Location-Aware MAC Scheduling in Industrial-Like Environment

Maurizio Rea[1,2](✉), Domenico Garlisi[3], Héctor Cordobés[1], and Domenico Giustiniano[1]

[1] IMDEA Networks Institute, Madrid, Spain
maurizio.rea@imdea.org
[2] University Carlos III of Madrid, Madrid, Spain
[3] CNIT and University of Palermo, Palermo, Italy

Abstract. We consider an environment strongly affected by the presence of metallic objects, that can be considered representative of an indoor industrial environment with metal obstacles. This scenario is a very harsh environment where radio communication has notorious difficulties, as metallic objects create a strong blockage component and surfaces are highly reflective. In this environment, we investigate how to dynamically allocate MAC resources in time to static and mobile users based on context awareness extracted from a legacy WiFi positioning system. In order to address this problem, we integrate our WiFi ranging and positioning system in the WiSHFUL architecture and then define a hypothesis test to declare if the link is in line-of-sight (LOS) or non-line-of-sight (NLOS) based on angular information derived from ranging and position information. We show that context information can help increase the network throughput in the above industrial-like scenario.

Keywords: MAC scheduler · Indoor localization system
Context awareness

1 Introduction

Pervasive positioning is a cornerstone to enable several data analytics and applications. While Location-Based Service (LBS) providers are ready to exploit new and better position information for data analytics for personalized services, the potential for networks applications of positioning data remains largely unleashed. Position could provide a much greater benefit to network applications than what done so far. In fact, localization may be exploited not only as a service offered to customers, but also in the network core to support anticipatory networking, enabling reliable mobile communications via advanced resource management policies and adaptive traffic engineering strategies. Last but not least, experimental evaluation in this research field is still in its early stage, as it is requires

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the integration of several network and positioning software and hardware components involving a large scientific and engineering effort. As a result, there is limited experimental understanding of what is possible to do coupling position and communication. Of particular interest for this paper is the medium access control (MAC) protocol, that serves a vital role in every network. It is directly responsible for controlling access to the shared communication resources. In most cases, the network designer does not know about the network conditions and has to assume that they may change during operation. The usual approach in most MAC protocols to handle unknown or changing conditions is to include some adaptation mechanism in order to adjust the operation to the actual network load and signal-to-noise ratio (for instance, using a different modulation scheme), and recover from failures in data transmission (for instance, detecting collisions). The objective of this work is to investigate how to dynamically allocate MAC resources in time to both static and mobile users based on context awareness extracted from a legacy WiFi positioning system. For our study, we consider an environment strongly affected by the presence of metallic objects, that can be considered representative of an industrial indoor environment with open spaces with metal obstacles. The scenario under study is a very harsh environment where radio communication has notorious difficulties. One of the key aspects is the fact that metallic objects create a strong blockage component, which must be taken into account for the MAC adaptation strategies. These types of environments are of particular interest with the advent of Industry 4.0 solutions to automate manufacturing technologies [3].

In order to address this problem, we first integrate our legacy ranging and positioning system [4] in the WiSHFUL architecture [6], which fully supports hybrid (centralized and distributed) control and network intelligence. We then define a hypothesis test to declare if the link is in line-of-sight (LOS) or non-line-of-sight (NLOS), and thus take effective actions in the allocation of MAC resources. Our preliminary experimental results show that this statistical angular information can help increase the network throughput in the above industrial-like scenario for static and mobile (robots) devices.

2 Motivation

This work targets the investigation and analysis of MAC scheduling strategies with static and mobile users operating in an industrial-like scenario (w.iLab.2 testbed[1] [1]). The environment under study is full of metal objects which block RF signals and cause strong reflections (impacting on the quality of the measurements). The problem we want to address in this work is whether location information can be used to optimize MAC scheduling decisions. The fundamental questions we want to investigate are:

- Can we improve network performance integrating positioning data in the MAC scheduler in mobile contexts?
- How well experiments can help us designing better MAC schedulers?

[1] http://doc.ilabt.imec.be/ilabt-documentation/.

– What gain is expected with respect to a classical approach without location and context knowledge, given that location information is far from perfect and it is subjected to position error?

