for example, topology control and flow control) to ensure time-critical data delivery. The immediate target was the Petrogal oil refinery located in 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 motivation of this work was raised from the need to monitor in real time the physiological condition of the refinery workers during their presence in toxic environments like oil storage tanks.

The rest of this paper is organized as follows: Section II describes related work regarding handoff decision mechanisms. The mobility scenario and requirements are introduced in Section III, and in Section IV the proposed handoff decision mechanism using fuzzy logic is illustrated. Section V shows the performance evaluation. Finally, the conclusion is given in Section VI.

II. RELATED WORK

In general, in order to have a handoff between two connection/attachment points a triggering decision must be occurred. In the majority of the related work ([2] [3], [4]) the handoff triggering is based on a single metric like the Received Signal Strength Indicator (RSSI) or the Packet Reception Rate (PRR).

The most commonly used triggering/handoff criteria are the following:

- **Better Signal Strength:** the MN selects the attachment point with the strongest RSSI. It can be considered as being a simple solution, but it can cause too many unnecessary handoffs. In case of sensor networks, it will increase the energy consumption since the MN must be always on (it is always triggered) for hearing for new attachment points.
- **Threshold:** if the current signal strength is less than the threshold the handoff is triggered. In case that a new attachment point with strongest RSSI is available the MN will handoff. The issue with this metric is the threshold value selection since low threshold may lead to late handoff where high threshold to early handoff.
- **Better Signal Strength with hysteresis:** the MN selects the attachment point with sufficiently stronger (by a hysteresis margin, h) RSSI compared to the one of the serving attachment point. Using this technique, the ping-pong phenomenon can be avoided. However, there may be the case where the handoff decision that occurs could be unnecessary since the serving attachment point signal may be strong enough to maintain the connectivity. In case of sensor networks, energy consumption is increased.
- **Threshold with hysteresis:** if the current signal strength is less than the threshold and a new attachment point with sufficiently stronger (by a hysteresis margin, h) RSSI is available, then the MN will handoff. Using this technique, the ping-pong phenomenon can be avoided.

In order to support the complex situations of mobility management such as the triggering procedures, mobility management solutions can use tools from the family of Computational Intelligence (CI). In [5], CI is defined as *the computational models and tools of intelligence capable of inputting raw numerical sensory data directly, processing them by exploiting the representational parallelism and pipelining the problem, generating reliable and timely responses and withstanding high fault tolerance*. Several examples of application of such CI tools were presented in the literature, but whose prime focus is not WSNs. Recently, researchers started thinking of ways to use CI tools in order to solve WSN issues such as design and deployment, localization, security, routing, data aggregation and QoS management. Examples of such work are presented in [6], [7] and [8]. An overview of the CI techniques in WSNs are presented in [9], where authors findings have been summarized in Figure 1.

Mobility management using a specific CI technique, namely fuzzy logic, was introduced in our initial work in [10]. In this poster paper, we have shown the performance evaluation of different mobility solutions that are based on the triggering/handoff criteria as stated above. Based on those results, the necessity of providing the concept of fuzzy logic control principles to intelligently control the handoff procedure was introduced. In addition, in [11] authors provided a fuzzy logic system to support the mobility procedure based on RSSI level,

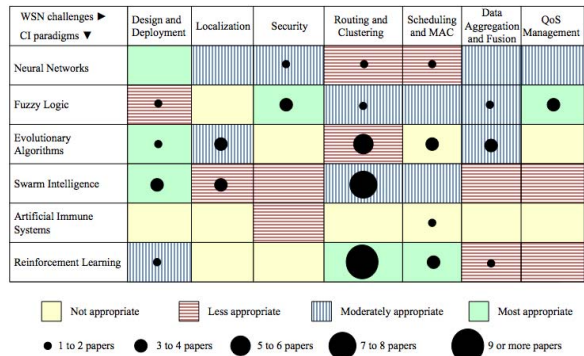


Fig. 1. WSN challenges and CI paradigms [9]

velocity of mobile node, number of hops to sink node, and some other metrics such as traffic load, energy level and link quality value. Although they have presented the design of their solution they did not provide any implementation or evaluation of it. In addition, the complexity overhead using several metrics was not discussed.

