# Investigation into the Doppler Component of the IEEE 802.11n Channel Model

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*Abstract* — **Simulations show that the Doppler component of the IEEE 802.11n channel model results in a dramatic decrease in transmit beamforming gain within only 20 ms delay, even though the model is intended for indoor WLAN environment with stationary devices. However, new measurements collected in an office environment show that degradation to transmit beamforming gain is much less sensitive to delay. With normal environmental conditions in the office environment, it was found that on average there was only a 22% decrease in transmit beamforming gain after 200 ms delay. Even with highly exaggerated motion, reasonable gain is maintained with over 100 ms of delay. Measurements with a moving device were also conducted with resulting sensitivity to delay similar to the 802.11n model. The measurements indicate that the Doppler component of the 802.11n channel model is more comparable to a moving device rather than a stationary device. The use of transmit beamforming in an indoor WLAN environment is more practical than simulations based on the IEEE 802.11n channel models would imply.**

***Keywords: IEEE 802.11, IEEE 802.11ac, IEEE 802.11n, transmit beamforming, Doppler, channel measurements, MIMO***

## I. INTRODUCTION

To enhance link quality in a wireless networking (WLAN) system, the IEEE 802.11n standard amendment includes a closed-loop transmit beamforming protocol. However, delay occurs between the collection of channel state information (CSI) and actual beamformed packet transmission, during which time the channel can change. Simulations have shown that the 802.11n transmit beamforming gain degrades significantly within 20 ms delay because of the Doppler component of the 802.11n indoor channel model [1].

To effectively exploit these short-lived gains, various techniques have been employed in 802.11n to provide frequent, rapid, and low overhead feedback. Techniques like immediate feedback were included in 802.11n to enable rapid feedback and eliminate sources of delay such as channel access in a heavily loaded wireless network. To reduce the impact of the feedback on the overall throughput additional techniques like compression, quantization, and grouping of subcarriers were also included in 802.11n.

In addition to transmit beamforming, advanced techniques like SDMA and multi-user MIMO that are being developed as the next generation to 802.11n (802.11ac), introduce additional challenges in providing timely feedback of CSI. Since feedback needs to be collected from multiple client devices, these techniques have to overcome the additional delay incurred between collection of CSI, computation of the transmitter weights, and the actual packet transmission.

A common approach used to evaluate the effectiveness of the various proposals to provide timely and low-overhead CSI feedback is based on simulations. Different wireless channel models are used to simulate different environmental conditions. A key component of the channel model that determines the rate of change of the channel is the Doppler component. Thus, the accuracy of the Doppler component directly impacts the design of the SDMA or multi-user MIMO technique and its ability to provide timely CSI feedback.

In this paper, we present channel measurements collected from an office environment that show that the degradation to transmit beamforming gain is much less sensitive to a CSI feedback delay even beyond 200 ms. These measurements contrast sharply with results generated using the 802.11n channel model that leads to a significant degradation of the beamforming gains within a 20 ms delay. The only other similar measurement that we are aware of is the recent measurement made by NTT [3], in which measurements were made with stationary devices in a "quiet" indoor office environment. Our detailed evaluation across varying levels of mobility in the environment indicates that the primary reason for this sharp contrast between the simulated and measured beamforming gains is due to an inaccurate Doppler model of the 802.11n channel model. Instead, we find that the Doppler model of the 802.11n channel model more closely matches measurements taken of a slowly moving terminal. We hope that insights obtained from our measurements would lead to further investigation on how to modify the 802.11n Doppler model as well as inform the design of advanced MIMO techniques like SDMA and multi-user MIMO in 802.11ac.

The rest of this paper is structured as follows. We first present an overview of the Doppler component of the current 802.11n channel model in Section II. This is followed by a description of the method in which transmit beamforming gain is computed, using this channel model, in Section III. New channel measurements are captured in an office environment between stationary devices with several types of environmental motion. The test setup is described in Section IV. Transmit beamforming gain with these channel measurements are given in Section V to compare with those using the 802.11n channel model. Measurements are also made with a slowly moving device as a second reference point. These results are given in Section VI. We summarize the analysis and results and provide suggestions for next steps in Section VII.

## II. OVERVIEW OF THE DOPPLER COMPONENT OF THE IEEE 802.11N CHANNEL MODEL

The intent of the Doppler model in the IEEE 802.11n channel model was to model an indoor home or office environment in which the wireless devices are stationary but the channel is dynamic because of people moving about in the environment [2]. This explicitly differs from outdoor mobile systems where the user terminal is typically moving.

