Poster: Bringing mmWave Communications to Raspberry Pi

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ABSTRACT

Recently there has been a huge interest in performing research on millimeter wave (mmWave) communications. Prior work utilize this technology in enabling Gbps wireless links. In contrast, we exploit mmWave technology in designing high-density IoT networks, where there are hundreds of nodes, but each requiring only a Mbps wireless link. However, existing mmWave radios are costly and have high power consumption which makes them unsuitable for IoT sensors. We have built mmPi: a low-cost and low-power mmWave radio that operates as a daughterboard for the Raspberry Pi platform. We believe that mmPi helps advance mmWave research in the IoT domain.

1 INTRODUCTION

The proliferation of IoT devices has placed a growing strain on today's Wi-Fi and cellular networks. Millimeter wave (mmWave) frequency bands address this problem by offering multi-GHz of unlicensed bandwidth. Recent studies have looked into this technology in enabling Gbps wireless links for emerging applications such as virtual reality [1, 2] and 5G [4]. Unfortunately, existing mmWave radios are costly and have high power consumption, which makes them unsuitable for low-cost and low-power IoT sensors. The main reason for the high-power consumption of existing mmWave radios is low efficiency circuit components at higher frequencies. Further, in contrast to traditional radios, mmWave radios require beam searching which makes the hardware more complex [3]. Specifically, they require phased arrays consist of amplifiers and phase shifters that excessively increases the cost and power consumption of these radios.

In this paper, we focus on building low-cost and low-power mmWave radios suitable for IoT sensors. Our mmWave radio shown in Figure 1 operates as a daughterboard for Raspberry Pi. In order to make our design low-power, we need to utilize minimum number of high frequency (mmWave) components. Therefore, we use the on-off-keying (OOK) modulation. This modulation is very simple and can be implemented using a simple oscillator and an Radio Frequency (RF) switch. Although, the OOK modulation cannot support very high data rates, it effectively suits our goal for Mbps data rates, which is sufficient for most IoT sensors. Moreover, instead of using phased arrays that require costly phase shifters, we have designed an antenna array with different beam directions. Therefore, by switching between different antennas we can choose the proper beam, eliminating the need for phase shifters.

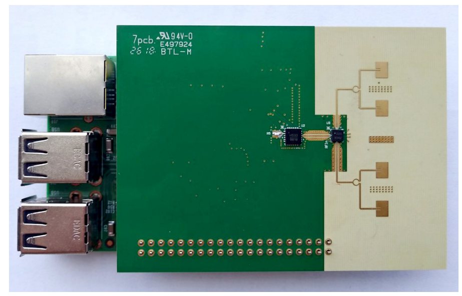

Figure 1: mmPi connected to a aspberry Pi

Our results show that mmPi can operate at different mmWave sub-bands and it achieves SNR of 37 dB even at 7 meters away from the transmitter. Finally, we believe that mmPi compatibility with Raspberry Pi opens up mmWave research for IoT and dense wireless network devices.

2 SYSTEM DESIGN

Our mmWave communication system consists of IoT devices (i.e., Raspberry Pi) equipped with mmPi radios that communicate with a common receiver. The receiver utilizes a Wi-Fi network to transmit control messages to Raspberry Pis to configure the mmPi radios. We now describe different aspects of mmPi namely, spectrum allocation, modulation, and beamforming.

2.1 Spectrum Allocation

To avoid collision between concurrent transmissions from two or more mmPi radios, the receiver assigns a separate

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channel to each device. Since the 24 GHz ISM band provides 250 MHz of bandwidth, many non-overlapping channels can be allocated. For instance, if 10 MHz channels are required, 25 non-overlapping channels can be assigned to 25 devices. The receiver utilizes Wi-Fi to communicate the information about which channel each device must use. Upon receiving the information about the frequency of the channel, each device tunes its carrier frequency using a VCO controlled by a DAC. In Section 3.2, we evaluate the capability of mmPi in adjusting its carrier frequency.