Our approach is to use fuzzy logic techniques to provide an effective mobility solution in WSNs. Further to [10], in this paper, we demonstrate via enriched simulative evaluation that such a fuzzy logic approach can efficiently control the handoff triggering procedure and provide high reliability. The selection of fuzzy logic system instead of any other CI technique is based on its simplicity and the fact that since it processes experts-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance.

III. MOBILITY SCENARIO

Due to the potential hazardous nature of refinery the collection of information is strictly time-critical. To achieve this target a set of control procedures were implemented in order to ensure deterministic behaviour and to allow the network to meet application specific performance targets. The design of such procedures are even more challenging when mobility is present. The GINSENG architecture uses a TDMA-based MAC protocol called GinMAC [12] at its main component. A number of additional modules like the Dynamic Topology Control [13] and the Performance Debugging were implemented. The network consists of a number of fixed nodes that create a network where the communication is achieved in a multi-hop manner through a tree-based topology, as shown in Figure 2.

A. Application scenario

One of the applications that were implemented in the context of GINSENG project was the real time monitoring of mobile workers while they are performing regular maintenance in hazardous areas of the refinery. The motivation behind this scenario is the fact that working in such typically toxic atmosphere there is a possibility for a worker to loose consciousness or become dizzy and fall. As the mobile worker moves around

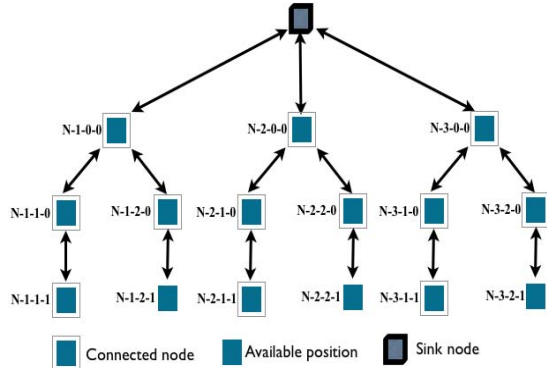


Fig. 2. Ginseng Tree Topology

the tank, orientation messages are sent from the sensor to the sink forwarded by intermediate nodes through the constructed tree topology. Similarly to other Ginseng scenarios, information must arrive at the control center within a few seconds. An example of the mobility application scenario is shown in Figure 3.

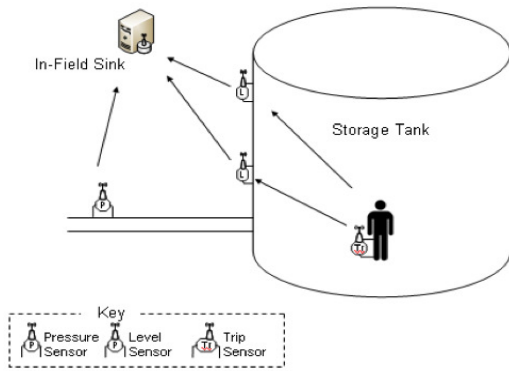


Fig. 3. Refinery Area

The application requirements for the above scenario are the following:

- Data Delivery: The data sent by the mobile node must arrive to the sink node within one second.
- Packet loss: Few packets can be lost. The packet loss for the mobility scenario must be as close to the target packet loss of the scenarios where no mobile nodes exist, which is no more than 1% of the total transmitted packets.
- Network: The network consists of 1 sink node, 12 fixed nodes and 1 mobile node.
- Topology: The nodes construct a 3-2-1 tree topology meaning that at each time there are 2 free available positions for the mobile node to handoff.
- The epoch duration was set to one second.
- The mobile node data frequency is more or equal to one second.
- The mobile node sends periodic upstream data to the sink. No burst data are created.

- The data can be time-critical or not.