In addition, there is very limited experimental work on MAC scheduling strategies that exploit a prototype location system. While this work does not provide a full answer to a vast topic, yet we believe it explores new directions of investigation.

3 System Architecture

As we aim to investigate how location information can help MAC protocols, we integrate our WiFi positioning system in the WiSHFUL architecture [6], which fully supports hybrid (centralized/distributed) control and network intelligence. The WiSHFUL control framework is provided as an open-source solution and it fully supports several type of devices, sensors and nodes wireless. The WiSHFUL control framework is based on a two-tier architecture which enables local, global and hierarchical control programs, thus supporting dynamic aggregation of radio monitoring by different nodes and configuration parameters. Nodes can be monitored and controlled individually or in clusters, by exploiting control services devised to coordinate through Unified Program Interface (UPI) calls, a very convenient programming interface that abstracts from the physical device an thus allows to make controlling programs independent from the device brand, model or even technology. Another significant aspect of WiSHFUL is the aim in reproducibility of results, as every experiment is programatically controlled in its entirety, even robot paths. As such, by integrating the positioning system, we can create reproducible location-based experiments for MAC scheduling. WiSHFUL integrates multiple experimentation platforms for which a software architecture devised to simplify MAC or PHY protocol prototyping was already available. In this work we use the provided Wireless MAC Processor (WMP) platform [7]. The WMP platform was developed exposing an API for controlling the driver, by enabling the possibility to specify the configuration parameters of the WiFi chipset in a declarative language. The API also supports a time-based channel access scheme based on functionality developed under the API to enable a Time-Division-Multiple Access (TDMA)-based scheme. This is performed by specifying the time intervals (slots) in which nodes, specifically packet flows, are allowed to transmit running the usual DCF scheme. The TDMA mechanism has been enhanced in this work to allow for finer scheduling decisions, as we will show next. **Control of TDMA resources allocation.** In order to dynamically allocate MAC resources based on context awareness, we implement both global and local control programs which make use of the WMP platform. The WMP implementation covers both the standard 802.11 CSMA/CA as well as TDMA access protocol or radio programs. For both protocols, communication occurs in the unlicensed 2.4 GHz band to unmodified target devices. In the TDMA radio program, the channel access is divided in periodic frames and each frame is divided in time slots. TDMA is a proven mechanism that can provide high throughput in high-dense environments. Each radio program can be activated after an explicit

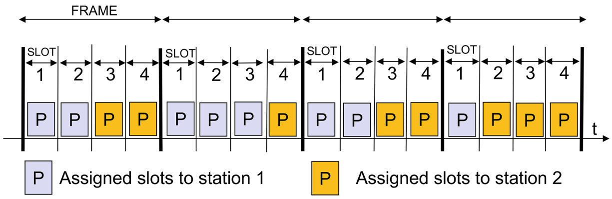


Fig. 1. WMP TDMA access scheme with pattern slots definition.

signaling from the control program and it receives parameters to configure channel access scheme. The TDMA radio program has three main parameters:

- TDMA_SUPER_FRAME_SIZE - Duration of periodic frames used for slot allocations in μs;
- TDMA_NUMBER_OF_SYNC_SLOT - Number of slots included in a super frame;
- TDMA_ALLOCATED_MASK_SLOT - Pattern of used slots in frame;

Figure 1 shows an example of 4 TDMA frames where two stations are active and each frame has 4 slots (pattern: "xxxx"). For instance, in the first frame, the TDMA_ALLOCATED_MASK_SLOT parameter of the station 1 is configured to use the slots 1 and 2 (pattern: "1100"), while the station 2 is configured to use the slots 3 and 4 (pattern: "0011"). The logic for activating the TDMA protocol and setting the relative mask pattern is embedded into the experiment control program.

