WSN Mobility Support for e-health Monitoring Using an Industrial Setting

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***Abstract*—A number of sensor network applications are envisioned to be applied to industry settings where the existence of mobile nodes (MN) is required. In critical applications, the real-time monitoring of a MN must always be available, something that requires the existence of a suitable mobility protocol to control the handoff procedure. In this paper, we use data from an industrial testbed to perform a comprehensive performance evaluation of different mobility solutions based on single- and multiple- metric options. The results show that a fuzzy logic based approach performs better compared to any single metric-based approach.**

***Index Terms*—Sensor Networks, Mobility Management, Fuzzy Logic**

I. INTRODUCTION

Wireless sensor networks are used in different application domains to detect emergency events and/or monitor physical parameters of interest. In such kind of applications, static sensor arrays are deployed to collect sensor readings from large or remote geographical areas to a central point. Therefore, algorithmic research in WSN has mostly focused on the study and design of energy-efficient and scalable algorithms for data transmission from the sensor nodes to the base station. Recently, the WSN applications have experienced a paradigm change from static deployments to dynamic environments, meaning that mobile sensor nodes exist. In addition, there has been a shift from applications without strong requirements on timeliness and reliability to new application types that require the collection of critical data under strong performance requirements. It is, therefore, not difficult to envision scenarios within such demanding applications and settings where mobility would also be required [1] [2] [3].

Mobility management deals with all actions that must be taken in a network to support the movement of mobile users without losing connectivity. When a mobile user/node moves to a new location it has to establish a new radio link with the target base-station/access-point/neighbor and release the connection with the previous, in a process called handoff. A basic handoff process consists of three main phases: (a) triggering phase, dealing with initiating the handoff, (b) the decision phase, dealing with the algorithm parameters and handover criteria, and (c) execution phase dealing with the executions of the handoff [4].

Supporting mobile nodes in an industrial environment is something that the existing industrial standards like WirelessHart [5] and ISA100 [6] do not give special attention to. WirelessHART and ISA100.11a use a centralized network management approach for communication scheduling. Despite the advantages of such approach when the network topology and application requirements are static and heavily preconfigured, it is not certain how these standards perform in dynamic situations involving node mobility. The inability to properly handle mobility may result in problems, including increased packet loss, delayed data delivery, and increased downtime, all of which increase the overall energy consumption. This becomes of utmost importance if we consider specific critical application like the health monitoring of a refinery's worker where a real-time monitoring system must always be available.

The paper is organized as follows. In Section II, the related work is presented. In Section III, the system and network architecture is presented, while in Section IV the basic methods for handoff control in industrial WSNs are discussed along with the fuzzy logic-based mobility approach. In Section V, the experimental evaluation and performance analysis are presented. Finally, in Section VI the conclusions of this work are offered.

II. RELATED WORK

The importance of the Received Signal Strenght Indicator (RSSI) metric as a quality indicator was argued in [7] where the authors have shown that generally for RSSI values greater than -87dBm the resulting Packet Reception Rate (PRR) is at least 85% indicating a very good link. Finally, they concluded that protocol designers looking for inexpensive and agile link estimators may choose RSSI over the Link Quality Indicator (LQI). In order to select the triggering threshold value several approaches have been proposed [8], [9]. Based on the these works the RSSI threshold value varies from -90dBm to -75dBm depending on the evaluation environment and on the targeted PRR.

Several works using fuzzy logic techniques appeared in the field of mobility management, with the majority targeting the support of vertical handoffs. In [10], a handoff decision for heterogeneous networks is identified as a fuzzy multiple attribute decision-making problem and fuzzy logic is applied to deal with the imprecise information. In [11], a handover algorithm is proposed to support vertical handovers between heterogeneous networks. This is achieved by incorporating the mobile IP principles in combination with fuzzy logic concepts utilizing different handover parameters. Furthermore, in [12], the authors deal with a vertical handover decision algorithm based on the fuzzy control theory. The algorithm takes into consider the factors of power level, cost, and bandwidth in order to decide about the vertical handover.