2.2 Modulation

Since we target low data rate applications and a low cost design, a simple modulation technique is suitable for our system. We utilize the on-off keying (OOK) modulation in which we either transmit a sine wave signal or do not transmit anything. Specifically, to transmit 1, the OOK modulation sends a sine wave for a specific duration of time and to transmit 0, it sends no signal. The OOK modulation has a few design advantages that we describe next.

Utilizing OOK modulation significantly reduces the complexity of the system, making the implementation low-power and cost-effective. On the transmitter, the OOK modulation can be simply implemented by using a Voltage-Controlled Oscillator (VCO) to generate a mmWave sine wave, followed by a simple Radio Frequency (RF) Single Pole Double Through (SPDT) switch, where the sine wave signal is either forwarded or not forwarded to the antenna. On the receiver, the signal can be decoded by performing a simple amplitude demodulation. Specifically, if the energy of the received signal is above a certain threshold, it is interpreted as 1, otherwise 0.

The second advantage of the OOK modulation is the robustness of this technique to noise, because of its low SNR requirements. A receiver typically can decode an OOK modulated signal with SNRs of as low as 11 dB [5], while achieving Mbps data rate, and a very low bit error rate. This is an advantage for mmWave communication because if the line-of-sight(LOS) path is blocked, the receiver has to rely on non-line-of-sight (NLOS) paths to receive the signal. The SNR of NLOS in the 24 GHz band is typically about 15 dB lower than the LOS [1]. As a result, the robust OOK modulation enables the mmWave communication system to operate even if the line-of-sight is blocked. Further, the ability to operate at low SNR regimes allows us to eliminate the need for high-gain narrow antenna beams. In the next section, we will explain how this helps in reducing mmPi power consumption and cost.

2.3 Beamforming

The high propagation loss in the mmWave spectrum urges to use directional beams rather than omni-directional antennas, which are quite common in lower frequencies. As a result, both the transmitter and receiver are required to perform beamforming to establish a communication link. The beamforming techniques usually rely on phased shifter components that are expensive and power hungry. For example, the power consumption of TGP2100 phase shifter working in the 28 to 32 GHz frequency range is 0.1 W [6], which is a large power consumption when multiplied by the number of antennas.

We utilize a communication mechanism in which the transmitter sends its signals using one of the predefined beams (i.e., fixed directions). Figure 2 illustrates that the transmitter has multiple options when selecting the beam. These beams cover almost the entire 180 degree space in front of the device. The receiver uses a Wi-Fi link to inform the transmitter about which beam it should use for communication at any point in time. This design is effective and yet low cost. We have implemented a prototype of our design with components that cost less than $100 in total. Note that mmWave systems that achieve Gbps throughput cost orders of magnitude more, rendering them unsuitable for IoT applications.

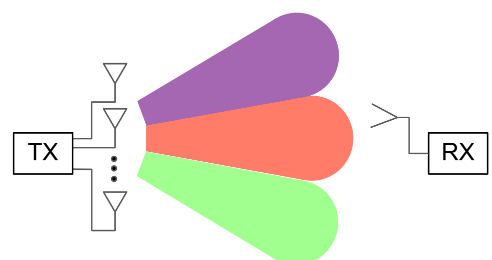

Figure 2: mmPi's beamforming mechanism

3 RESULTS

In this section, we evaluate the performance of our prototype implementation of mmPi in terms of frequency tuning and radiation characteristics.

3.1 Antenna Design

The prototype we have designed employs arrays of patch antennas, capable of creating different beams. Figure 3 illustrates the radiation patterns of the antenna arrays in the ANSYS HFSS electromagnetic simulation software. As depicted, beam 1 is directed toward broadside (i.e., 0 degree) while Beam 2 points toward ± 30 degrees from the broadside. In order to optimize the radiated power, the two beams are designed orthogonal to each other and the overlap between them is very small, suitable to cover the area effectively.