4 Integration of Location System

In the following sections, we first review our legacy WiFi positioning system and then present our effort to integrate it in the WiSHFUL architecture. **Mobile Tracking System.** For the positioning system to help MAC-level decisions, we integrate our Time-of-Flight (ToF) based positioning system [4,5]. Our ToF-based positioning system uses COTS APs with customized firmware operating in the core of the 802.11 MAC state machine of a low-cost WiFi chipset. It can estimate the position of WiFi legacy devices. The distance from each AP to mobile targets is estimated with ToF two-way ranging measurements, taking advantage of DATA/ACK traffic exchange. Position estimates are then performed based on multi-lateration principle. The system is orchestrated by the Central Location Unit (CLU), which issues measurement rounds to the APs and generates traffic towards target devices. In our system, the APs are equipped with Broadcom WiFi chipsets that run our customized version of the 802.11 OpenFWWF firmware. ToF measurements are passed from the firmware to the open-source b43 driver running in the AP, and subsequently sent in a batch to the CLU. Details of the ranging technique and the overall system can be found in [4,5]. With these ToF ranges, the CLU estimates the distances to the

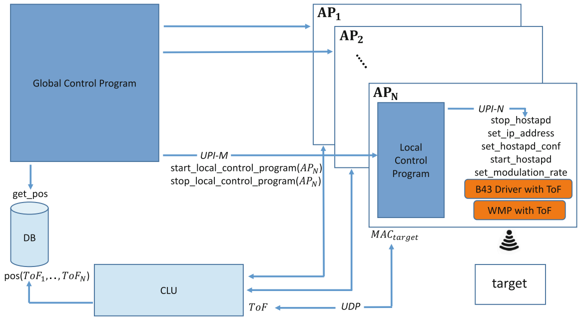


Fig. 2. System architecture: Positioning system integrated in the WiSHFUL framework

APs and the mobile position, and connects to a database where the results are stored, making the data available to location-based applications. **Details of the integration.** We integrate the positioning system to the WiSHFUL testbed (cf. Fig. 2):

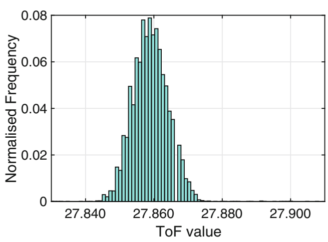
- The CLU is our main process, which runs, separate from the APs, on a server. It computes position estimates based on the ToF ranging information obtained from the APs and stores it on a Database (DB), so that it can be exploited by third parties.
- Upon a command from the CLU, the APs send probe packets to the target and measures the response time, which is sent back to the CLU. These APs run the WMP firmware, which enables them to obtain this information and pre-filters out invalid measurements. This is a mandatory step as this system makes use of standard 802.11 messages, so it is needed to identify and process only those messages used for positioning.
- The target is associated to any of the ranging APs by means of a specific SSID common to the whole set of APs. Being connected to one of the APs does not keep the device from responding on the probes from the rest of APs.
- Once the CLU receives all the measurements, it runs a series of algorithms to generate position estimates for that target and instant, and stores it on the DB so it can be retrieved later on by any other entity. In our case, the context-aware MAC resource mechanism.
- We control the whole system by a Global Control Program (GCP) deployed in the same server as the CLU, and we run a Local Control Program (LCP) in each of the APs to handle the elements through Unified Programming Interface (UPI) calls [2].