Effort in the industrial field usually considers the definition of several applications that use sensors nodes in order to perform a monitoring task. For instance, Salvadori et al [13] describe an application to monitor electrical systems, Merrett et al [14] describe an application to monitor water-pumping stations, and Ramamurthi et al [15] consider industrial control. Despite that, the applicability of the proposed systems in real environments is not validated. In addition, RACNet [16] is a sensor network that monitors a data center's environmental conditions. They maintain robust data collection trees rooted at the network's gateways. The performance results of this work were promising since they have shown a data reliability up to 99% and timely delivery of data. Even though there are some similarities with the objectives of this work concerning the general architecture and the performance issues, like tree topology and high reliability, there is one major difference that distinguishes both works and makes the contribution presented in this thesis unique in the fact that it supports mobile users.

In this work, we use a fuzzy-based solution that does not change the existing conventional algorithms, but uses operations of them in order to provide a system that will manage to control the handoff procedure and provide improved performance. In addition, our target is to provide a distributed solution, meaning that there should not be any central entity with full knowledge of the system and in turn decide about the handoff procedure. Therefore all the information, which is used, is locally available at each node and no communication overhead is added.

III. SYSTEM AND NETWORK ARCHITECTURE

The main architectural characteristics that were assumed in the system design are the following:

1) The network is made up of resource constrained embedded systems where the majority of the nodes are deployed in fixed and predetermined positions.
2) Nodes report data frequently with relatively high rate (up to once per second) and data must reach the sink within a given time bound Ts.
3) The network uses multi-hop communication through a tree-based topology. The tree consists of H layers, where H is equal to the number of hops from the sink.
4) The network topology is controlled dynamically. Each node is attached to the best available tree position during the construction of the network topology.
5) Each node can set its slots to the following modes: trasmitting, receiving, idle, and scanning.
6) Use of a TDMA-based MAC protocol. Time is divided into epochs where each epoch has a predefined number of slots. Every node is assigned specific slots to transmit and receive packets.

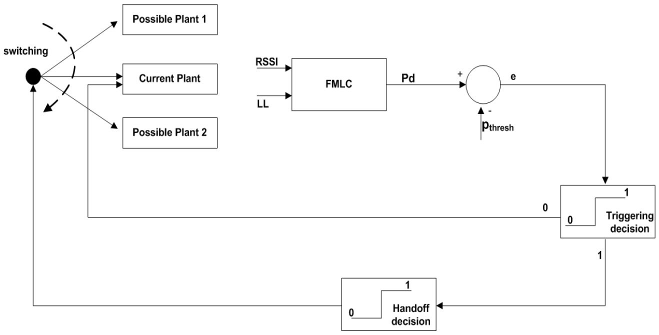

Figure 1: Fuzzy Logic-based Mobility controller (FLMC)

IV. MOBILITY SOLUTIONS

A. Single Metric-based Solutions

The first phase of a handoff deals with the triggering/initialization of the whole process. A range of metrics could potentially be used in the triggering procedure. Authors of [18], focused on two easy-to-find local values, namely the RSSI and the Local Link Loss (LL) in order to support the triggering of the handoff. Using these two metrics, they envisioned several triggering variations like their Simple Moving Average (SMA), Estimated Weighted Moving Average (EWMA) and Burst losses. In this work, we will use these single metric-based option to compare them with the multi-metric based solution.

B. Fuzzy Logic-based Mobility Controller Solution (FLMC)

Due to the highly dynamic nature of industrial environments we believe that the use of fuzzy logic to control the triggering procedure is an appropriate approach. The selection of fuzzy logic is supported by the fact that it can handle multiple inputs with minimum overhead. Thus, we utilized a two-input, single-output fuzzy controller on each sensor MN in WSNs [19].