IV. PROPOSED MOBILITY MANAGEMENT SOLUTION

Since workers are mobile objects, a mobility management protocol that will efficiently maintain the connectivity of the mobile node by controlling the handoff procedure is required. In order to efficiently monitor or control a mobile person moving inside a WSN area, the mobile entity must be able to handoff between different networks while performing its movement. Our approach to provide mobility support for mobile workers resides on the fact that we have to control the handoff procedure, which means that at a first stage we have to control the handoff triggering procedure. Due to the limitations of the sensor nodes it was decided at the beginning that the design of the mobility support would use existing information so that to avoid imposing any additional overhead to the system. In addition, our target was to provide a distributed solution, meaning that there is no central entity that has full knowledge of the system and will decide about the handoff procedure. Therefore, all the information that is used is locally available at each node and no communication overhead is added.

At first, we decided that a mobility solution can be implemented that will follow the same approach as the majority of the related work, which is the use of the RSSI as an indicator to initiate the handoff procedure. In order to do so, we used the theoretically best RSSI-based solution which is the Threshold-based with hysteresis.

A. RSSI-based solution

As mentioned above the first metric that was used for supporting the handoff triggering was the Received Signal Strength Indicator (RSSI). Therefore, in order to support the mobile workers' movement we have implemented and evaluated the S-GinMOB solution [14] [15] [16]. The RSSI-based solutions provided several options like the support of hard-handoff, soft-handoff, and simple thresholding. The threshold was set to -78dB based on long-term (two weeks continuous test) information obtained from the refinery area. Based on that work it was shown that although RSSI could help, it could not provide an adequate solution with controlled performance. The system has shown an increase on the number of triggers, which has as a consequence an increase of the overhead of the solution. The main reason for that is the unpredictability of the RSSI especially in harsh environments, where it suffers from fluctuations phenomena. Example of that behavior of the RSSI is shown in Figure 4.

To avoid the problems that have been created due to the sole use of RSSI, our proposed solution combines information using the link loss along with RSSI. Due to the dynamic refinery environment, we expect that the system does not behave linearly, therefore any use of a mathematical model would be difficult to be obtained. Thus, we selected to use a fuzzy logic approach since is the most efficient artificial intelligence model [17] concerning the limitations of sensor networks.

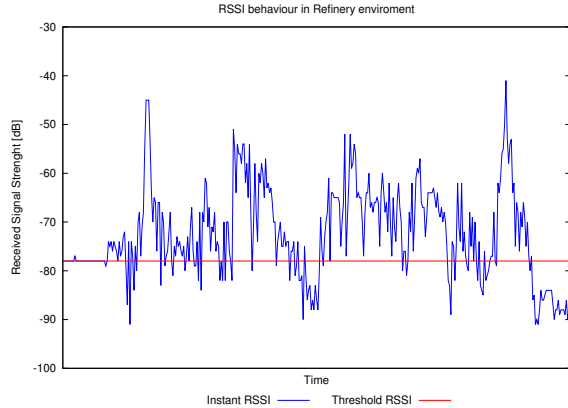


Fig. 4. RSSI behavior in refinery

B. Fuzzy Logic Mobility Controller

A novel, intelligent controller, based on fuzzy logic control (FLC) [18] [19], is proposed to be applied to GINSENGS project, in order to support the mobile workers scenario and to help sensor mobile nodes to decide whether they have to handoff to a new position or not. FLC, in general, concentrates on attaining an intuitive understanding of the way to control the process, incorporating human reasoning in the control algorithm. It is independent of mathematical models of the system to be controlled. It achieves inherent robustness and reduces design complexity. We use fuzzy logic control principles to design a simple, effective and efficient nonlinear control law, in order to offer inherent robustness with effective control of the system. Due to the mobility of the node and the resulting highly dynamic network environment, the proposed control mechanism needs to operate in a decentralized and self-organized way, i.e. locally at each sensor mobile node. Using linguistic rules (see Table I) that describe the behaviour of the environment in widely differing operating conditions, the proposed fuzzy logic mobility controller (FLMC) dynamically calculates the decision probability (to trigger the decision whether a sensor mobile node has to handoff to a new position or not), based on two network state inputs: the instantaneous value of the signal strength indication (RSSI), and the link-to-link loss rate, both taken at the end of each sampling period. The philosophy behind the knowledge base of the proposed scheme is that of being aggressive when the RSSI is low and the Link Loss is high, but on the other hand being able to smoothly respond in the case of adequate conditions in the environment. Due to computational simplicity, we select trapezoidal and triangular shaped membership functions in the proposed control scheme to describe the linguistic values of the fuzzy input and output variables. The amount of overlapping between the membership functions areas is chosen so as to have at most two membership functions overlapping, thus we will never have more than four rules activated at a given time. This offers computational simplicity on the implementation of the proposed scheme, a design objective.