3.2 Spectrum Allocation

Our prototype utilizes the HMC533 VCO to generate a sine wave in the 24 GHz band. This signal is connected to the antennas through a RF SPDT switch. The SPDT selects the

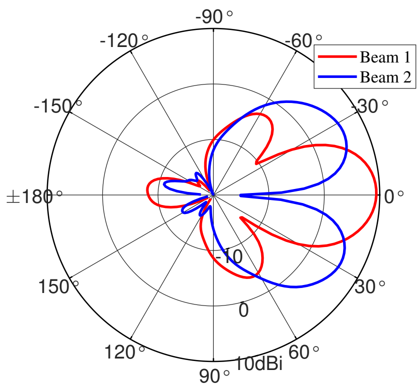

Figure 3: Simulated antenna patterns

proper beam for transmission. First, we measure the VCO frequency span by controlling the tuning voltage of the VCO. We utilize an N9030A PXA signal analyzer to measure the frequency of the signal transmitted by our prototype. Figure 4 shows the generated frequency of the VCO when the control voltage is changed from 3.5 to 5 V. As shown in the figure, the signal's carrier frequency ranges from 23.95 GHz to 24.25 GHz, providing 255 MHz of frequency span. This frequency span is more than what is required to cover the 24 GHz ISM band, therefore the mmPi prototype is able to change its center frequency to transmit on any channel assigned by the receiver.

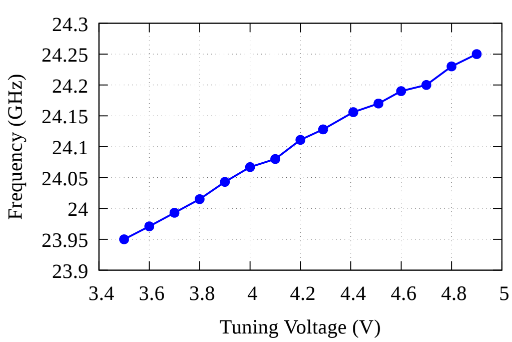

Figure 4: VCO's control voltage vs. carrier frequency

3.3 Range

In the next experiment, we empirically measure the radiated power of mmPi to evaluate the potential range of the designed communication system. We measure the received signal strength by a N9030A PXA Signal Analyzer using a patch and a horn antenna as the receiving antenna. The horn antenna is a Quinstar QWH-KPRS-00 antenna that provides about 20 dBi gain in the mid band. In addition, we have designed and fabricated the patch antenna, which provides about 6 dBi gain. we change the distance between the mmPi and the receiver from 1 to 7 meters and measure the LOS received signal. Figure 5 depicts the received signal strength when the receiver is placed at different distances from the mmPi board. The figure shows that the received signal strength is significantly high, sufficient to decode OOK signals even from distances as far as 7 meters with a simple patch antenna. Note that the typical noise floor for a 10 MHz channel is about -100 dBm. Therefore the signal strength values in Figure 5 are translated to high SNR values (i.e., 37 to 52 dB for the patch antenna).

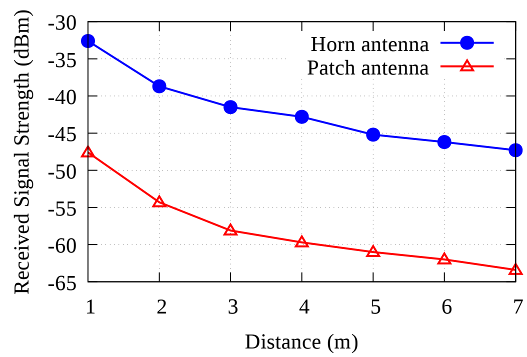

Figure 5: Measured Received Signal Strength (RSS) for different communication distances

4 CONCLUSIONS

In this work, we present the design of mmPi, a low-cost and low-power mmWave transmitter for Raspberry Pi. We experimentally evaluate the performance of our prototype implementation of mmPi. Our evaluations show that mmPi is able to tune its transmission frequency by adjusting the control voltage of the VCO. In addition, our measurements show that the received signal strength is strong enough for the on-off keying modulation when the distance between mmPi and the receiver is 7 meters or possibly more.

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