The FMLC is shown in Figure 1, where all quantities are considered at the discrete instant kT:

1) T is the sampling period. The sampling period is equal to the time bound Ts.
2) RSSI(kT) is the signal strength indication, taken every sampling period.
3) LL(kT) is the link loss rate measured at each sampling period.
4) Pd(kT) is the calculated decision point that triggers the handoff procedure
5) $SGi_{1,2}\,(kT)$ are the input scaling gains.
6) $P_{Threshold}$ is a predefined threshold that indicates if the the specific $Pd(kT)$ will trigger the handoff

The FLMC follows a distributed approach allows the system to adapt quickly to disturbances or changes within the network in real-time. This approach also includes some other critical targets like learning how the testbed environment operates.

Table I: Simulation Parameters

Simulation Time	2000 seconds
Testbed Size	35 x 25 meters
Transmission Range	20 meters
Number of fixed/mobile nodes	13/1
Mobility model/Waypoint paths	Random Waypoint /10
Packet Rate	1 packet / 3 seconds
Topology	tree-based (3-2-1 tree)
Number of free tree positions	2

Table II: On-Time Triggering Results

Solution	On-time
RSSI Threshold, -78dBm	32.4
EWMA RSSI, $t = 5, a = 0.33$	17.92
SMA RSSI, $n = 10$	22.2
Link Loss, Threshold 1%	45.3
EWMA Link Loss 10%, $t = 5, a = 0.33$	21.6
SMA Link Loss 10%, $n = 10$	38.9
Fuzzy, $P_{threshold} = 0.16$	54.2

V. EVALUATION

In the experiments, we used the COOJA [20] simulator and refinery data to mimic the behaviour of an industrial refinery setting. The basic parameters that were used for our simulations are shown in Table I. In the following evaluation section some of these parameters are modified in order to show the applicability of different solutions under different settings based on their comparison, which is the main purpose of this paper.

A. Evaluation of the On-Time Triggering

The first evaluation scenario deals with the use of the basic configuration as shown in Table I in order to measure the on-time triggering. The on-time triggering indicates if the MN initiates (triggers) the handoff on-time when the one-hop link quality between the MN and the attachment node is not sufficient. The results are shown in Table II where we can observe that the Fuzzy Logic solution with specific $P_{threshold} = 0.16$ present the higher on-time triggering. The selection of the specific parameters of the single metric -based solutions was based on the evaluation section presented by the authors of [18] and the values shown in Table II are based on our simuation scenario configuration.

B. Evaluation using different Packet Rates

In this set of experiments, we have changed the application packet rate from 1 packet per 3 seconds to 1 packet per second in order to conclude if the packet rate affects the overall performance. We performed 100 experiments and the results are shown in Figures 2-5.

Based on the results, it is clear that the higher data rate does not affect the operation of the mobility solutions since in all the metrics the results are close to the lower packet rates results. The only remarkable point is the fact that in case of higher packet data rates (ex. 1 packet per second) the total power consumption is increased. This is due to the increased number of packet transmissions.