To model this difference, the 802.11n channel model uses a Bell shaped Doppler spectrum defined by

$$S(f) = \frac{1}{1 + 9 \cdot \left( \frac{f}{f_d} \right)^2}, \tag{1}$$

where $S(f)$ is expressed as linear (not dB). The Doppler spread $f_d$, which is equal to $\frac{v_o}{\lambda}$ is based on an environmental speed, $v_o$, fixed at 1.2 km/h, and $\lambda$ is the wavelength. At a center frequency of 5.25 GHz, the Doppler spread is approximately 6 Hz and at 2.4 GHz it is approximately 3 Hz. The coherence time of this Bell shape spectrum is given by

$$T = \frac{3}{2\pi f_d} \cdot \ln(2). \tag{2}$$

This model yields a coherence time of approximately 60 ms in the 5 GHz band and approximately 125 ms at 2.4 GHz.

Even though a Bell-shaped spectrum was chosen rather than the "horn spectrum" that is typically used in a mobile channel model, the Doppler spectrum of this stationary model is still applied to every channel tap of the impulse response as would be done in a mobile channel model. As will be seen in the following sections, this critical similarity between the two leads to much higher simulated variation in the channel than typically observed in an indoor environment with stationary devices.

## III. Transmit Beamforming Capacity with 802.11n Channel Model

With coherence times of 60 to 125 ms and maximum packet length on the order of a few milliseconds, open-loop packet transmission and reception with basic tracking mechanisms in the receiver will be minimally affected by the simulated channel variation. Rather, the impact to the 802.11n system due to the Doppler component will arise when implementing the closed loop transmit beamforming (TxBF) protocol. Delay between the measurement of the CSI and transmission of the beamformed packet will result in a mismatch between the TxBF weights and the actual channel during transmission.

Physical layer simulation results described in [1] demonstrated that the capacity gain of TxBF greatly diminishes within 20 ms of delay. These simulations were performed with four transmit antennas and four receive antennas. As we describe in Section IV, the equipment we used to make measurements only has three transmit and three receive antennas.

We now present additional simulation results to better match the measurement configuration, three transmit antennas at the transmitting device and three receive antennas at the receiving device. Capacity is computed for two types of systems: 1) a basic open loop spatial division multiplexing (SDM) system with an MMSE receiver, and 2) TxBF w/ an MMSE receiver. We will compare the capacity of TxBF to that of basic SDM. For this particular example, we specify the SNR to be 30 dB. In addition, the simulation uses the 802.11n channel model D (50 nsec RMS delay spread).

A semi-analytic capacity formulation is used to compute capacity, as described in [1]. The expression for the mean square error (MSE) at the receiver is

$$J_{MxM} = \frac{\rho}{M} W H_{eff} H_{eff}^{*} W^{*} + W \Phi_Z W^{*} - 2\sqrt{\frac{\rho}{M}} \operatorname{Re}(W H_{eff}) + I, \tag{3}$$

where $H_{eff}$ is the effective channel matrix, $H_{eff}^{*}$ is the conjugate transpose of $H_{eff}$, $\Phi_Z$ is the noise covariance matrix, $I$ is the identity matrix from the signal covariance, and $M$ is the number of data streams. Minimizing the MSE expression with respect to $W$, we arrive the following solution for $W$:

$$W = \sqrt{\frac{\rho}{M}} H_{eff}^{*} \left( \frac{\rho}{M} H_{eff} H_{eff}^{*} + \Phi_Z \right)^{-1}. \tag{4}$$

The output SNR for the $i^{th}$ data stream for MMSE is given by

$$\text{SNR}_i = \frac{1 - J_i}{J_i}, \tag{5}$$

where $J_i$ is the $i^{th}$ diagonal element of the MSE matrix given in (3). The formula for capacity based on output SNR is given by

$$C = \sum_{i=1}^{M} \log_2 \left( 1 + SNR_i \right). \tag{6}$$

A cumulative distribution function of capacity is computed over all the subcarriers in the channel and over 1000 independent instantiations. The values for capacity given in Figure 1 correspond to 10% probability of the cumulative distribution function.

With basic SDM, the $H_{eff}$ of (3) and **(4)** is equivalent to the channel matrix $H$ of a single subcarrier computed with the 802.11n channel model. With TxBF, we assume an SVD-based solution for transmitter weights with $H_{eff} = H\hat{V}$, where $\hat{V}$ are the Eigen-vectors of $\hat{H}$. The two channel matrices $H$ and $\hat{H}$ were derived separated by a specified delay.

