Poster: A Millimeter Wave Software Defined Radio Platform with Phased Arrays

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Summary– Recently, there has been significant interest in performing research on millimeter wave (mmWave) communications. However, there do not exist any mmWave radio platforms with phased arrays available to the networking community. All existing mmWave platforms use horn antennas which require mechanical steering and are not suitable for non-static links or multi-user networks. We have built MiRa: a full-fledged mmWave radio with phased arrays capable of beam steering. MiRa operates as a daughterboard for the USRP software radio which enables easy manipulation of mmWave signals using standard GNU-radio software. With its reconfigurable architecture, steerable phased arrays and open SDR platform, MiRa can help advance mmWave research in the mobile and networking community.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design

Keywords

Millimeter Wave; Phased Array; Wireless

1. Introduction

The ever increasing demand for mobile and wireless data has prompted the FCC to release multiple GHz of bandwidth for both licensed and unlicensed use in the millimeter wave (mmWave) bands above 24 GHz. mmWave technology is expected to play a central role in next-generation (5G) cellular networks [4] as well as wireless LANs which led to multiple mmWave standards such as IEEE 802.11ad, 802.15.3c and ECMA-387. However, mmWave signals attenuate quickly with distance and hence they need to use highly directional antennas to focus their power. First generation mmWave radios used horn antennas [2, 3], which require mechanical steering and are not suitable for mobile networks. More advanced mmWave radios use phased-array antennas, which can be steered electronically. Working implementations of phased array mmWave systems have been limited to industry with few known examples such as Qualcomm's 28 GHz demo [1], and Samsung's 28 GHz prototype [5]. However, these systems are not available to the research community which significantly hinders mmWave research.

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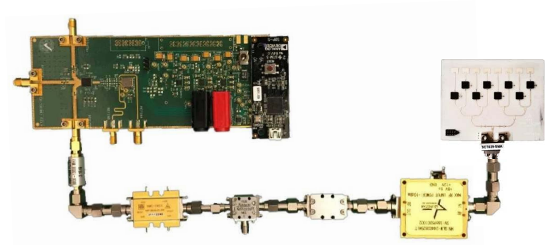

Figure 1— MiRa Platform: The figure shows the phased array and mmWave radio we built to operate as a daughterboard for the USRP software radio.

This paper addresses this limitation by presenting MiRa: a full-fledged mmWave software defined radio platform with electronically steerable antenna arrays. Our mmWave radio shown in Fig. 1 operates as a daughterboard for the USRP software radio. This enables easy manipulation of mmWave signals using standard GNU-radio software, and helps bring mmWave to the GNU-radio community. The platform operates in the ISM band at 24GHz and is easy to reconfigure and replicate. The platform is equipped with phased arrays. Each phased array has 8 antennas as shown in Fig. 1(a), but the same device can have multiple such phased arrays. The design enables all USRP-GNU functions to be performed in mmWave frequencies. For example, one can control the bandwidth of the signal, change the center frequency, and coordinate multiple USRPs with a shared clock to act as a MIMO device.

Our results show that MiRa delivers up to 256 QAM modulation and can operate at distances that exceed 100 meters. Finally, we believe that MiRa's GNU-radio SDR platform with its phased arrays helps open up mmWave research to the networking community.

2. MiRa Software Radio Platform

Our mmWave radio platform is shown in Fig.1. Our radio platform addresses critical design issues that are described below.
(a) Heterodyne Architecture: mmWave hardware is significantly more expensive than hardware operating at a few GHz. Thus, we advocate a heterodyne architecture where the mmWave signal is first taken into an intermediate frequency (IF) of a few GHz, before the I and Q (real & imaginary) components are separated. Such a design reduces the number of components that need to operate at very high frequencies (mixers, filters, etc) and replaces them with components that operate at a few GHz, which are much cheaper.

The architecture of MiRa's radio is shown in 2. The first block of our design is a mmWave phased array which allow us to steer the beam electronically. The phased array consists of antenna elements where each element is connected to a phase shifter component. The outputs of the phase shifters are combined and fed to

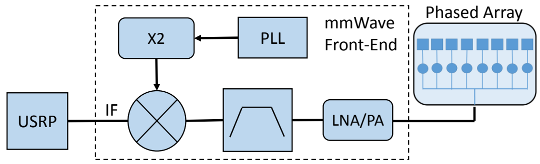

Figure 2— MiRa's Architecture: MiRa uses a heterodyne architecture where the mmWave signal is first taken into an intermediate frequency, before the I and Q components are separated.

a single mmWave front-end. The mmWave front-end consists of a low-noise amplifier (LNA) to amplify the received signal, a band-pass filter to remove the out-of-band noise and interference signals, and a mixer to downconvert the mmWave signal to the IF signal. The IF signal is then fed to the daughterboard on the USRP which samples it and passes the digitized samples to the UHD driver.