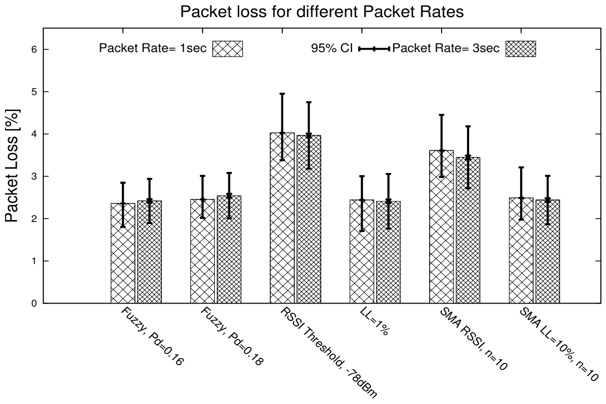

Figure 2: Packet Loss comparison of different Packet Rates

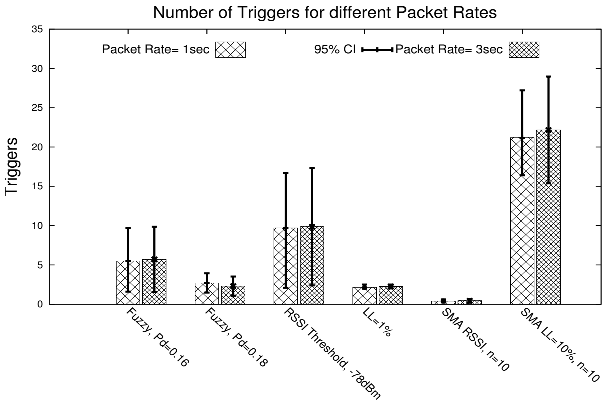

Figure 3: Triggers comparison of different Packet Rates

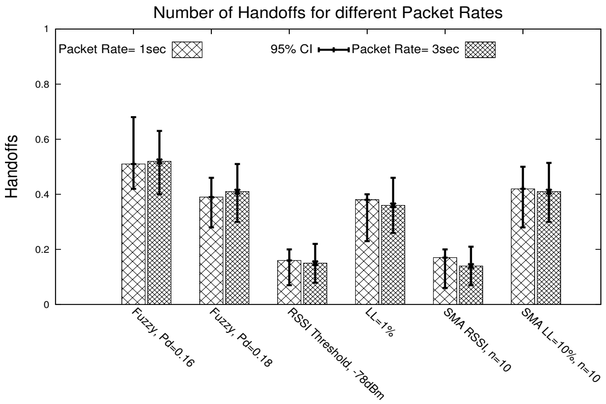

Figure 4: Handoff comparison of different Packet Rates

C. Evaluation using different Trees and number of Nodes

A new set of experiments was performed in order to identify how different tree structures and number of nodes affects the overall performance of the system. We selected the new tree to be the 4-2-1 (Figure 6) tree which supports in total 21 nodes compared to 16 nodes supported by the 3-2-1 tree.

In these experiments, we considered two different scenarios. In the first scenario, we used the 4-2-1 tree with the same number of nodes and the same placement as in case of the

