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Feasibility of Commodity WiFi for Operations Control in an Autonomous Production Site

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Abstract—Automated Guided Vehicles (AGVs) are increasingly being employed in logistics to carry out tiring and repetitive tasks inside large industrial buildings. In these settings, AGVs perform more efficiently than human workers in that they exhibit no signs of fatigue, their movements can be tracked automatically and their path can be timed to feed/collect objects in a quasi-predictable time frame and to even perform some object manipulations/refinement during transportation. In this article, we present a simulation analysis assessing the feasibility of commodity WiFi for operations control in an autonomous production site. In this context, AGVs and infrastructure endpoints are involved in periodic data exchange, the later gathering and acting upon AGV health data in order to ensure the systems operations continuity. To this end, we have setup a realistic simulation scenario mimicking the sites’ operational environment discussing some trade-offs that emerge.

Keywords—AGV; Fog Computing; Wireless Communication; Performance Evaluation

I. INTRODUCTION

The fourth industrial revolution (referred to as Industry 4.0) is taking place thanks to the continuous development of information and operation technology. In this domain, robotics is one of the principal technologies witnessing an increasing growth, with deployments continuing to take place in factories worldwide, employed to help human workers with many tedious, repetitive, and heavy jobs [1]. A remarkable example in this context is the Amazon Robotic system, in which Autonomous Guided Vehicles (AGVs) are utilized for logistics in e-commerce warehouses. To this end, a plant-wise, (semi)automatic coordination logic is employed ensuring the AGVs operations and their co-existence in a mixed human-operator/AGV environment [2].

A lot of research has been carried out in this domain ranging from AGV embedded control logic to system-wide control-theoretic approaches aimed at guaranteeing correct system behaviour, ensuring operational safety [3], [4]. Yet, AGV technology embodies many open challenges including but not limited to navigation, steering control, path decision, and traffic control [4]. These challenges are further exacerbated when considering the stringent Quality of Service (QoS) requirements that some deployment scenarios embody [5].

In this context, the cloud-to-thing continuum is a recent and natural evolution of the cloud-centric paradigm, including and accounting for additional, untapped resources found in the path towards the network edge. In this direction, a lot of research effort has been invested and several proposals have emerged with different levels of maturity and industry adoption. In specific, the mobile edge computing reference architecture proposed by the European Telecommunication Standards Institute (ETSI) [6], fog computing by the OpenFog consortium [7] etc. have acquired a lot traction and are seen as a viable solution capable of addressing deployment specific latency, security and reliability requirements [8].

In this article, we present a feasibility analysis of commodity WiFi through a realistic simulation study mimicking an autonomous production environment. The reference scenario is comprised of a multitude of WiFi-enabled AGVs and infrastructure endpoints, the later deployed locally and used to perform plant-wide diagnosis. Both AGVs and infrastructure endpoints are involved in continuous data exchange occurring under different operational regimes. Decision making at the infrastructure side has strict QoS requirements e.g., a failure of a production element (i.e., AGV not responsive), could have system wide consequences, stalling (parts of) the production or worse. The objective of this study is to assess the feasibility of commodity WiFi in sustaining frequent and periodically network operations.

The article is organized as follows: Sec. II provides relevant background on the 802.11 standard and negative phenomena one needs to be aware of and plan for. Section III introduces the reference scenario along with some practical deployment considerations. Section IV and Sec. V introduce different simulation scenarios mimicking realistic system behaviour, discussing the tradeoffs that emerge. Finally, in Sec. VI the conclusions are drawn.
II. BACKGROUND

The IEEE 802.11 standard is by far the most widely used wireless networking standard and its popularity has been driven by the convenience of untethered communications. While this networking standard provides a simple and intuitive network model based on the datagram delivery model of IP, it is ill-suited to QoS provisioning [9], [10].