Evaluation of Ranging Technique. We study the distribution of the raw ToF samples, considering the original OpenFWWF firmware used in past works [4], and the modified WMP firmware used in this work. In Fig. 3(a), we show the results for the original OpenFWWF firmware used in the AP. In Fig. 3(b), we show the results for the modified WMP firmware. For both tests, the target is a B43 WiFi chipset with unmodified OpenFWWF firmware. From Fig. 3(a) and 3(b), we observe that the expected value is shifted. This is a minor issue, as it just needs to have a different reference (the value we identify as distance zero). Nevertheless, it requires some recalibration actions that we perform making multiple tests at given known distance. **Context-aware MAC protocol.** Once the positioning system is laid out, we use location data to elaborate different performance measurements using MAC protocols with context awareness at different positions on the test area. An illustration of the concept is presented in Fig. 4. The mobile measurements are done using mobile nodes (Turtlebot II Robotic platforms) as user equipment (UE), and configurable AP that use Alixes boards. Here, the MAC resources are configured to make measurements in different scenarios. All the control is performed from a controlling function running on the server. On the map in Fig. 5, we depict the area of interest for the experiments, of about 11×22 m. We use AP_1 and AP_4 as context-aware MAC APs, and all five APs for positioning. AP_1 and AP_4 run a program which can adapt the MAC resources. **Metallic obstacle management.** We consider a system where the network has access to the estimated UE location. We also consider that the location of metallic objects in the environment is known and so each AP should avoid to transmit to a UE if it can anticipate that the UE is going behind a metallic blockage. The reason is that the link would be totally disrupted in these conditions. In order to make such as decision, in the ideal case of perfect location position, the AP should "draw a line" between the AP and the UE, and verify if the metallic blockage is in-between. Since noise and obstacles affect the positioning system, the only line between the AP and the estimated UE location does not ensure that the UE is affected by blockage. For this reason, it is convenient to *map position information, including the error, into angular information*. We consider a scenario with a fixed AP and a mobile UE. We assume a two dimensional Cartesian coordinate system. The AP position is known and equal to $\mathbf{p}^{\mathrm{AP}} \in \mathbb{R}^{2\times 1}$. The UE real and estimated positions are $\mathbf{p}^{\mathrm{UE}} = P(x, y) \in \mathbb{R}^{2\times 1}$ and $\hat{\mathbf{p}}^{\mathrm{UE}} = \hat{P}(\hat{x}, \hat{y}) \in \mathbb{R}^{2\times 1}$, respectively, where $\hat{x} = x + e_x$ and $\hat{y} = y + e_y$. The terms e_x and e_y represent the location errors on the x- and y-axis, respectively. We model the error as a bi-variate normal distribution, where the statistical processes e_x and e_y have no correlation, and that e_x and e_y have zero mean. We can compute the *unit vector of the direction* between the AP transmitting data and the estimated UE position as:

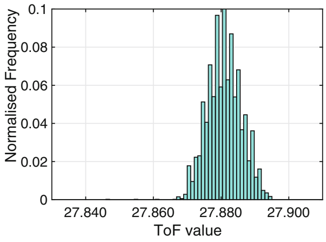
$$(\mathbf{p}^{\mathrm{AP}} - \hat{\mathbf{p}}^{\mathrm{UE}})^T / \|\mathbf{p}^{\mathrm{AP}} - \hat{\mathbf{p}}^{\mathrm{UE}}\|, \tag{1}$$

with the UE within the angular error of width 2θ based on trigonometric considerations, with

$$\theta = \sin^{-1}\left(\frac{\sqrt{{e_x}^2 + {e_y}^2}}{\|\mathbf{p}^{\mathrm{AP}} - \hat{\mathbf{p}}^{\mathrm{UE}}\|}\right). \tag{2}$$



(a) Original OpenFWWF firmware used in the AP.



(b) Modified WMP firmware used in the AP.

Fig. 3. Histogram of ToF values.

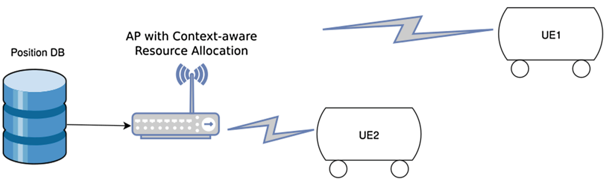


Fig. 4. High-level illustration to exploit context-aware decisions in the allocation of MAC resources.

We then introduce a simple criterion to infer the link state. Knowing the real position of the metallic obstacles, let us define the hypotheses H_1 and H_2 as:

$$\begin{cases} H_1 : \text{“LOS”} \\ H_2 : \text{“NLOS”} \end{cases}$$

The test is as follows. Accept H_2 if both conditions below are fulfilled:

- The position of an obstacle falls within the angular portion 2θ;
- The estimated distance $\hat{d} = \|\mathbf{p}^{\mathrm{AP}} - \hat{\mathbf{p}}^{\mathrm{UE}}\|$ is higher than the radius from the AP to the metallic object.

Stay with H_1 otherwise. Given the strong link quality degradation in presence of metallic blockage, we allocate the MAC resources only for those links that satisfies the hypothesis H_1 only. In this work, we consider a preset error of 3 m for our positioning system on the x and y axis, which represents fairly well the typical performance of our system observed in several scenarios [4]. The presence of more APs used for positioning guarantees that some of them is in LOS to the UE, which would guarantee fairly good location accuracy also in industrial-like scenario. This benefit would not be present directly computing angular information with phased array antennas with the AP communicating.