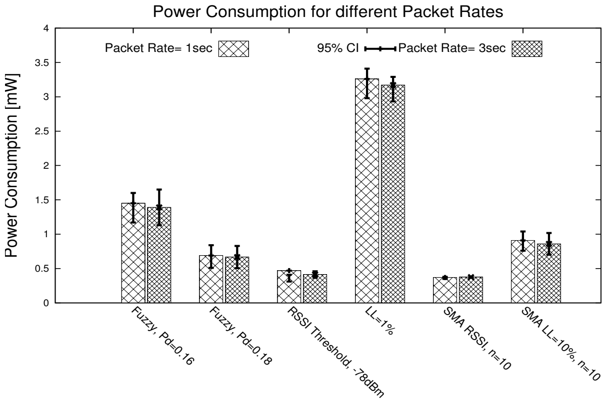

Figure 5: Power Consumption comparison of different Packet Rates

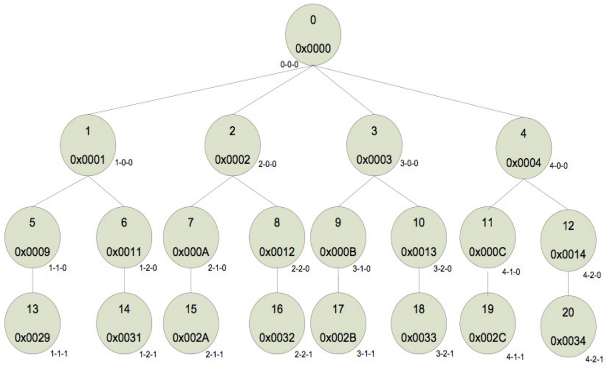

Figure 6: 4-2-1 Tree Topology

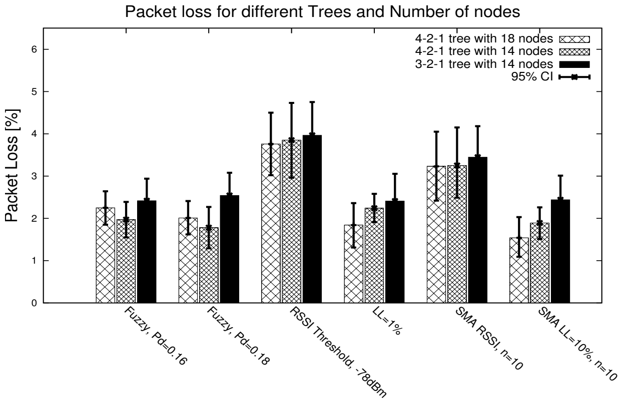

Figure 7: Packet Loss comparison of different Tree and Nodes

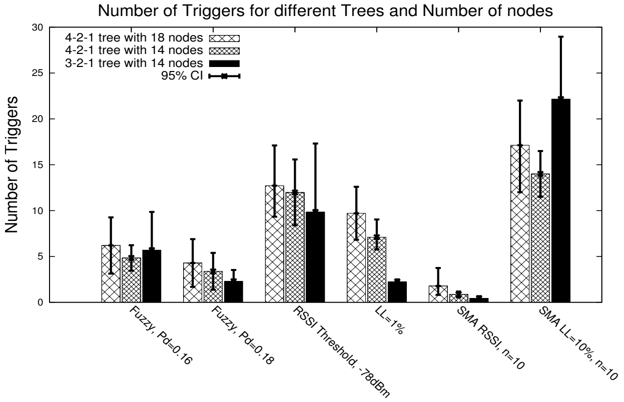

Figure 8: Triggers comparison of different Tree and Nodes

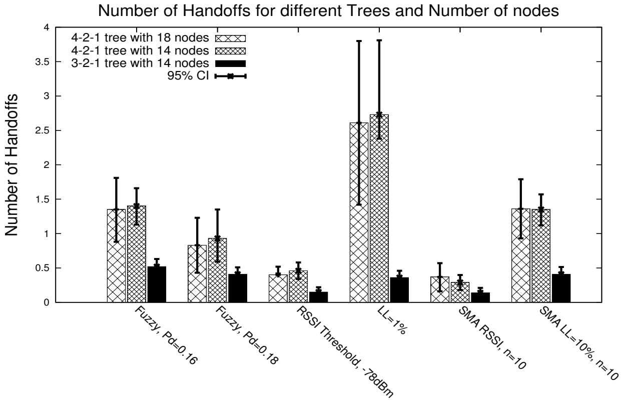

Figure 9: Handoff comparison of different Tree and Nodes

3-2-1 tree, meaning 13 fixed nodes and one MN with the refinery placement. Therefore, this scenario provides more free positions for the MN to handoff. In the second scenario, we used the 4-2-1 tree with 17 and 18 accordingly fixed nodes and one MN. For the 13 fixed nodes we had the same placement as in the refinery topology and the 4 or 5 new nodes were randomly distributed in the testbed area. This scenario provides higher connectivity due to the extra nodes than the 3-2-1 and 4-2-1 with 14 nodes.

We then proceeded with the evaluation of the 4-2-1 tree. Regarding the packet losses as shown in Figure 7, we observed that both scenarios using 4-2-1 tree provide fewer losses compared to the basic 3-2-1 tree scenario. This is explained in two ways: in case of 4-2-1 tree with 18 nodes the reduction is due to the connectivity improvement that was achieved by the 4 randomly placed nodes, where in case of the 4-2-1 tree with 14 nodes the reduction is due to the extra attachment positions, which means that the MN can easier find a new better attachment point to connect.

Figure 8 shows the total number of triggers. We see that the number of triggers in case of 4-2-1 scenarios is bigger compared to the 3-2-1 basic scenario. This is due to the fact that the triggers led to increased number of handoffs and therefore the MN is not continuously (using the same trigger) searching for a new attachment point. Despite that someone could claim that this could be a drawback, observing Figure 10 we conclude that 4-2-1 could have more triggers but the scanning duration is smaller since it has more free positions or better placement, therefore the power consumption is less.