In addition, the wireless medium is more prone to error and interference making QoS provisioning in this settings even more challenging. Differently from its wired counterpart in the LAN domain, the 802.11 is half-duplex in nature allowing for the transmission of only one packet at a time. As interference, errors, fading and mobility can cause a packet loss, the IEEE 802.11 MAC layer reacts through local retransmissions which, in turn, cause subsequent packets to queue up until the preceding ones or their retransmissions eventually reach the receiver. Last but not least, there is the probabilistic nature of the IEEE 802.11 medium access protocol, introducing an increased amount of time before attempting a retransmission [11].

The lack of a service differentiation mechanism further exacerbates the problem of QoS guarantees in the traditional IEEE 802.11. To this end, ensuring an acceptable QoS level, different metrics extracted from the general traffic layout have been adopted e.g., use of the goodput metric as a measure of packet arrival rate during a certain period of time; load level indicating the usage of a medium on a given time frame; and available bandwidth measuring the rate which new flows can send traffic without impairing existing traffic in the network etc. Since its deployment, a lot of research effort has been devoted to tackle the various issues, addressing the problems at different layer of the TCP/IP protocol stack ranging from physical to the application layer [12], [13], [14].

In the next section, we briefly present the scenario of interest consisting of an autonomous production site and mobile robots involved in the transportation of goods from/to different production areas. The mobile robots (AGVs) periodically and continuously transmit and receive data from health/operational data to infrastructure endpoints. The data is exploited to by intelligent, locally deployed algorithms ensuring operations continuity and correctness. Considering the 802.11 dynamics, the goal is to assess whether a commodity WiFi network deployment is capable of sustaining the network load while meeting the plants operational constraints in terms of message delivery times and losses.

III. THE PRODUCTION SITE

Figure 1 presents a high level view of the reference scenario of interest, consisting of an autonomous site divided in different areas of production each equipped with specialized machinery handling parts of the process. Mobile AGVs move between the areas of production at a near constant speed of 1 m/s along a-priori designed paths, transporting materials from one area to the other. AGVs are equipped with a 802.11 interface and an on-board battery resource which is periodically recharged at designated stop points.

Triangles denote the WiFi-enabled infrastructure endpoints, customized access points (APs) running dedicated logic, used to collect health data from the AGVs, continuously monitoring plant operations in order to ensure operations continuity. To this end, all the actors are involved in a continuous feedback loop exchanging messages amongst each other. The messages contain essential information used for monitoring and diagnosis purposes. Without loss of generality, in a case of an AGV component malfunction reflected in the data transmitted from the AGV to the infrastructure, the infrastructure endpoint in charge might issue a shutdown command, effectively excluding the AGV from the production chain. The entities are governed by proprietary software which is outside the scope of this article.

Table I provides some additional details concerning the data packets from/to the AGV and the APs. These data are transmitted and should be delivered inside a so-called operational regime. This duty cycle entails the transmission and reception of unicast data from/to AGV and AP. A desirable operational regime should not exceed a duty cycle of 100 ms, that is all exchanged data have value only in case this are transmitted and received inside this timeframe. Data freshness is more important than the reliability of individual messages.

In the following, we discuss the simulation scenario and the relevant metrics used to assess the feasibility of WiFi in support of operational continuity. To this end, we start
with a simulation study considering multiple APs serving the production site and successively assess the operational limits of a single WiFi AP scenario with varying number of served AGVs and different operational regimes.

IV. MULTIPLE AP SCENARIO

To evaluate the 802.11 network conditions, hence the feasibility of employing commodity WiFi, we measure the packet loss and the end-to-end (e2e) delay metric for both sides of the communications involving the AGV/AP pairs. The end-to-end delay measures the time lapse between the transmission time of a data packet and the time the packet is received by the counterpart involved in the communication. This metric serves as an indication of the utility of the packet delivery time, that is, if the message is delivered outside an operational cycle. In case the message is delivered outside the time horizon identified by the duty cycle i.e., due to congestion phenomena, the corresponding utility is null. As mentioned before, we are not solely interested in delivering the data but more importantly in its freshness.