Figure 1 illustrates the degradation in TxBF capacity as the delay between the measurement of the CSI and actual beamformed transmission increases. We demonstrate that the 802.11n channel model results in almost no TxBF gain after 20 ms delay.

## IV. Measurements in an Office Environment

Measurements were captured in an 802.11n test bed deployed on one floor of an indoor office environment. The dimensions of the floor of the building are 90 ft X 90 ft (~27.4 m X 27.4 m). In the center of the floor are labs, elevators, and a kitchen area. Along the walls are workspaces with groups of cubicles and conference rooms. The deployment is shown in Figure 2.

The numbered circles indicate device locations. All the devices are actual 802.11n stations consisting of a desktop PC with an Intel WiFi Wireless Link 5300 radio card and external antennas. The configuration of one node is shown in Figure 3. Channel state is measured by having each device in turn transmit a stream of 802.11n packets, while all the other devices receive the packets. Packets are transmitted every 0.8 ms. This provides measurements as the channel changes in time between every combination of devices on the floor.

The packets use a three-stream format and are transmitted with three antennas. All the receiving devices use three antennas on reception. All measurements are made at 5.3GHz, on an empty channel. Channel state information is measured from the long training field of each packet. This provides a 3x3 channel matrix $H$ for each measured subcarrier, across the 20 MHz bandwidth, observed every 0.8 ms. Received signal level data and noise level data are also captured. This is used to compute received SNR.

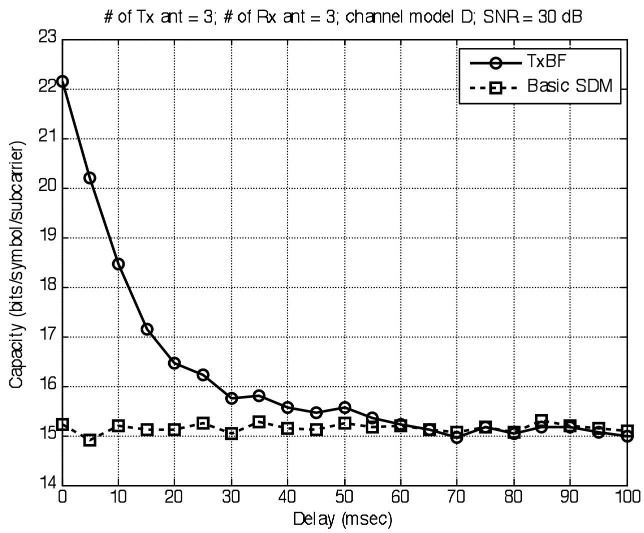


**Figure 1: Degradation in TxBF capacity with delay**

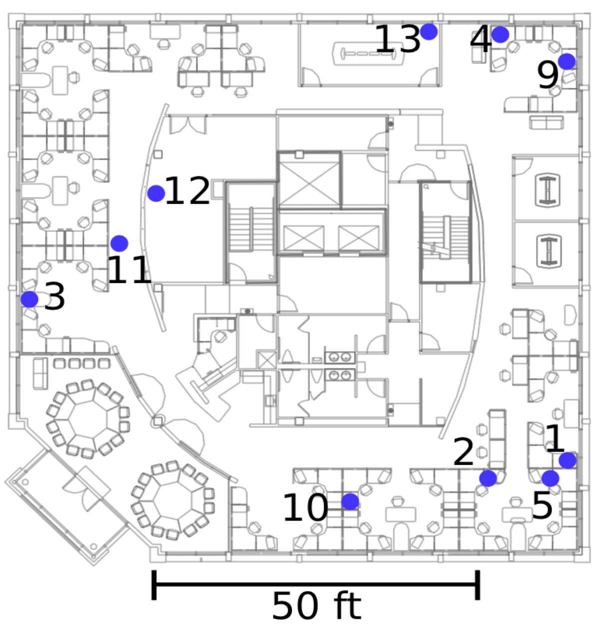


**Figure 2: Office test bed floor plan**

**Figure 3: 802.11n measurement device**

## V. Transmit Beamforming Capacity with Measured Data

To measure the channel variation for stationary nodes in a time-varying indoor environment, measurements were collected with four different types of environmental motion. The four types of motion were chosen to represent a range of variation that might be experienced in a typical indoor office environment, and are presented in order of increasing proximity and stress to the measured links.