In Figure 9, we observed the total number of handoffs where both scenarios using 4-2-1 present higher number of handoffs. Again, this is due to the extra free positions and to the better coverage of the testbed area.

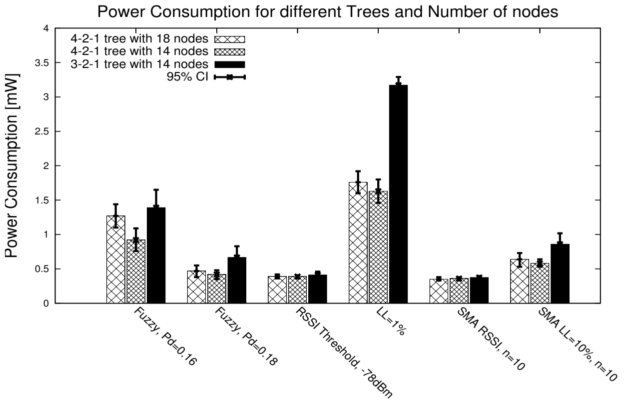

Figure 10: Power Consumption comparison of different Tree and Nodes

Finally, Figure 10 shows the total power consumption where we can see that, in general, the power consumption of both 4-2-1 tree scenarios is less compared to the 3-2-1 basic scenario. This is due to the fact that in 3-2-1 basic scenario the scanning periods are longer since the MN has less free positions and worst coverage than the 4-2-1 tree scenarios. Concluding, based on the results presented in this sub-section, we can assume that the different mobility solutions are not affected by the different tree structure or larger number of nodes since the performance comparison between them is the same, fuzzy logic performs always better than any other solution. Despite that, it is clear that a tree with more free positions or a scenario with more nodes that provide better coverage will lead to an improved performance.

VI. ADAPTIVE FMLC

Based on the results presented until now, it is clear that the use of Fuzzy Logic-based triggering outperforms any other triggering option. The only point that someone can argue about the performance of the Fuzzy Logic-based solution is the power consumption which in some cases is increased. In order to minimize the power consumption, we must first identify the reason of this behaviour. Using the "problematic" scenarios regarding the refinery environment, we observe that the reason of the increased power consumption was the long scanning period in some scenarios where the node did not manage to find a new attachment point. The way of initiating and terminating the scanning mode is critical. For example the lowest power consumption is appeared using the RSSI-based solution. The reason for this is the overall behaviour of the RSSI since the trigger is terminated as easily as it is initiated. Therefore, although this solution presents high number of triggers, the duration of the scanning period is small, hence the power consumption is low. On the other hand, the Link Loss triggering shows the exact opposite behaviour since it triggers the handoff fewer times but the duration of scanning period is high (especially when the threshold is low (1%)). Finally, the Fuzzy Logic-based solution presents in the 60% of the scenarios, low power consumption where in the remaining scenarios the power consumption is high. In order to solve this issue, we optimize the FLMC using adaptive thresholding, meaning that we adaptively change the $P_{threshold}$ during running time instead of having a fixed value, which was the case until now. The implementation and the operation of the adaptive functionality must be kept as simple as possible so that to avoid extra overhead on the system operation. In order to adapt the $P_{threshold}$, we selected two metrics where the first relates to the scanning duration and the other relates to the burst losses. The meaning of the first metric is to increase the $P_{threshold}$ when the MN operates in scanning mode for x continues epochs and the meaning of the second metric is to decrease the $P_{threshold}$ when burst losses occur. The second metric could also be used to increase the on-time triggering. Figure 11 shows the modified FLMC system after the addition of the adaptive thresholding module.