Figure 2 depicts the simulation scenario comprising different production paths and respective AGVs. Mobile AGV distribution along each path can vary and is planned a-priori. Concerning the AP distribution and deployment model, in this current setting we employ one AP per production path, hence a subset of AGVs are controlled via dedicated WiFi APs. In this study, we rely on the 802.11n standard. To minimize inter-area interference the APs are configured accordingly and operate in non-overlapping wireless channels. APs, on their turn, send periodical status reports to a logically centralized monitoring station which has a global view of the entire plant operations. In the current study, the battery resource and dynamics associated to it are not taken into account.

A. SIMULATION PARAMETERS

We have implemented the scenario in the Network Simulator v. 3.25 (NS-3.25 [15]), a simulation framework well-renowned in the networking community. In specific, each AP is equipped and configure with a 802.11n (5 GHz) Phy/MAC operating in non-overlapping wireless channels. In this simulation scenario, a constant rate manager is employed, that is both WiFi control and data packets are transmitted using a constant rate and encoding scheme which do not adapt to sensed channel conditions.

The multiple AP scenario comprises a total of 5 APs and 116 AGVs moving at constant speed along the production paths. The green path (Fig. 1) represents a heavy loaded production path w.r.t to the red ones, hence the (sub)network controlling this area is subject to a higher load. For redundancy, this area traffic is handled by three APs with each AP handling a chunk of traffic from randomly selected AGVs. In the following, we assess different distribution schemes which are as follows:

- **Deployment(30/30/30)**: a total of 90 AGVs deployed on green (central) path. Each AP in this area monitors a total of 30 AGVs while other area APs monitor 13 AGVs each;
- **Deployment(13/13/64)**: the difference with the prior scenario is the distribution of the AGVs in the green path, where a single access point manages 64 AGVs and the rest (26) are equally divided among the other two APs, that is the upper and lower areas;
- **Deployment(19/19/40)**: 4 out of 5 APs manage 19 AGVs each with the exception of the one AP in the green path monitoring 40 AGVs.

It is noteworthy to point out that the division of AGVs along the production areas is a consequence of the production plant operational details and of little interest to this study. To model the traffic and the minimal application logic needed, we implemented an NS-3 application generating a constant bit rate (CBR) UDP traffic using the packet sizes reported in Tab. I. The data packets are generated with a periodicity of 100 ms, denoting the operational cycle or duty cycling regime. This value represents a desirable target and cannot be exceeded without a re-planning of the plants layout.

In the following, we discuss the packet loss and e2e delay metrics for each of the above configurations.

B. RESULTS

To increase the confidence in the obtained results, we perform 40 simulation runs for each available configuration and report the average values computed with a confidence internal of 95%. Figure 3 reports the packet loss of the individual deployment schemes under a duty cycle of 100 ms. A common trend noticeable in all distribution schemes, points to a higher packet loss for AP transmissions. This can be explained by considering the traffic generation pattern of the APs which needs to transmit several unicast data packets, one for each AGV under its management. On the other side, an AGV has to transmit a single packet inside an operational cycle. Also, one can observe a slight increase in packet loss from **Deployment(19/19/40)** to
Deployment(13/13/64) showing that a more homogeneous distribution of load among APs is beneficial. It is difficult to make any a-priori judgement on the acceptable packet loss ratio as it depends on the criticality of the control message itself. However, from the data available emerges a worst-case scenario, pointing to approximately 1 packet loss every 3000 operational cycles.

As discussed through Sec. II, MAC layer contention can give rise to undesirable effects; packets can get queued at the sending node and if not dropped, risk being delayed and possibly delivered outside the operational cycle. This phenomena might naively be interpreted as a packet drop. However, with network queues filling up, successive packet transmission and respective delivery delays accumulate and, may completely impair network operations.

To measure this phenomena, we compute the end-to-end delay of data at the application layer, denoting the time lapse between a message being sent and received by the intended destination. We measure the metric for both side of all communications. For the sake of brevity, we report the measurements from the Deployment(13/13/64) in Fig. 4 and Fig. 5. The other configurations show similar performance trends and do not present any anomaly.

