ABSTRACT
We investigate the applicability of IEEE 802.11ac for entertainment low-latency show control systems (to wirelessly support free-riding vehicles in an orchestrated theme-park environment in the future) by experimentally characterizing the indoor throughput and latency performance of 802.11ac using statistical analysis. We show that multiple linear regression provides valuable insight on the impact of 802.11ac independent features and their combinations on performance, for various link and interference scenarios. We show that 802.11ac WLANs can be used for not only delivering very high throughput for multimedia streaming, but also supporting low latency show control systems.

Categories and Subject Descriptors
C.2.1 [Computer-Communication Networks]: Network Architecture and Design–Wireless communication

General Terms
Experimentation, Measurements, Performance, WLAN

Keywords
802.11ac, Analysis, Characterization, MIMO

1. INTRODUCTION
A recent study reports that “by 2016 the amount of mobile devices’ traffic, relying on Wireless Local Area Networks (WLANs) for Internet access, will exceed the traffic from wired devices” [1]. IEEE 802.11ac [2] was introduced to address this increased need in wireless traffic. It has the potential to deliver multi-gigabit per second throughput, by incorporating wider channels, more spatial streams, and a denser modulation than 802.11n.

We report on an investigation of the available 802.11ac features on throughput and latency performance across a wide range of link qualities, via extensive real-world testbed experimentation. We want to explore if 802.11ac is a standard that could support low latency show control systems (Fig. 1). As a first step in this direction, we perform a thorough real-world evaluation and characterization study of 802.11ac performance in indoor environments using already available hardware in an 802.11ac testbed.

Zeng et al. conduct an outdoor characterization of 802.11ac focusing on power consumption and the impact of channel width [3]. We present a more complete evaluation of the standard by considering all available features and their combinational impact on performance.

2. METHODOLOGY
2.1 Testbed setup
We deploy an indoor 802.11ac WLAN testbed, covering a 40 × 15m² area, as shown in Fig. 2; the blue square indicates the access point, and the red circles represent the clients of the WLAN. Each node is a laptop running Ubuntu with kernel 3.16, equipped with a 3 × 3 Qualcomm Atheros QCA9880 chipset–based mini PCI express, and the open source ath10k wireless driver. The transmission power is always fixed to the default (i.e., 30 dBm for channels 149-161, and 17 dBm for 32-44).

The metrics we use to evaluate our testbed’s performance, are application level throughput and jitter on the receiver side. Note that MAC layer packet loss related statistics were not available using the ath10k driver. We demonstrate results in no interference and real-world interference scenarios, in varying channel conditions. For the no interference scenario we use the 5 GHz band and channel 149, where no activity was de-
tected by our spectrum analyser, during night hours. In the case of real-world interference we use channel 36 in the 5GHz band, where another 9 access points are operating at the same channels, during working hours to account for human interference, too. The Iperf tool is used for UDP traffic generation from the clients to the access point for thirty seconds. The average RSSI and other characteristics of each link is described in Table 1.

We consider all 802.11ac features in our characterization study, namely channel bonding (CB), spatial streams (SS), guard interval (GI), and modulation and coding schemes (MCS). For channel bonding, we explore the options of 20, 40 and 80 MHz channel width; for spatial streams we vary from one to three streams, and for the MCS index explore the ten options as indicated by the 802.11ac standard. Finally, for the guard interval option there is the long (LGI) or short guard interval (SGI). There are 180 combinations for each link/interference type. Given that our testbed has eight nodes, and we consider two interference scenarios, our dataset increases to almost 3000 different configurations. There we explore the use of statistical techniques on this dataset to gain insights.

### 2.2 Multiple Linear Regression

Multiple linear regression [4] is a predominant empirical tool in epidemiology, economics and other sciences, used to generate compelling evidence of causal relationships between parameters and observational data of controlled experiments. We use it to model the relationship between two or more explanatory variables, as well as their influence on a response variable.

Our explanatory variables are 802.11ac features (i.e., CB, SS, GI and MCS), and the response variable is our respective metric (i.e., throughput and jitter). Hence, we can use the coefficients to infer, e.g., whether the impact of wider channels is positive or negative on the throughput performance by the sign of the CB coefficient. For normalized coefficients across different links, we can also confirm that a specific feature has a higher impact than another in certain scenarios.

To evaluate whether multiple linear regression is applicable to our data, we examine the significance ($p$-value) of the regression model's F-test. If the $p$-value is lower than an alpha threshold, then the model can accurately describe the data. We set the alpha threshold to 0.05 (i.e., the model describes 95% of the data), and we find that indeed the $p$-value is always lower than alpha, validating that multiple linear regression can fit our data, and therefore its results can be trusted.

### 3. EXPERIMENTAL EVALUATION

We follow the methodology described in the previous section for the “no interference” and “real world interference” scenarios. Fig. 3 depicts the maximum throughput (Fig. 3(a)) observed for each link in the testbed (Fig. 2), under both setups of interference, as well as the corresponding jitter observed (Fig. 3(b)). We cannot gain much insight on why an observed change happens just by looking at the measurements. But we really area looking for answers to questions like: Why does jitter increase rapidly for weak links? Are there setting combinations to minimize jitter, but maximize throughput performance?

To answer such questions, we use multiple linear regression on our measurements. Results in Fig. 4 show the impact of single features, and their combinations on throughput and jitter performance, under no and real world interference. Warmer colors (i.e., redder) mean that this feature combination has a higher positive impact on the performance, when its value is higher, and colder colors indicate negative impact. For example, red CB impact means that larger channel width increases throughput performance. Note that for the case of GI, a redder color GI indicates that enabling SGI increases throughput performance. Green indicates that the specific feature combination does not have a significant impact on the performance of the examined metric.
As far as the SS is concerned, we see that on average, better link qualities (i.e., A–E) have an increased jitter with higher channel width, compared to the poorer links (i.e., F–H), because better links have less losses, so more delayed packets. We see this changing for the real world interference case, where the losses are so high that most packets do not arrive at all, so jitter cannot be measured, which also explains the high jitter noticed in link G (Fig. 3).

Moreover, higher MCS indexes reduce the jitter, in both interference cases. Jitter performance increases with higher MCS indexes in the case of poor links (i.e., H), for similar reasons to the channel bonding case (Fig. 3).

We also see that not only single parameter estimation is significant for achieving better performance but also for combinations of multiple parameters. Fig. 4 shows the combinations that are more significant and their impact. It is surprising that even though increasing only the channel width or only the spatial stream number have a negative impact on throughput, increasing the channel width and spatial stream number jointly has a highly positive impact on throughput performance and at the same time decreases jitter, no matter the interference scenario. Finally, we see that jointly increasing the SS and MCS index increases the latency, even though this combination has no significant impact on throughput performance. This is the case as the reduced transmission power for more streams reduces the link’s quality even further and thus introducing errors.

4. CONCLUSION

We have performed an extensive experimental characterization of the latency and throughput performance of 802.11ac WLANs. Unlike previous approaches we consider all 802.11ac features in our study. We show that regression analysis can provide valuable insight in analysing network performance measurements. Finally, our study indicates that surprisingly 802.11ac can be used not only for delivering high throughput, but also for low latency applications.

5. REFERENCES