Further, there is no need for a fuzzy inference engine to be built in each sensor mobile node. After the linguistic rules have been found and the linguistic values are tuned using “trial and error” approach, the control surface is known and can be stored as a lookup table (size of $n * n$) for selected sampling points requiring only a few kilobytes of memory in a fuzzy-capable sensor mobile node. In our case n is equal to 25, therefore the lookup table has 625 values. The size of the table depends on the available memory of the sensor node. In that way, we addressed the several limitations of sensor networks like memory and computation.

TABLE I
FLMC LINGUISTIC RULES - RULE BASE

Decision Propability		Link Loss Rate			
		<i>L</i> ¹	<i>M</i>	<i>H</i>	<i>VH</i>
RSSI	<i>L</i>	LM	M	H	VH
	<i>M</i>	LM	M	H	VH
	<i>H</i>	L	M	H	VH
	<i>VH</i>	L	LM	H	VH

V. PERFORMANCE EVALUATION

The proposed fuzzy-based mobility solution was evaluated by running a large number of tests using the COOJA simulator [20]. The simulated network consists of 13 static nodes and one mobile node (MN). We used the same placement of the nodes as in the real testbed. The MN was introduced in the network area and followed different random walks. We used one testing area with dimensions 35 meters x 25 meters. Figure 5 shows the testing area. This area was divided into 12 sub-areas of dimensions 10 meters x 10 meters.

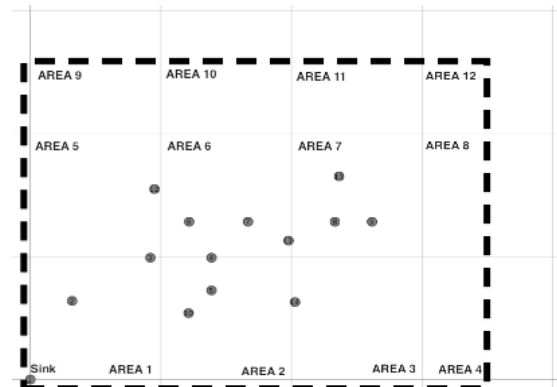


Fig. 5. Testing areas

The parameters that we used for our simulations are shown in Table II.

Figure 6 shows two examples of the mobility paths that were used for the evaluation of the proposed fuzzy-based mobility solution and the RSSI-based mobility solution. The mobility paths were created using the Bonnmotion tool [21].

Table III shows the percentage of the average time that the MN was in a specific area for the 5 mobility patterns.

¹low (L), low-medium (LM), medium (M), high (H), very high (VH)

TABLE II
SIMULATION PARAMETERS

Simulation Time	2000 seconds
Number of simulations	1500
Number of fixed nodes	13
Number of mobile nodes	1
Mobility model	Random Waypoint
Number of Waypoint paths	5
Packet Rate	1 packet/3 seconds

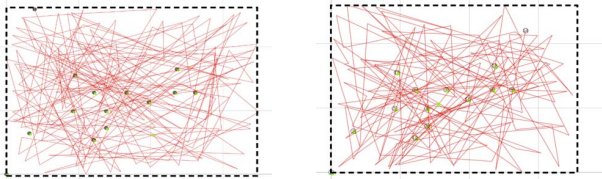


Fig. 6. Mobility Patterns

In addition, it shows the percentage of the coverage of each area by all nodes. This information is important since it will help us identify the contribution of each area to the total packet loss. Such information will help to improve the deployment of the static nodes.