The first set of measurements illustrates typical motion in this office environment. This includes people working in the lab and in cubicles and others that may happen to be walking around on the floor. We compute capacity with the measured channel matrices and as described in Section III. An example of these results measured between device 11 and device 9 is given in Figure 4. As can be seen, the TxBF capacity barely decreases even after 200 ms. With no delay the capacity of TxBF is 11.7 bits/symbol/subcarrier and the capacity of basic SDM is approximately 8 bits/symbol/subcarrier, with an SNR of 20 dB. The TxBF capacity decreases to 11.3 bits/symbol/subcarrier after 200 ms delay. The gain of TxBF over basic SDM with no delay is 50%, which decreases to 45% with 200 ms delay. This results in a 10% decrease in gain over 200 ms. We term this type of motion as "light motion" or **LM**.

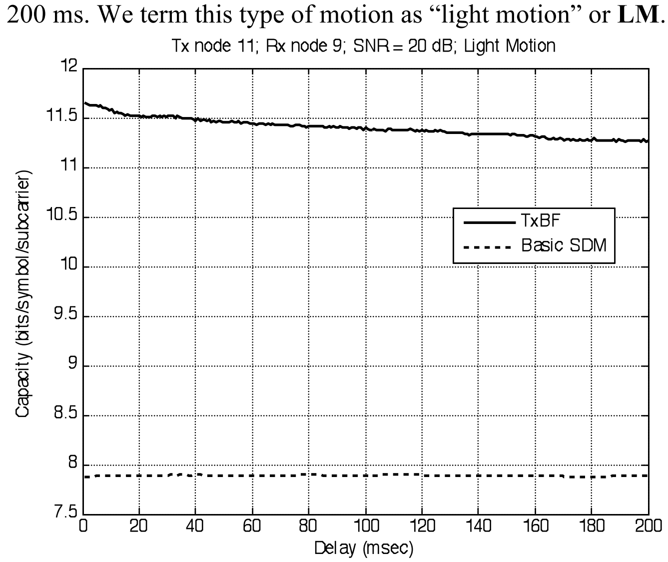


**Figure 4: Example of capacity with typical motion in the office environment**

Next, to artificially increase the motion in the environment, a group of five people purposely walked around the floor during the measurements. We term this type of motion as "people motion" or **PM**.

An example of the capacity of one set of this type of measurements is given in Figure 5 for the link between device 5 and device 10. In this case the TxBF capacity is 30.0 bits/symbol/subcarrier and the basic SDM capacity is 24.3 bits/symbol/subcarrier, with an SNR of 37 dB. The TxBF capacity decreases to 26.7 bits/symbol/subcarrier after 200 ms. The TxBF gain decreases by 53%. This demonstrates that additional people walking the environment will increase the amount change in the channel over time. However, this example still shows much less sensitivity of TxBF to delay than the 802.11n channel model.

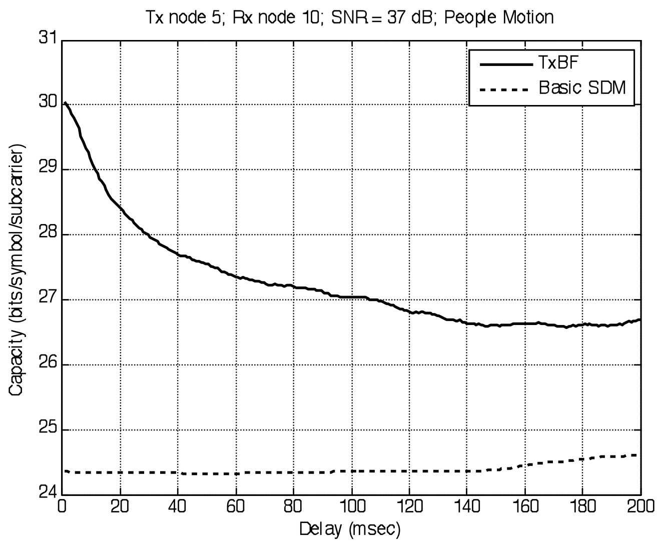


**Figure 5: Example of capacity with additional people moving about in the office environment**

Third, we introduce a motion in the environment targeted to one of the devices in a link. In this experiment, a person was standing in front of the antennas of one of the devices in a link and waving their hands. This is to model an individual working next to a computer with a wireless LAN device and perhaps making a gesture. We term this type of motion as "single motion" or **SM**. The example in Figure 6 illustrated the performance for a link between device 5 and device 4. In this particular example the TxBF capacity decreases from 20.5 to 18.8 bits/symbol/subcarrier in 200 ms. The capacity of basic SDM is approximately 14 bits/symbol/subcarrier. The TxBF gain decreases by 28%.