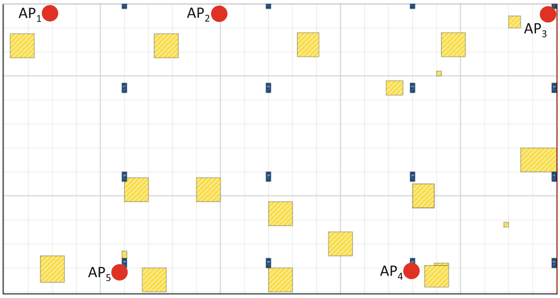
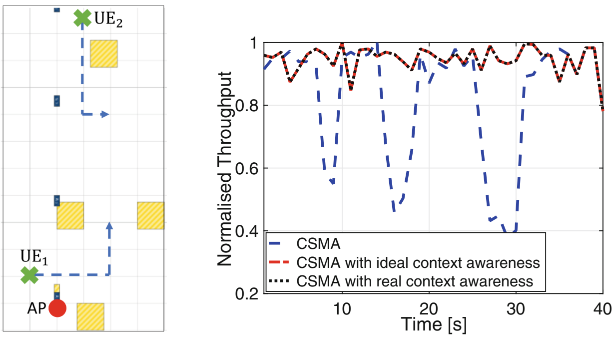


Fig. 5. Map of the testbed.

5 Exploitation of Context Awareness with CSMA/CA

The first scenario considers a MAC based on CSMA/CA with two mobile robots. We focus our attention on a specific scenario, shown in Fig. 6(a), where the positions of UE_1 (robot 15) and UE_2 (robot 13) are in movement with respect to the AP (alix02). The robots are initially positioned on the spots marked with a green cross. From this position, each robot requests access to the 802.11 network and a reliable link is established. The robots move along their given trajectories, and due to the environment (mainly metallic obstacles, marked on the map as yellow rectangles), from a given position and onwards the link quality decreases, drastically reducing the network throughput. To avoid this degradation we apply the method presented in Sect. 4 to allocate traffic only for links accepting the hypothesis H_1. Figure 6(b) shows the results in terms of network throughput, normalized with the respect to the maximum achieved throughput, along the 40-second UE_1 and UE_2 trajectories. Throughput is measured with the tool Iperf. Some time-aggregation effects may appear in the figure as the



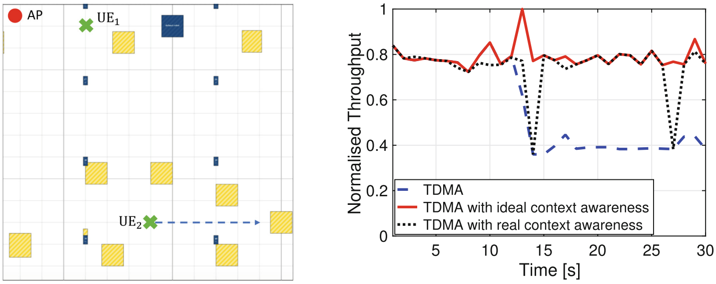
(a) Scenario 1. (b) Network throughput.

Fig. 6. Allocation of MAC CSMA/CA resources in presence of blockage with different resources allocation strategies in Scenario 1. (Color figure online)

measurement cycles may not match each other. When using simple CSMA/CA, the performance presents a degradation in accordance with the radio link blockage. As we know the real position of the user along its trajectory (this is possible thanks to the knowledge of the actual position as provided by the high accurate Localization and Positioning Engine, LPE, engine in WiSHFUL), we can verify the performance of the algorithm in the ideal condition where the direct link for UE_2 and the AP is subject to blockage and without any error in the position estimation. In case the link is in a NLOS state, we stop allocating traffic for the target, so other UEs may use the AP capacity, therefore maintaining the network throughput constant (red solid line, TDMA with ideal context awareness). Next, we use the positioning system as a source of context awareness information to compare a real-world scenario against the previous ideal scenario. In this case, we use the angular estimation as input to decide whether the UE is in a zone of low network coverage. The overall performance (dotted black line, CSMA with real context awareness) in our experiment shows no difference between real and ideal results, suggesting that the positioning error is low enough for the link decision. In fact, pointing at the estimated position of the user and taking its angular error, we have that the real position is inside the angular error (UE_2 in Fig. 6(a)), and so we cluster the links as NLOS as the real case. **Exploitation of context awareness with TDMA allocation.** We then study a MAC-based on TDMA allocation in two different scenarios. Implementation-wise, in the latter cases we do not stop the traffic, but we allocate different time slots, using the implementation presented in Sect. 3. In particular, the control program configures the TDMA assigned slot based on context awareness extracted from the positioning system itself.