TABLE III
MOBILITY AND COVERAGE

	Average Time(%)	Coverage(%)
Area 1	9,92	91
Area 2	13,47	100
Area 3	10,50	92
Area 4	4,33	89
Area 5	11,19	96
Area 6	13,35	95
Area 7	12,57	92
Area 8	4,97	90
Area 9	6,18	94
Area 10	5,70	96
Area 11	5,30	90
Area 12	2,52	85

The first test that we performed was to identify how the hysteresis margin for the received signal strength affects the packet loss. To do so, we set three different values of 1dB, 2dB and 3dB. We repeated 250 tests for each mobility solution using the three different hysteresis values. Based on our results the lowest packet loss for both solutions was obtained when the hysteresis value was equal to 3dB. Figure 7 depicts the obtained packet loss values for the fuzzy logic- and the RSSI-based mobility solutions using the best case of both solutions; that is, the 3dB hysteresis value case.

Based on the obtained results, the first observation made is that the fuzzy-based solution, compared with the RSSI-based solution, performs better, since it manages to decrease the end-to-end packet loss almost at the half value of the conventional one (see Figure 7). The second observation made, based on the three different hysteresis-values cases, is that the hysteresis margin affects the packet loss. The reason is that when the quality of the link with the parent node drops, the MN will trigger the handoff procedure and will search for a new attachment point. When a new advertisement is received, the MN will check the RSSI value and will select to handoff

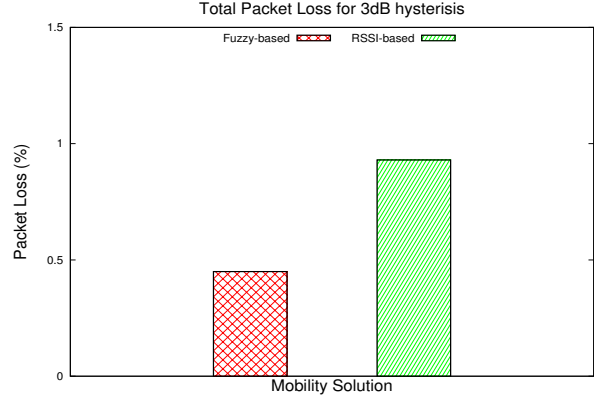


Fig. 7. Total Packet Loss

if the RSSI of the new attachment point is better than the current RSSI. Therefore, the hysteresis margin denotes how better the new attachment point will be compared with the current link with the parent node. Therefore, the higher the hysteresis margin values, the better the quality of the new link.

The remaining of the results are based on the 3db hysteresis value case. Figure 8 depicts the number of triggers and the number of handoffs for both mobility solutions. It is obvious that in the case of the fuzzy-based solution we have less triggers compared with the RSSI-based solution; that is, the proposed solution controls better the handoff triggering procedure compared to the conventional solution by minimizing the number of unnecessary handoffs. This is due to the fact that the fuzzy-based solution is not solely affected by the RSSI fluctuations. The better success ratio (meaning the triggers that led to handoff - see the Triggers/Handoff bar in Figure 8) it is observed when using the fuzzy-based solution.

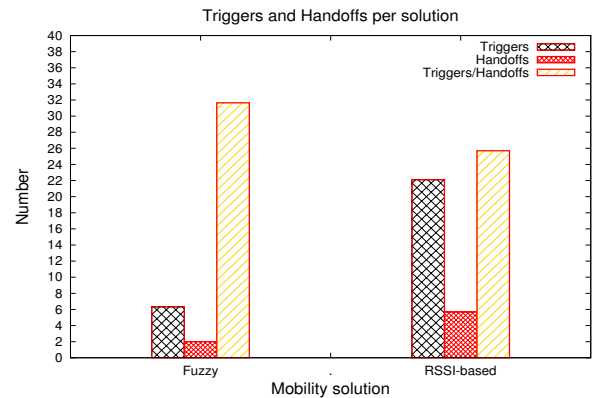


Fig. 8. Triggers and Handoffs

Another observation made, is that the coverage of the testing area (as shown in Figure 5) affects the packet loss. This is due to the fact that the transmission range of the nodes is limited to some meters (25 meters), hence when a node moves at the

borders of the area there is a possibility to lose connectivity with the parent node and the data will be lost as a consequence. On the other hand, when moving in the middle of the area there is a greater probability to find a new attachment point since the node is within the transmission range of a number of nodes.