Finally, in the more extreme case where people could be moving in front of the access point as well, measurements were made with one person standing waving their hands next to each of the transmitting and receiving devices. We term this type of motion as "double motion" or **DM**. In the example illustrated in Figure 7 between device 2 and device 4, the TxBF capacity decreases from 22 bits/symbol/subcarrier to 18 bits/symbol/subcarrier over 200 ms. The basic SDM capacity is approximately 16 bits/symbol/subcarrier. This represents a 65% decrease in TxBF gain.

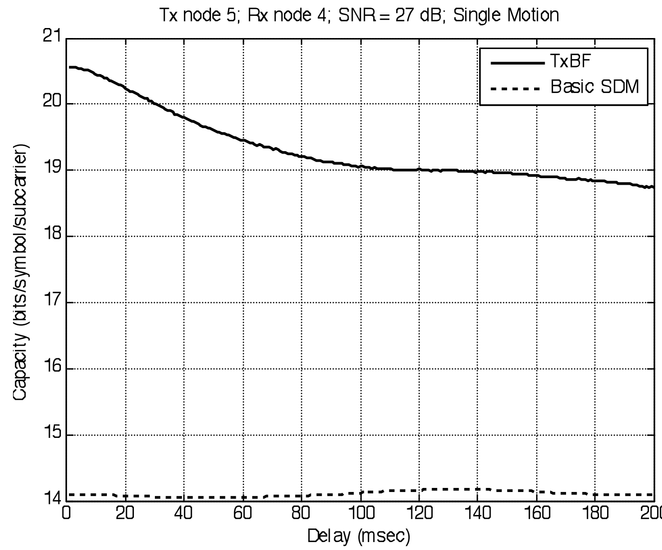


**Figure 6: Example of capacity with person waving their hands next to a single device in the link**

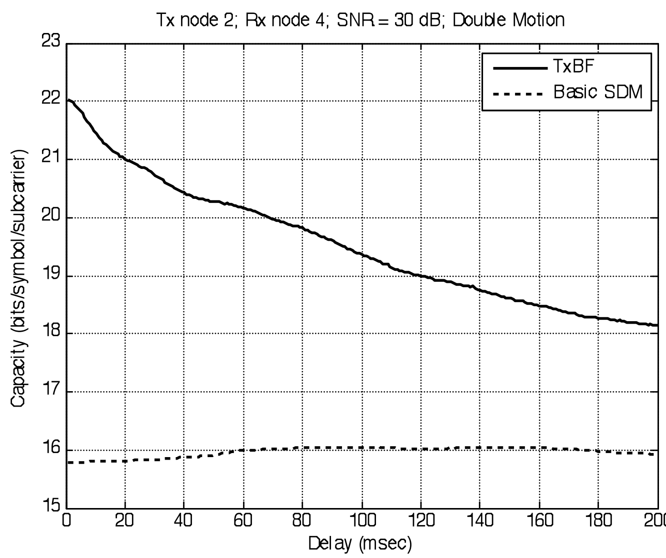


**Figure 7: Example of capacity with one person next to each device in the link waving their hands**

To summarize, measurements with different types of motion in the environment were captured as follows:

1. typical motion in office environment (Light Motion)
2. many people known to be walking around (People Motion)
3. someone waving their hands in front of the device at one end of the link (Single Motion)
4. someone waving their hands in front of the device at both ends of the link (Double Motion)

Table 1 summarizes the SNR and percent degradation of TxBF gain of the measurements for each motion type averaged over multiple links. People waving their hands at both ends of the link caused the most motion, but still exhibit much less degradation to TxBF gain than the Doppler component of the 802.11n channel model. More typical motion (LM, PM, SM) causes a small amount of degradation and links can still retain majority of TxBF gain after 200 ms. The measurements also show that the variation of TxBF gain increases with people walking around as demonstrated by the increase in the standard error of the PM results relative to the other results.