(b) Integration with GNU-Radio: To support flexible development, we designed our platform as a daughterboard for the USRP software radio. This enables easy manipulation of mmWave signals using standard GNU-radio software, and helps bring mmWave to the GNU-radio community. For example, one can use typical GNU-radio functions to transmit and receive, control the bandwidth of the signal, and change the center frequency. One can also use our radio to support mmWave MIMO functions, in a manner similar to how one builds a MIMO USRP node –i.e., by coordinating multiple USRPs with a shared clock to act as a MIMO device.

(c) Phased Array Calibration: mmWave phased arrays require a one-time calibration. The need for calibration stems from the non-linearity of phase shifters. Specifically, phase shifters are analog components used to change the phase of an RF signal. The phase shift introduced by a phase shifter is a function of its control voltage. This function is typically provided by the manufacturer as a plot which shows the phase shift for each control voltage. However, once these phase shifters are mounted on the phased array board, they perform differently due to the finite size of the antenna array, variation in antenna's feeding network, etc. Hence, it is required to calibrate individual phase shifters after mounting them on the board. To do so, we fix the input of all phase shifters except one, which we vary to scan the whole range of input. We empirically observe the phase shift resulting from each input and create a table that maps a phase shifter's input to the resulting phase.

(d) Implementation Details: We implemented the design in Fig. 2 using off-the-shelf components. For the mmWave low-noise amplifier (LNA) and power amplifier (PA), we use Hittite HMC-C020 and Quinstar QLW-2440, respectively. For the mmWave mixer, we use Marki M1R-0726MS. To generate local oscillator (LO) signals, we use Analog Devices ADF5355 PLL and Hittite HMC-C035 frequency doubler. We use a USRP X310 as an IF and baseband signal processing unit. The phased array is designed using HFSS software and fabricated on a printed circuit board (PCB) using Rogers substrate. The phased array includes 8 antenna elements separated by $\frac{\lambda}{2}$, where each element is connected to a Hittite HMC-933 analog phase shifter. We use Analog Device AD7228 digital-to-analog converters (DAC) and Arduino Due micro-controller board to digitally control the phase shifters.

3. Experimental Results

We evaluate MiRa's performance in indoor and outdoor senarios.

A. MiRa's Performance: We first evaluate MiRa's ability in enabling high data rates and long range communication using phased arrays. We measure the effective SNR of the received signal for different distances between MiRa's receiver and transmitter. Both transmitter and receiver use phased array antennas and the transmit power complies with FCC part15. At each distance, we run 30 different measurements where we transmit OFDM packets. We then decode the packets and calculate the effective SNR at the receiver side. Fig. 3 shows the effective SNR at the receiver side versus the distance between transmitter and receiver ranging from 2.5 m to 100 meters. The figure shows that MiRa provides SNR of more than 30 dB for distances smaller than 10 m. As expected, the SNR degrades as the distance increases. However, even at 100 meters, MiRa enables an SNR of 17 dB which is sufficient for relatively dense modulations such as 16 QAM [6].[1] Fig. 3 shows the constellation for 256 QAM and 16 QAM signals received at 2.5 and 100 meters, respectively. This provides visual evidence that the receiver can accurately decode the received signal, even for very dense constellations like 256 QAM and hence can deliver very high data rates.

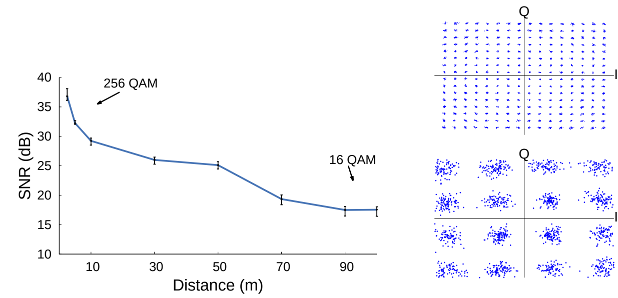

Figure 3— MiRa Coverage and Constellation. Figure shows effective SNR at the receiver versus distance between receiver and transmitter. It also shows that MiRa provides a full OFDM PHY capable of delivering up to 256 QAM and 16QAM for short and long distances, respectively.

B. MiRa's Extension MU-MIMO: MiRa provides a flexible platform that operates as a daughterboard for the USRP software radios. One can use multiple of the MiRa radios to support mmWave MU-MIMO. We simply connect two USRPs each equipped with an MiRa daughterboad to an external shared clock and we connect the MiRa radios to the single PLL. This gives us a mmWave MIMO node with two chains. We use this node as an access point (AP) transmitter and we implement MU-MIMO enabling it to send two streams simultaneously to two independent clients. We vary the positions of the clients in our office space and measure the gain in throughput of using MiRa's MU-MIMO over a mmWave system with no MIMO capability where the access point transmits only one stream at any point in time. Our results show that MU-MIMO increase the network throughput by 60% in average.

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[1] Note that, while one would expect higher SNR at closer distances, the increase in SNR is limited by the dynamic range of the USRP.