Particularly, Figure 9 depicts the packets that were lost in each area for both solutions. It is clear that for Area 2 up to Area 11 the fuzzy-based solution outperforms the conventional solution in terms of lost packets. Area 1 shows increased packet loss due to the tree construction algorithm. Based on [13], the sink node will select with high probability the nodes that are close to it to be the level-1 nodes (nodes 1-0-0, 2-0-0, 3-0-0 from Figure 2). Therefore, when the tree is constructed, the freely available positions are not expected to be close to the sink. This means that when the MN moves at the borders of Area 1 it may move out of the range of its current attachment point, and may not have an alternative attachment point.

Looking into Area 1 and Area 12, both mobility solutions show similar behavior. In the case of the fuzzy-based solution, those two areas contribute up to 75% of the total packet losses, where in case of RSSI there is a more distributed way of losses and these two areas contribute up to 32% of the total packet losses. Comparing only the losses in these areas for both solutions we have in case of fuzzy 107 packets lost and in case of RSSI 95 packets lost. Nevertheless, the RSSI-based solution shows its inadequacy to efficiently control the handoff triggering procedure in general, since it produces in total higher number of packet losses compared to the fuzzy-based solution. This phenomenon could be improved using tree optimization and re-configuration techniques.

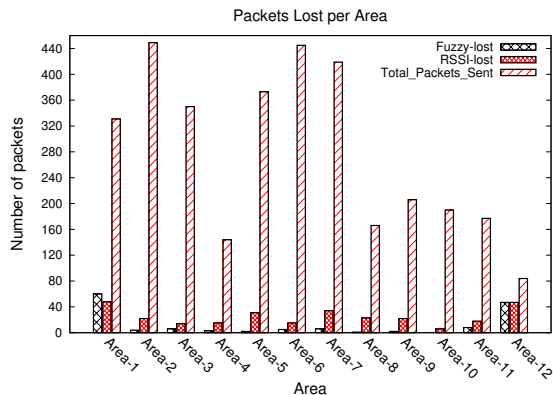


Fig. 9. Packets Lost per Area

Finally, Figure 10 shows the loss rate per area where we can observe that, in case of Area 12, more than the half packets transmitted were lost. This is caused by the fact that Area 12 is the area with the lowest coverage percentage (see Table III). Therefore, none of the solutions can handle adequately this situation. On the other hand, we can see that the fuzzy-based solution managed to maintain good links in the remaining areas since as it is observed that the loss rate

is much less than the RSSI-based solution; that is, it offers higher reliability. Based on the results we conclude that the handoff triggering operation of the fuzzy solution is obviously much more effective.

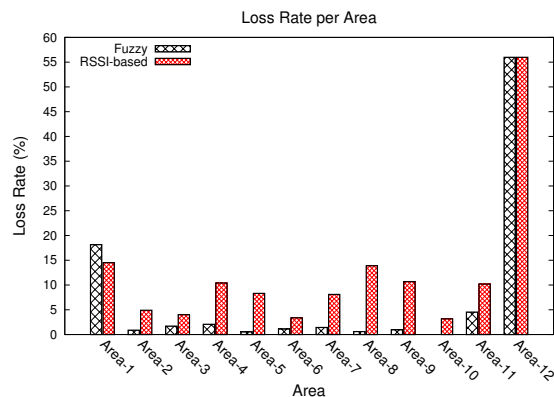


Fig. 10. Loss Rate per Area

VI. CONCLUSIONS

Supporting mobile users inside hazardous areas requires a mechanism that will be designed to support the mobility process, is able to guarantee easy connectivity, and can provide controlled performance. In this paper, we present a mobility solution in WSNs that is created to support mobile workers inside a refinery environment. The main objective was to optimize the handoff triggering procedure and to maximize reliability. We conclude that using fuzzy logic techniques to support the mobility procedure, higher reliability is achieved by means of minimizing the packet losses and at the same time the number of unnecessary handoffs is minimized, as compared with the conventional RSSI-based solution. As future work, the evaluation of the proposed mobility solution as applied in the real testbed of Sines refinery will be shown. In addition, we aim to extend the evaluation efforts to assess the applicability of the proposed approach in other WSN topologies and deployments.

Acknowledgements

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