**Table 1: Summary of measurements of stationary devices**

| | | | % degradation of TxBF gain | | | |
|---|---|---|---|---|---|---|
| Motion type | | SNR (dB) | 20ms | 50ms | 100ms | 200ms |
| DM | avg | 34.3 | 18.6 | 38 | 49 | 58 |
| | std err | 2.2 | 1.3 | 3.2 | 3.6 | 4.1 |
| SM | avg | 31.0 | 9.2 | 20.3 | 28.9 | 34.2 |
| | std err | 2.9 | 1.5 | 3.4 | 4.0 | 4.4 |
| PM | avg | 27.6 | 20.2 | 27.1 | 33.3 | 38.7 |
| | std err | 2.8 | 6.3 | 6.8 | 7.7 | 8.2 |
| LM | avg | 22.4 | 8.3 | 12.6 | 17.2 | 22.0 |
| | std err | 2.8 | 2.4 | 3.1 | 4.3 | 5.1 |

## VI. MEASUREMENTS WITH A MOVING PLATFORM

As described in Section II, Doppler is applied to every channel tap in the impulse response in the 802.11n channel model. Since the measurements with stationary devices resulted in TxBF behavior different than that with the 802.11n channel model, one begins to suspect that such a Doppler model may only apply to mobile devices. To test this hypothesis, a WLAN radio card was connected to a laptop rather than a desktop PC. This device was place on a cart (labeled Node 99) and pushed around the office at a slow walking speed to mimic the environmental speed of Doppler component of the 802.11n channel model. A lap was made around the central part of the office with Node 99 transmitting and devices 1, 3, and 4 receiving. For this data collection, the packets were transmitted every 0.4 msec. Because of the large size of the data collection, each data set was divided into smaller segments for processing and results were averaged together. The results are given in Table 2. As we can see, TxBF gain is significantly degraded by 20 ms, very similar to the results based on the 802.11n channel model.

**Table 2: Summary of measurements with a mobile device**

| | | | | % degradation of TxBF gain | |
|---|---|---|---|---|---|
| Dest | Source | | SNR (dB) | 20ms | 50ms |
| 1 | 99 | avg | 18.8 | 69.3 | 86 |
| | | std err | 1.7 | 3.3 | 1.5 |
| 3 | 99 | avg | 21.0 | 69.0 | 87.6 |
| | | std err | 1.3 | 2.5 | 1.0 |
| 4 | 99 | avg | 22.2 | 66.2 | 84.9 |
| | | std err | 1.3 | 2.9 | 2.0 |

## VII. CONCLUSIONS

The Doppler component of the 802.11n channel model results in significant degradation to transmit beamforming performance after 20 ms in a simulated channel. However, recent measured results in [3] showed no degradation to Eigen-mode transmission after 100 ms delay. We presented additional new office environment measurements that also showed minimal degradation to TxBF gain after 20 ms. This insight holds even in experiments that we specifically designed to exaggerate environmental motion, such as hands waving simultaneously in front of both the access point and client. Our measurements show that the majority of TxBF gain is retained after 200 ms.

The implication of these results for system architecture is deep: variation in the channel has a big impact on the gains achievable from different techniques and the system requirements to achieve them. To employ transmit beamforming in channels with short coherence time, frequent, immediate overhead is required that may eliminate gain. This is especially true when applying newly proposed multi-user MIMO techniques in 802.11ac, which require feedback from multiple client devices. Short coherence time may also result in the over-emphasis of MAC architecture on immediate and frequent feedback and compression techniques, as it did in 802.11n. In contrast, these measurements imply that typical channels for stationary devices have much longer coherence times than initially perceived. These channels are significantly more forgiving the 802.11n channel model implies, and thus better tolerate delay and require less communication overhead.

Additionally, our measurements with a mobile 802.11n terminal indicate that the 802.11n Doppler model produces results similar to a slowly moving device, rather than for the stationary devices it was originally intended. Thus, the model may be applicable to handheld devices utilizing WLAN, though for laptops, typical usages will still be stationary.

More investigation on how to modify the 802.11n Doppler model is necessary to better model stationary devices and to be applicable to 802.11ac. The 802.11n Doppler component is applied to every tap more like a device slowly moving rather than stationary devices like a laptop upon a desk or set top box. One alternative is to apply the Doppler component to a subset of the channel taps in the channel impulse response. Further analysis of the measurement data is required to determine to which taps to apply the Doppler.

Following measurements in this paper and in [3], 802.11ac adopted a simple modification to the 11n Doppler model for stationary devices. The environmental speed in the 802.11ac channel Doppler model was change to 0.089 km/hr for stationary devices (equating to a channel coherence time of 800 ms or an RMS Doppler spread of 0.414 Hz at a carrier frequency of 5 GHz) [4].

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