Figure 4 shows that all the traffic from the AP managing 13 AGVs is delivered under 0.5 ms, well below the operational constraints. One can notice, a slight increase in delivery times of traffic originating from the AP managing 64 AGVs with 70% of traffic being delivered under 1 ms and 100% under 3 ms. Of course this increase is negligible and well below the upper bound. There is a difference between the end-to-end delay profiles of the AP and the AGVs (Fig. 5). The AGVs appear to be susceptible to more network contention when compared to the APs and this can be explained due to a higher, nearby crosstalk among neighboring AGVs. However, even in this case the data are delivered within the operational cycle.

V. Single AP Scenario

In this scenario, we are interested to understand the operational boundaries of a commodity 802.11n AP, that is answer to the following question: how many AGVs can be served by a single AP while adhering to the operational constraints imposed by the AGV control system operational regime?

To this end, we have devised a simulation scenario where AGVs are static and randomly positioned inside the area served by the WiFi AP. The simulation settings are the same as in the prior scenario with the sole exception that both the WiFi AP station and AGVs make use of the Minstrel [16] rate manager; a practical rate selection algorithm for commodity 802.11 radios and the default solution in the Linux kernel which is also available in the NS - 3 simulation framework.

To assess the feasibility of this scenario, we consider an operational regime of 100 ms and an additional, more constrained, setting amounting to a 50 ms control cycle. Figure 6 shows the packet loss in both configuration scenarios under varying number of served AGVs. In both configurations, the AP is susceptible to a higher packet loss.
when compared to the AGVs and this is to be expected considering the higher amount of control traffic it has to transmit. In particular, considering the 100 ms control cycle, the system can support up to 140 AGVs with less than 1% of packet loss, while this number is significantly lower in the 50 ms configuration. Indeed, to achieve a similar packet loss ratio, the 50 ms configuration could serve a number no higher than 65 AGVs.

Table II provides a summary of the delivery profiles and recommendations for the different configurations. Concerning the end-to-end delay, for sake of brevity, Fig. 7 reports the AP delay metric for the 50 ms operational regime. The configurations serving up to 65 nodes behave well, delivering all the data within an operational cycle. Increasing the number of nodes above 65 nodes, we notice the e2e delay is subject to an increase due to network contention, reaching values beyond the limits imposed by the operational cycle.

VI. Conclusion

Industrial automation is one of the sectors where traditional information technology cannot keep up with the necessary volume, latency, mobility, reliability, security,
privacy, and network bandwidth challenges. Thanks to the fog/edge computing paradigm, factories can become more connected, can take advantage of local data processing for standard operations, and can scale up with a more complex solution in the cloud in a seamless way.

In this article, we presented a simulation analysis mimicking a realistic autonomous production environment comprising a multitude of AGVs controlled by commodity WiFi APs. In this setting, AGVs periodically transmit and receive operational data to/from the fog/edge nodes. Timely data transmission and reception is of paramount importance for the correct behaviour of the overall system. Assessing the feasibility of the scenario, different scenarios were analyzed and operational regimes considered evidencing the tradeoffs that emerge. As future work, we aim to further investigate possible optimizations of the 802.11 Phy/MAC aiming to introduce reliability features in this industrial scenario taking into consideration the AGV energy expenditure criteria.

TABLE II
SUMMARY OF OPERATIONAL PROFILES AND RECOMMENDATIONS UNDER DIFFERENT OPERATIONAL REGIMES.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>50 ms</th>
<th>100 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet loss</td>
<td>100 AGVs (&lt; 1%)</td>
<td>140 AGVs (&lt; 1%)</td>
</tr>
<tr>
<td>Delay</td>
<td>65 AGVs (&lt; 5 ms)</td>
<td>120 AGVs (&lt; 6 ms)</td>
</tr>
<tr>
<td>Recommended</td>
<td>65 AGVs</td>
<td>120 AGVs</td>
</tr>
</tbody>
</table>

REFERENCES