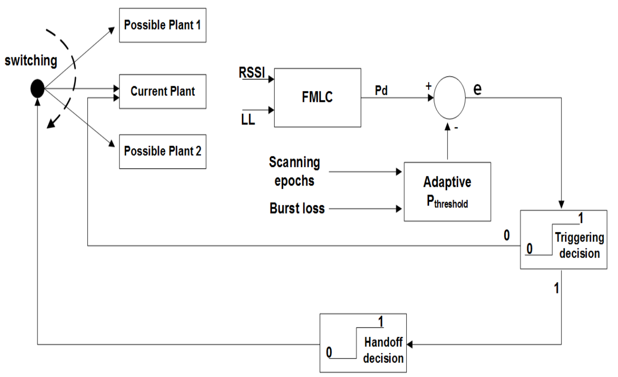

Figure 11: Fuzzy Logic System

In order to evaluate the updated system we set the $P_{threshold} = 0.16$, the scanning epoch threshold equal to 5 and we assume that we have burst losses if 3 consecutive packet are lost. Algorithm 1 shows the algorithm implemented to adapt the $P_{threshold}$.

Algorithm 1 Adaptive Thresholding

```
if $cont\_scanning > 4$ & $burst <= 2$ then
    $P_{threshold} = P_{threshold} + 0.01$
else if $burst > 2$ then
    $P_{threshold} = P_{threshold} - 0.01$
else
    $P_{threshold} = P_{threshold}$
end if
```

We ran the simulations of the FLMC system with adaptive thresholding using the same simulation parameters as previously. We compared the performance of the adaptive thresholding $P_{threshold}$ with the performance of the fixed $P_{threshold} = 0.16$. Figure 12 shows the comparison results. It is observed that using the adaptive feature, the packet loss was reduced by 6% and the power consumption was reduced by 59.6%. In addition, we have a small increment for the handoffs and an increment of 50.4% for the triggers.

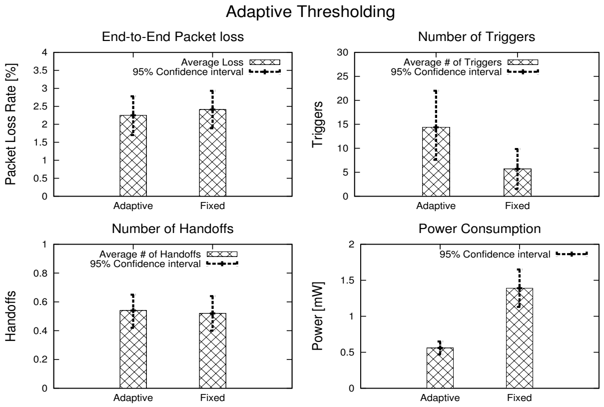

Figure 12: Adaptive Thresholding

In addition to the above, Figure 13 shows the comparison of the on-time triggering. It is obvious that the adaptive thresholding increase the on-time triggering due to its ability to adapt the $P_{threshold}$ based on the burst losses.

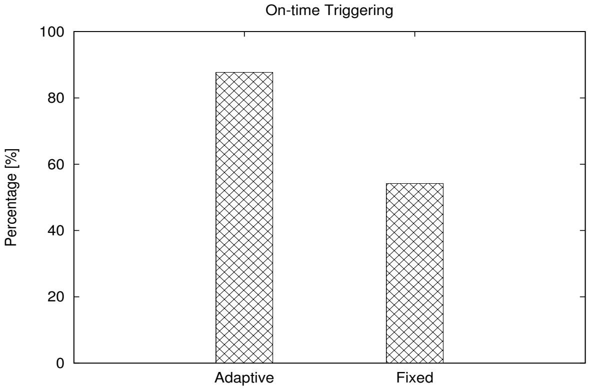

Figure 13: Ontime Triggering Adaptive Thresholding

VII. CONCLUSIONS

In this paper, our objective has been to ... The results clearly show that the proposed mobility solution outperforms any single-based mobility solution, in terms of packet loss, power consumption, and on-time triggering. Finally, in order to further improve the performance of the Fuzzy Logic-based solution we implemented an adaptive thresholding solution with the main target to reduce the power consumption and to increase the on-time triggering. It worths to mention that the proposed approach can be used over any underlying architecture since it was designed in a way that requires only the existence of two general metrics, the RSSI and the Link Loss.

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