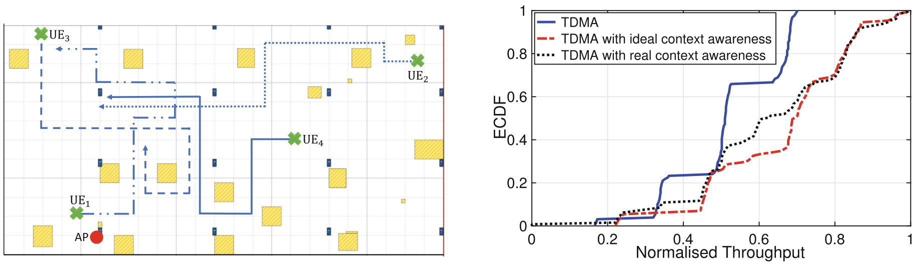
Two Target Devices. The second scenario is illustrated in Fig. 7(a) and it considers a MAC-based on TDMA allocation with one static and one mobile node. Specifically, UE_1 (robot 15) is fixed, while UE_2 (robot 13) is in movement with respect to the AP (alix02). We analyze the normalized network throughput along a 30-second trajectory. From Fig. 7(b), we observe that using simple TDMA with a fair (equality-wise) allocation of the resources (50%–50% with 2 nodes, blue dashed line), the performance presents a degradation in accordance with the radio link blockage. As stated before, if we are aware of the provided context information, we are able to avoid the overall degradation, therefore maintaining an optimal network throughput. The overall performance (dotted black line, TDMA with real context awareness) shows the throughput improvement compared to the simple-TDMA setting, but this time it shows some performance loss compared to the ideal case due to estimation error in the positioning. Yet, the gain with respect to a simple TDMA allocation of 50%–50% is evident from the figure.

Four Target Devices. The third and last scenario is illustrated in Fig. 8(a) and it considers a MAC-based on TDMA allocation with four mobile nodes. We analyze the normalized network throughput along 130-second trajectories.



(a) Scenario 2. (b) Network throughput.

Fig. 7. Allocation of MAC TDMA resources in presence of blockage with different resources allocation strategies in Scenario 2. (Color figure online)



(a) Scenario 3. (b) Network throughput.

Fig. 8. ECDF of the normalized network throughput for Scenario 3 with different MAC TDMA resources allocation strategies for scenario 3. (Color figure online)

We plot the Empirical Cumulative Distribution Function (ECDF) of the normalized network throughput in Fig. 8(b). We observe that using simple TDMA with a fair (equality-wise) allocation of the resources (25% for each node, blue line), the ECDF presents a maximum normalized throughput close to 0.7, which corresponds to the median value of TDMA with ideal context awareness. Also this time the dotted black line (TDMA with real context awareness) shows the throughput improvement compared to the simple-TDMA setting, and at the same time it shows some performance loss compared to the ideal case due to estimation error in the positioning.

6 Conclusion

The goal of this work was experimenting context-awareness capable MACs in industrial-like scenarios. Our WiFi positioning system has been integrated in the WiSHFUL testbed and we have elaborated simple MAC resource allocation strategies based on position estimations that effectively improve the performance of a network with high-load from stations at different positions and deployed in a harsh environment full of metallic objects and walls. The AP allocates the MAC resources depending on the estimated position of the mobile targets. We have shown the higher network performance of a context-aware strategy in presence of signal blockage from metals. While our results are encouraging, we stress that more studies should be conducted to understand how to exploit context information in diverse scenarios. Our metric is conservative and should be also improved to consider false positive detection of blockage. Yet we have proven that positioning mobile targets can already be beneficial in harsh environments and context data should be integrated in network protocol stack to optimize the overall network performance.

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